Chapter 7

Site Selection, Preparation and Installation of Seismic Stations

(Amended version, September 2011; DOI: 10.2312/GFZ.NMSOP-2_ch7)

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7.1 Factors affecting seismic site quality and site selection procedure (A. Trnkoczy; version 2002)

7.1.1 Introduction

Seismic site selection is not often given the amount of study it requires. The capacity of any new seismic network to detect earthquakes and to record representative event waveforms will be governed by the signal and noise characteristics of its sites, no matter how technologically advanced and expensive the equipment used. If seismic noise at the sites is too high, many of the benefits of modern, high dynamic-range equipment will be lost. If the noise contains excessive spikes or other transients, or if man-made seismic noise is present, high trigger thresholds will be needed and result in poor network detectability. If a station is situated on soft ground, very broadband (VBB) or even broadband (BB) recording can be useless and short-period (SP) signals may be unrepresentative due to local ground effects. If the network layout is inappropriate, the location of seismic events will be inaccurate, systematically biased, or even impossible. A professional site-selection procedure is therefore essential for the success of any new seismic station or network.

It is best to begin the process of site selection by choosing, generally, two to three times as many potential sites as will finally be used. One can then study each one and choose the sites that meet as many desired criteria as possible. One may even model the performance of a few most-likely network layouts and, by comparing the results, be able to make an informed decision about which layout will best record and locate seismic events.

All parameters relevant to the site selection process are discussed here and the process is demonstrated by seeking the best locations for a six-station network around a nuclear power plant. The main goals of this particular project (Trnkoczy and Živčić, 1992) were to monitor local seismicity with a high network detectability and the ability to accurately locate local events. Thus, the placement of short-period seismometers and of surface seismic vaults were mainly, but not solely, considered.

7.1.2 Offsite studies

The site selection procedure includes off-site studies and fieldwork. Off-site, or "office" studies are relatively inexpensive. They should be performed first. One can study maps and gather information about the potential sites from local and regional authorities. Once we have gathered all this information, it is likely that many potential sites will be eliminated for one reason or another. This will minimize future fieldwork and its associated costs.

A list of parameters usually included in the off-site study includes:

- geographic region of interest
- seismo-geological conditions
- topographic conditions
- accessibility

• seismic noise sources in the region
• data transmission and power considerations
• land ownership and future land use issues
• climatic conditions

7.1.2.1 Definition of the geographic region of interest

The first step is defining the goals and the geographic region of interest taking both socio-economic and seismic information into account. If the main goal of the new seismic network is monitoring of the general seismicity in an entire country, this stage is greatly simplified. For other projects, one has to examine all the known major geologic faults from geological maps with a view to assess their neotectonic activity and potential, identify seismotectonic features from seismotectonic maps, if available, and compile all available information about the seismicity in the area. One has also to compile historical and instrumentally recorded events in the broader region from earthquake catalogs and other sources. The results of such a study are shown in the following figures for an area in Slovenia. Fig. 7.1 shows the broader region chosen for our example and the main geological faults within it.

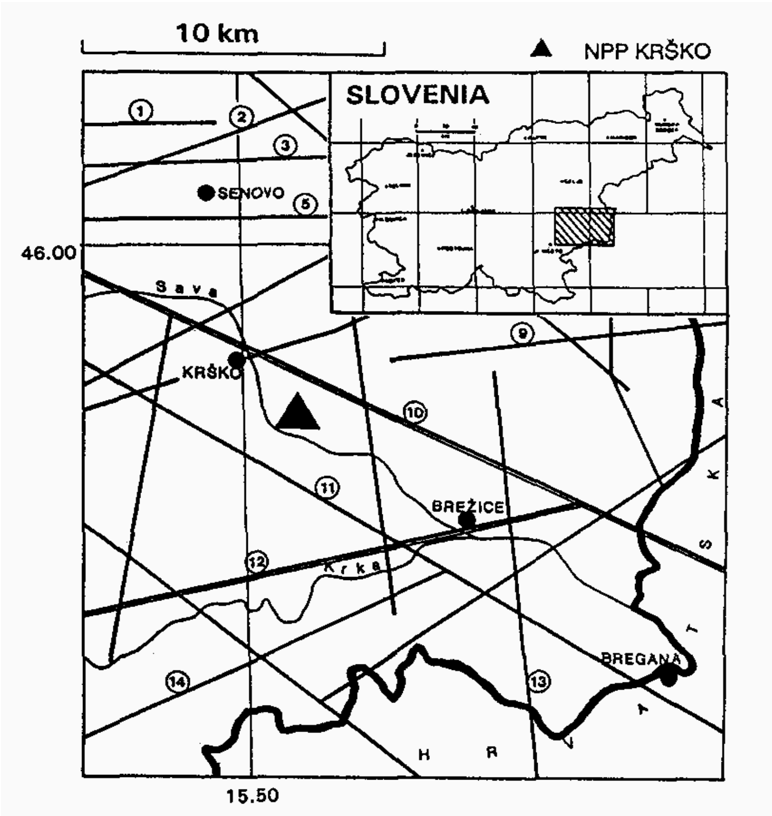


Fig. 7.1 The broader region chosen for the network in Slovenia and the main geological faults in this area (9 - Artice fault, 10 - Brestanica fault, 11 - Sava fault, 12 - Podbocje fault, 13 - Brezice fault, 14 - Orehovec fault).

Fig. 7.2 shows the distribution of earthquake epicenters as taken from seismic catalogs while Fig. 7.3 depicts the isolines of seismic energy release during the time-span of the catalogs and the hatched area finally chosen for the detailed study.

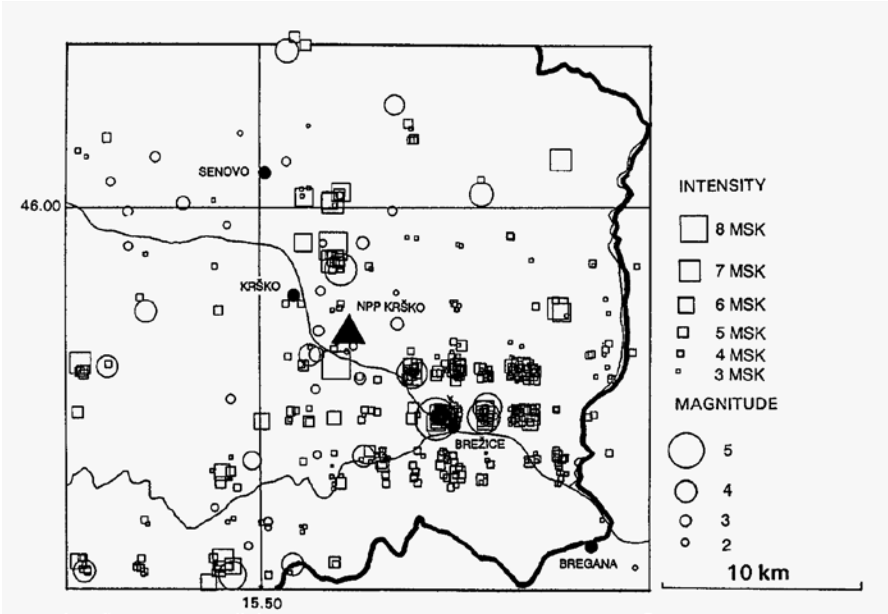


Fig. 7.2 Earthquakes in the wider region under investigation in Slovenia. The data were compiled from all available earthquake catalogs.

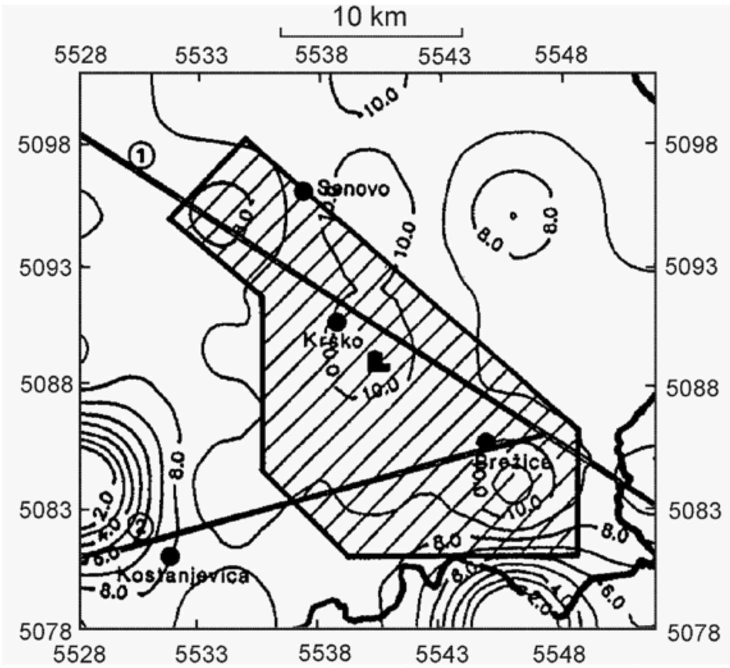


Fig. 7.3 Final choice of the area to be studied in detail by the seismic network (hatched area). Also shown are the isolines of released log-seismic energy during the time-span of the catalogs (in J/km^2).

7.1.2.2 Seismo-geological considerations

The underground conditions at a station influence both the seismic signal and the noise conditions and thus have a significant bearing on the potential sensitivity of a seismic station. Usually, the higher the acoustic impedance of the bedrock, the smaller the seismic noise and the higher the maximum possible gain of a station. Therefore, for each new seismic network, one should at least prepare a map showing simplified seismo-geological conditions. One may then infer a related map in terms of acoustic impedance or bedrock quality grades with respect to their suitability for the installation of seismic recording sites. Fig. 7.4 shows an example for the region under study while Tab. 7.1 gives an example of how bedrock “quality” grades may be classified.

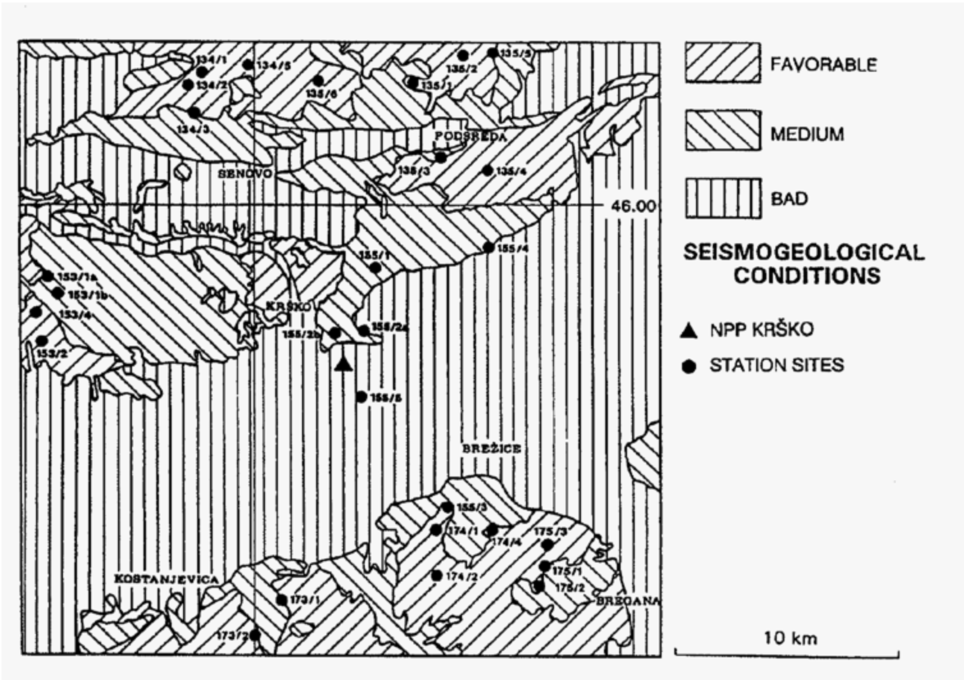


Fig. 7.4 Subdivision of the region shown in Fig. 7.2 into three grades of bedrock quality. The dots mark the positions of considered station sites.

Tab. 7.1 Classification of different types of outcropping geological formations in “quality” categories (according to R. Vidrih, personal communication 2001). Grade 5 is the best rock for seismic recordings and grade 1 is the worst.

Grade	Type of sediments/rocks	S-wave velocity
1	Unconsolidated (Alluvial) sediments (clays, sands, mud)	< 100 – 600 m/s
2	Consolidated clastic sediments (sandstone, marls); schist	500 – 2100 m/s
3	Less compact carbonatic rocks (limestone, dolomite) and less compact metamorphic rocks; conglomerates, breccia, ophiolite	1800 – 3800 m/s
4	Compact metamorphic rocks and carbonatic rocks	2100 – 3800 m/s
5	Magmatic rocks (granites, basalts) ; marble, quartzite	2500 - > 4000 m/s

Note: Shear-wave velocities given by engineers (e.g. Ambraseys et al., 1996) in relation to the category “ bedrock” (> 750 m/s) are significantly smaller than for competent hard rock due to near surface weathering (see 7.1.3.3) and the consideration of very short wavelengths only.

7.1.2.3 Topographical considerations

The topography in the vicinity of a potential site has to be considered. Extremely steep mountain slopes or deep valleys may unpredictably and unfavorably influence seismic waveforms and signal amplitudes. In addition, mountain peaks are usually much more susceptible to wind-generated seismic noise, lightning strikes, and perhaps icing of the communications equipment. Therefore it is wise to avoid such locations, if possible. Sites in moderately changing topography are preferable.

The topography also has to be considered for radio-frequency (RF) telemetry networks. Establishing RF links is much simpler if hill-top sites are selected, but it is important not to let this consideration compromise the seismological considerations. (See IS 7.2 Using existing communication tower sites as seismic sites.)

7.1.2.4 Station access considerations

Seismic stations are generally located in remote areas, as far as possible away from any human activity. This can often result in relatively difficult access. Public roads do not (or should not) reach most good seismic stations and walking a considerable distance, or the use of off-road vehicles, is more or less inevitable. Inexperience in site-selection often leads to too much compromise in this respect. One needs to find a reasonable trade-off between remoteness and ease of access. Stations which are too difficult to access are expensive to establish and maintain. In consequence, they often suffer from inadequate maintenance and long repair times.

Road maps and 1:25.000 scale topographic maps usually allow an approximate estimate of the difficulties and time needed to access any potential sites. In mountainous regions both the distance from the nearest road accessible by vehicle and the elevation difference between the site and the last point accessible by vehicle are important. One should allow between 15 and 30 min of cross-country walking time for each km of distance (25 to 50 min for each mile), depending on vegetation cover, and between 20 and 30 min for each 100 m (300 feet) of height difference. Stations which require more than half an hour of cross-country walking are rare. However, one has sometimes to accept longer walking distances, particularly if RF telemetry is involved.

Seismic stations are frequently set up at existing meteorological stations. This often happens in countries which are not experienced in seismometry and especially when meteorological institutions are appointed to maintain seismic installations. Such combination of stations or network operations are not advisable, since seismological and meteorological site selection criteria are very different.

7.1.2.5 Evaluation of seismic noise sources

An assessment of man-made and natural seismic noise sources in the region from maps is only the first stage of a proper seismic noise study. It should always be followed by field measurements of the noise. Nevertheless, road and railway traffic, heavy industry, mining and quarry activities, extensively exploited agricultural areas, and many other sources of man-made seismic noise around the potential sites, along with natural sources like ocean and lake shores, rivers or waterfalls can be evaluated in a qualitative manner from the maps and by inquiry of local authorities. Willmore (1979) gives valuable information about the recommended minimum distances between the site and these types of noise sources.

Distances are given for three different sensitivities of a seismic station, two different geological conditions and both high and low seismic coupling between noise source and station site. The table is reproduced in IS 7.3 along with instructions for its use. An example for its application for the station Loma Palo Benito is given in Fig. 7.5. Nearly all the minimum distance requirements for recordings with a gain around 1 Hz of between 50,000 and 150,000 are fulfilled (the distance to the lake shore is an exception). Six criteria are not fulfilled for a gain of 200,000 or more (see shaded cells).

Note that the above guidelines were designed for 1960's technology (analog paper seismographs). They are most applicable for seismic signal frequencies above 0.1 Hz; i.e., for the medium- and high-frequency range of seismic signals. Seismic noise at lower frequencies is mainly influenced by seismo-geological and climatic conditions (see 7.1.2.8) at the recording site and much less by the seismic noise sources dealt with in the table.

STATION SITE NAME: Loma Palo Bonito COORDINATES: N 18° 46' 58.4" W 70° 13' 20.1"		SITE #:7			DATE OF VISIST: 02/14/1998			ACTUAL DISTANCE
		HARD ROCK GRANITE, ETC.			HARDPAN HARD CLAY, ETC.			
		RECOMMENDED MINIMAL DISTANCES [KM]						
		A	**B**	**C**	**A**	**B**	**C**	[km]
1. Oceans, coastal mountains systems		**300**	**50**	**1**	300	50	1	**75**
2. Large lakes		**150**	**25**	**1**	150	25	1	**22**
3. Large dams, waterfalls	a	**40**	**10**	**1**	150	25	5	**22**
	b	**60**	**15**	**5**	50	15	10	
4. Large oil pipelines	a	**20**	**10**	**5**	30	15	5	
	b	**100**	**30**	**10**	100	30	10	
5. Small lakes	a	**20**	**10**	**1**	20	10	1	**20**
	b	**50**	**15**	**1**	50	15	1	
6. Heavy machinery, reciprocating machinery	a	**15**	**3**	**1**	20	5	2	**25**
	b	**25**	**5**	**2**	40	15	3	
7. Low waterfalls, rapids of a large river, intermittent flow over large dams	a	**5**	**2**	**0.1**	15	5	1	
	b	**15**	**3**	**1**	25	8	2	**6**
8. Railway, frequent operation	a	**6**	**3**	**1**	10	5	1	**40**
	b	**15**	**5**	**1**	20	10	1	
9. Airport, air traffic		**6**	**3**	**1**	6	3	1	
10. Non-reciprocating machinery, balanced industrial machinery	a	**2**	**0.5**	**0.1**	10	4	1	**25**
	b	**4**	**1**	**0.2**	15	6	1	
11. Busy highway, large farms		**1**	**0.3**	**0.1**	6	1	0.5	**2.3**
12. Country roads, high buildings		**0.3**	**0.2**	**0.05**	2	1	0.5	**2.0**
13. Low buildings, high trees and masts		**0.1**	**0.03**	**0.01**	0.1	0.1	0.05	**0.03**
14. High fences, low trees, high bushes, large rocks		**0.05**	**0.02**	**0.005**	0.06	0.03	0.01	**0.02**

Legend:

A - Seismic station with a gain of 200,000 or more at 1 Hz

B - Seismic station with a gain from 50,000 to 150,000 at 1 Hz

C - Seismic station with a gain of approximately 25,000 at 1 Hz

a - Source and seismometer on widely different formations or that mountain ranges or valleys intervene

b - Source and seismometer on the same formation and with no intervening alluvial valley or mountain ranges

Fig. 7.5 Minimum recommended noise-source-to-station-site distances according to Willmore (1979) and actual distances for the seismic station Loma Palo Bonito, which is placed on hard granite rock. Shaded cells indicate that for these criteria the conditions for a class A site are not fulfilled.

Nowadays, with the ready availability of seismic recorders with a large dynamic range, it would be preferable to express the seismometer gain classes A – C in terms of the achievable minimum resolution of ground displacement or velocity amplitudes above the noise level at about 1 Hz. These would be approximately < 5 nm or < 30 nm/s, respectively, for class A and about 2-4 times and > 8 times larger for classes B and C.

For each potential site in a network, one should determine, using maps, the actual distances of the site from relevant seismic noise sources (the extreme right column) and compare them with the recommended minimum distances. The sites which satisfy all or most of the recommendations are the best. Note, however, that local seismic noise sources like trees, buildings, fences, would require on-site evaluation. This information can be added to the table later during fieldwork.

Once we have gathered this information for all the potential sites in a network, we can draw a map, similar to that in Fig. 7.6, where all the potential sites and minimum recommended distances from known seismic noise sources are shown. The latter is achieved by drawing circles around point noise sources and bands of appropriate width along roads or railways. This gives a good overview of all the noise sources at once and helps us to see which ones and how many of them influence a particular potential seismic site.

Fig. 7.6 Map of the seismic network region with all potential station sites (full dots) and known seismic noise sources (roads, railway, cities, villages, industrial facilities, quarries, etc) with circles of minimum recommended distances drawn around them for the case of gain 25.000 for SP seismic stations at 1 Hz set on hard clay, hardpan and similar ground, i.e., case

C b (i.e., source and seismometer on same formation and with no intervening alluvial valley or mountain range) according to Willmore (1979).

7.1.2.6 Seismic data transmission and power considerations

For radio-telemetry networks we must consider the topography within the entire network in order to design the data transmission links. Topographic maps (1:50.000 or 1:25.000) are best for this purpose. We look for a topography which enables reliable direct radio frequency (RF) links from the remote stations to the central recording site, or the minimum number of RF repeaters if topography and/or distance do not allow direct connection. More information is given in section 7.3.

If telephone lines are used for seismic data transmission, we must first check for line availability and the distances over which new lines would have to be installed. This information can be obtained from local telephone companies. New phone lines are often a significant proportion of the total cost of site preparation.

The next question concerns the power supply. If mains power is not available on site, we need to calculate the distance over which new power lines would have to be laid and the likely costs. If this is not possible, or the cost is too great, the cost for solar panels has to be evaluated.

7.1.2.7 Land ownership and future land use

During planning of a new network it is very important to clarify the ownership of the land being considered for a station and any plans for its future use. It makes no sense to undertake extensive studies if one is actually unable to use certain sites because of property ownership issues or if it appears that future development will make the site unsuitable for a seismic station. This information should be gathered from local (land ownership) and regional (future land use) public offices and authorities.

If the land is privately owned, one should contact the owner as soon as possible and make every effort to agree on a renting or purchasing contract to the satisfaction of both parties. It is very important to have "friends" rather than "enemies" around the seismic stations. In many countries this may be very important for the security of the installed equipment.

7.1.2.8 Climatic considerations

Several climatic parameters can influence seismic site selection. Regional or national meteorological surveys can provide this information. It can also be found in yearly or longer-term bulletins, which are published by nearly every meteorological institution. In developing countries it is sometimes not easy to get complete information. However, we do not need precise values for these parameters and even rough estimates can help in site selection and design of seismic shelters.

The following climatic parameters are important:

- The minimum and maximum temperatures at a site determine how much thermal insulation will be needed for the seismic vault and instruments. Temperatures below zero degrees Celsius may cause icing of antennae. Special shielding is often required in high mountains and polar regions.

• We need to know the frequency and maximum wind speeds at sites. Wind is a major source of seismic noise, so sites with less wind are preferable to sites placed on windy mountain ridges.

• Solar data is needed to determine the minimum size required for solar panels, if they are required to provide power. The number of sunny days in the worst month and/or the longest expected uninterrupted cloudy period in a year can serve as a measure.

• The frequency and amount of precipitation (total precipitation per year and maximum precipitation per hour) will determine protection measures required to keep the vaults dry.

• In colder climates, annual snowfall levels determine how accessible a station will be during the winter, the waterproofing measures required and – if used – the optimum installation angle and size for solar panels.

• Protection against lightning is very important and has significant financial consequences. One needs to decide on what protection equipment is necessary using information on the observed frequency of lightning. Alternatively, one has to calculate how much lightning damage is likely if protection measures are not implemented. The best method for this is to obtain isokeraunic isolines, which are related to the probability of a lightning strike. This data is rarely available and it is often easier to obtain less specific but more generally available meteorological parameters – such as the annual number of days with severe thunderstorms in the area. Lightning usually varies enormously from one region to another and also varies locally, depending on the topography. Serious consideration of these parameters and the knowledge of local people on these issues are definitely worthwhile.

7.1.3 Field studies

Field studies are the next step in the site selection process. Expect to make several visits to each potential site. A seismologist familiar with seismic noise measurements, a seismo-geologist, and a communications expert (if a telemetry network is considered) should all visit the sites. You should allow between one and three days per site to accomplish the fieldwork. This assumes that all pertinent maps and information are available in advance and the logistics are well organized. Much also depends on a country's infrastructure and the size of the network. If the network will use RF telemetry, add an extra 20% to the time for topographical profiling and RF link calculations.

If site selection is purchased as part of the services provided by an equipment manufacturer, see IS 7.1 for a summary of the information that should be provided to them.

In general, experts visiting the sites should:

- verify the ease (in any weather) of access to the site;
- search for very local man-made seismic noise sources which might influence the site, but may not be indicated on maps (see text to Fig. 7.7);
- perform seismic noise measurements;
- study the local seismo-geological conditions;
- investigate the local RF data transmission conditions (if applicable);
- verify availability of power and telephone lines.

7.1.3.1 Station access verification

Station access should generally be possible throughout the year. However, a few days of inaccessibility due to snow or high water per year can normally be tolerated. This can be checked by talking to local people.

If non-public dirt roads are used to access the site, we need to ask about the future of these roads since roads built and owned by private, military, or forest authorities are sometimes abandoned. If there is no guarantee that such roads will be maintained in future, it is better to reposition the seismic site.

7.1.3.2 Local seismic noise sources and seismic noise measurements

During fieldwork, one should explore the vicinity of the potential site for local sources of seismic noise, usually man-made, which may not be resolvable from the available maps. A single small private "industrial" facility too close to the site may ruin its seismic noise performances completely. Local people are the best source of information.

Measuring seismic noise at the site is an important task. Seismic noise varies greatly depending on the season of the year, weather conditions, and innumerable daily occurrences. Seasonal variability of seismic noise has mainly natural causes and is clearly developed for periods, T, greater than 2 s. The variation may be as large as 20 dB at the spectral peak for ocean-storm microseisms close to T = 7 s. In contrast, high-frequency noise is mostly man-made (traffic, machinery), often with a pronounced diurnal variation of the order of 10 to 20 dB. In order to accurately record all these factors, it is best to take measurements at each site over a long period of time; long enough to record a number of earthquakes. These will allow a comparison of the sites based on signal-to-noise ratio, which is the main guiding parameter for the quality of a site.

Sufficiently long measurements are often not performed for financial reasons. In such cases, some measurements are much better than none at all. Short-term measurements can not provide complete information about the noise levels at a site, but they are still very useful to identify man-made noise sources and to assess the daily noise fluctuations in the important frequency range for small local and teleseismic events (i.e. from 0.5 Hz to 20 Hz). It is important that any short-term measurements (say of 15 min duration) are carried out during specific times when maximum and minimum noise conditions are expected.

To assess the potential influence of long-term natural seismic noise variation, we should also obtain noise data from existing seismic stations in the region. If there are none of these, we have to set up one or more temporal reference stations which are not moved from site to site. By comparing noise records taken at the same time at the reference station(s) and the potential new site locations we can, at least with respect to the long-period natural seismic noise, assess the representativeness of the noise data sampled at the potential sites by scaling it to the reference site(s). This assures that any variations in natural seismic noise levels over time will not affect the comparison of different potential sites.

Records of seismic noise are usually presented as noise spectra. These can reveal more information about the type and importance of various seismic noise sources around the site than the corresponding time-domain records alone. A typical noise spectrum is shown in Fig. 7.7. We can easily see high levels of man-made seismic noise (frequencies around 15 Hz). Spectral spikes from 3 to 5 Hz shown in this spectrum originate from heavy machinery working in a quarry at 4 km distance.

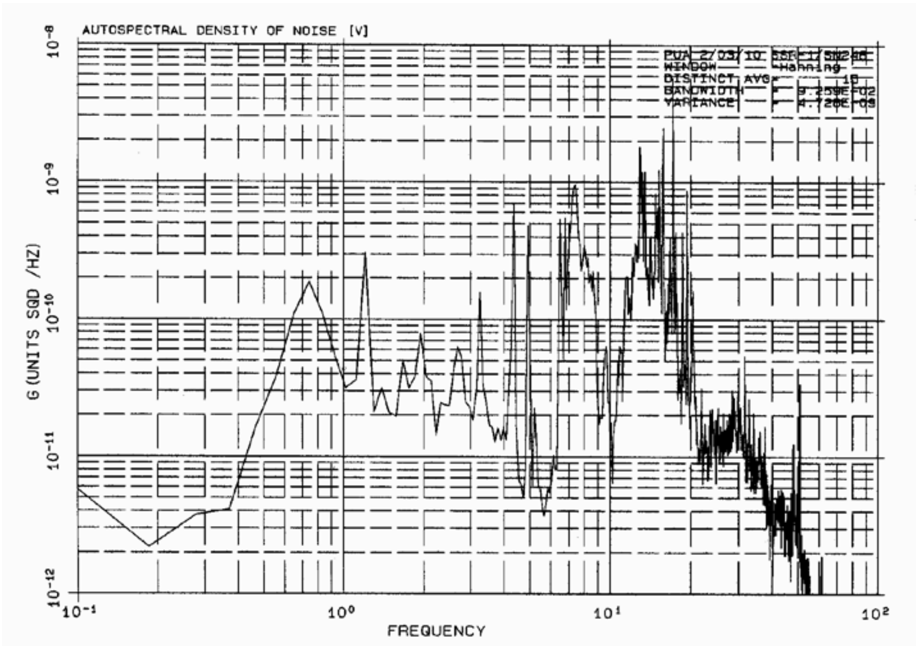


Fig. 7.7 Typical seismic noise spectrum (ground velocity power density in $m^2/s^2/Hz$) at a potential seismic station site showing man-made seismic noise generated by a nearby city and heavy machinery working in a 4 km distant quarry.

However, noise spectra should never be determined without prior inspection of the original time domain records which have to be cleaned of unrepresentative spurious or transient events. Also the analysis of noise conditions should never be made on the basis of the calculated spectra alone but always in conjunction with the related time-domain records. Examples are given in sub-Chapter 7.2.

The data requirements for noise analysis depend on the type of station to be installed. For short-period stations, use noise records that are at least two minutes long to allow calculation of stable seismic noise spectra in the frequency range from 0.1 to 50 Hz. For broadband stations, use noise records that are at least twenty minutes long for noise spectra calculations from 0.01 to 50 Hz. The sampling rate should be at least 100 Hz in both cases. In order to reduce any bias due to diurnal noise variations, the measurements at the various sites should be taken at about the same time of the day. Whenever possible, use identical equipment and processing methods at all potential sites and at the reference station(s). This greatly simplifies the normalization procedure. More information about seismic noise and its measurement is given in sub-Chapter 7.2

It should be mentioned here that the assessment of seismic noise for a Very-Broad-Band (VBB) seismic station requires much more effort. Days or even months of measurement are often required to get a full picture of the seismic noise conditions at the potential site (see

Uhrhammer et al., 1998). A quiet short-period station site is not necessarily a good long-period noise site. Seismic noise may behave differently in the different frequency ranges.

7.1.3.3 Field study of seismo-geological conditions

A seismo-geologist should study the geology to determine its local complexity. Uniform local underground conditions are preferred for seismic stations. The seismo-geologist should also verify the actual quality of bedrock as compared to that given in geologic maps and try to estimate the degree of weathering that local rocks have undergone. This can sometimes give a rough estimate of the depth required for the seismic vault to place the seismometers on unweathered bedrock. Unfortunately, it is often highly unreliable to judge the required vault depth in this way. At most sites only shallow seismic profiling, drilling, or actual digging of the vault can reliably reveal how deeply the rock is weathered and how deep the seismic vault must be. If shallow profiling is planned (see 7.1.3.5 below), the seismo-geologist should precisely determine the position of the profiles.

If there are local sources of high-frequent seismic noise around the site, a seismologist should carefully assess, both by inspection and measurement, to what extent they might affect recordings at the site. If the noise sources and the site are located on the same rock or soil formation, one can expect a high degree of seismic coupling between the noise source and the station. On the other hand, when the noise sources and the station are located on different geological formations with a significant impedance contrast between them, the seismic coupling is rather weak. In this case even nearby noise sources might not disturb seismic records much. The station BRG in Germany is a striking example. This is one of the best stations in the German Regional Seismograph Network (GRSN). The station is located in the middle of a busy resort town, next to a main road built on the aggraded bank of a rushing creek. The seismographs have been placed 150 m away from the road in an abandoned mining gallery which was driven horizontally from the road level into an outcropping Devonian hornschist rock cliff. Thus, the seismic sensors are well decoupled from the nearby-generated traffic noise. The site quality of BRG would correspond to B in Fig. 7.5.

7.1.3.4 Field survey of radio frequency (RF) conditions

A communications expert visiting the site should examine potential obstacles to radio-wave transmission. He or she should also examine the immediate topography surrounding the site because frequently it can not be resolved from 1:50,000 scale maps, normally used in RF topographical profiling. This study needs to define the minimum required antenna height for reliable data transmission. For more information see sub-Chapter 7.3.

7.1.3.5 Shallow seismic profiling

Shallow seismic profiling is usually the last step in the site selection process. It is probably the most expensive step and has usually to be contracted out to a seismic-engineering company. It should be done only at the most likely and most important sites. Shallow refraction profiles yield quantitative parameters on the rheological quality of the bedrock and enable determination of the depth of weathering. The results can determine the best position of the seismic vault as well as its required depth. One should use two approximately perpendicular profiles, each about 100 meters long, in order to determine the seismic wave velocity (for P and/or S waves, depending on the type of source used) down to a depth of 20 to 30 meters. This is enough even for the deepest seismic vaults considered. If the seismometer is to be installed in a borehole, seismic profiling needs to penetrate to depths of about 100m, the typical maximum borehole depth.

If seismic profiling is not included in the site evaluation, most likely for financial reasons, unexpected results may occur when digging the seismic vault. One should dig until reaching bedrock and that can sometimes be unexpectedly deep. One needs to anticipate that vaults will have to be repositioned and re-dug if weathered bedrock happens to be extremely thick. This often makes the relatively high cost of profiling a wise investment. The same argument applies to boreholes, although it is easier and less costly to deepen or move a borehole than it is for a vault.

7.1.4 Using computer models to determine network layout capabilities

Once we have decided on the final number of seismic stations and are very close to the final layout of the system, meaning that we have chosen two or three possible network layouts, the next useful step is to make a computer model of the network. The modeling should answer the question: Which particular network layout performs best for different aspects of network performances? One can then use these results to choose the best possible network layout for particular requirements. Among the parameters one may wish to study are:

- network detectability in terms of the spatial distribution of minimum magnitude of events which can still be recorded with a given signal-to-noise ratio (Fig. 7.8);
- precision (i.e., calculated accuracy) of event epicenter determinations in the region (Fig. 7.9);
- precision of event hypocenter determination in the region (Fig. 7.10);
- maximum magnitude of events that can be recorded without clipping (this requires an assumed gain and dynamic range of the recording equipment to used in the network).

Note that optimal configurations for event location are often not optimal for source mechanism determination, tomographic studies or other tasks (Hardt and Scherbaum, 1994).

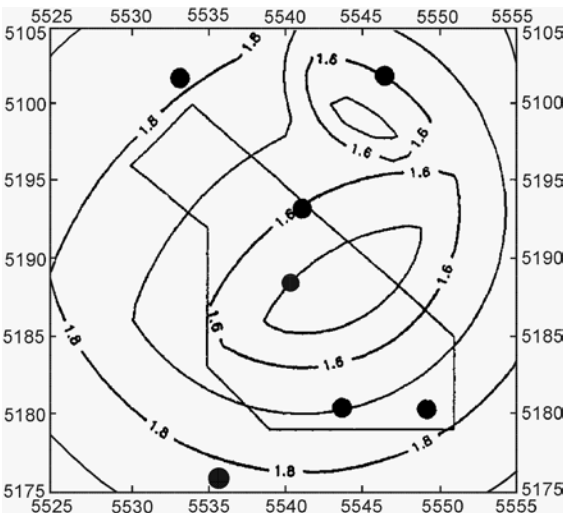


Fig. 7.8 An example of computer modeling of network capabilities. Isolines of minimum magnitude of events detected at 5 seismic stations (from six in the network) with a signal-to-noise-ratio >20 dB are shown for the best of the alternative network layouts.

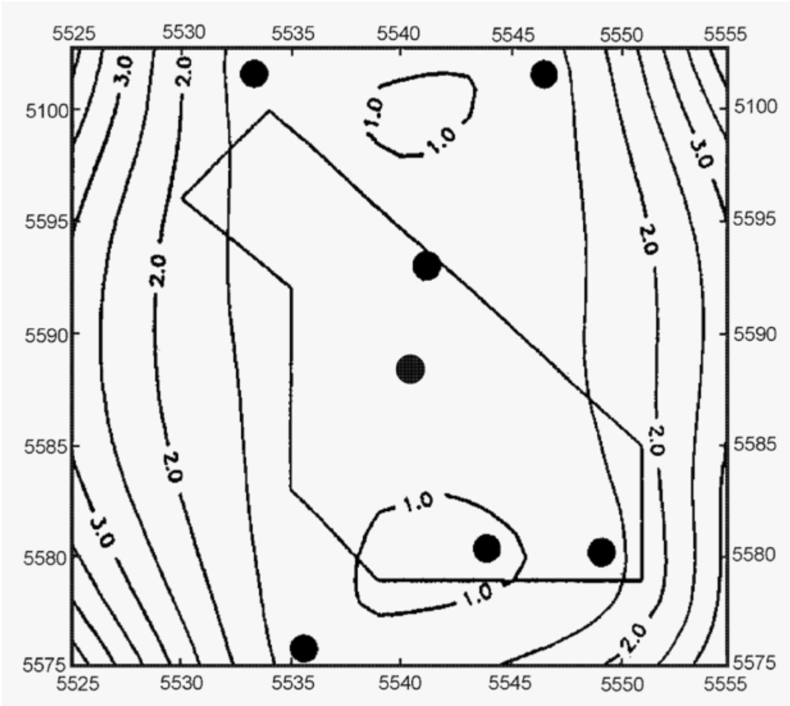


Fig. 7.9 An example of computer modeling of network capabilities. Isolines of uncertainty of epicenter determination in km (± 1 standard deviation) are shown for the best of the alternative network layouts.

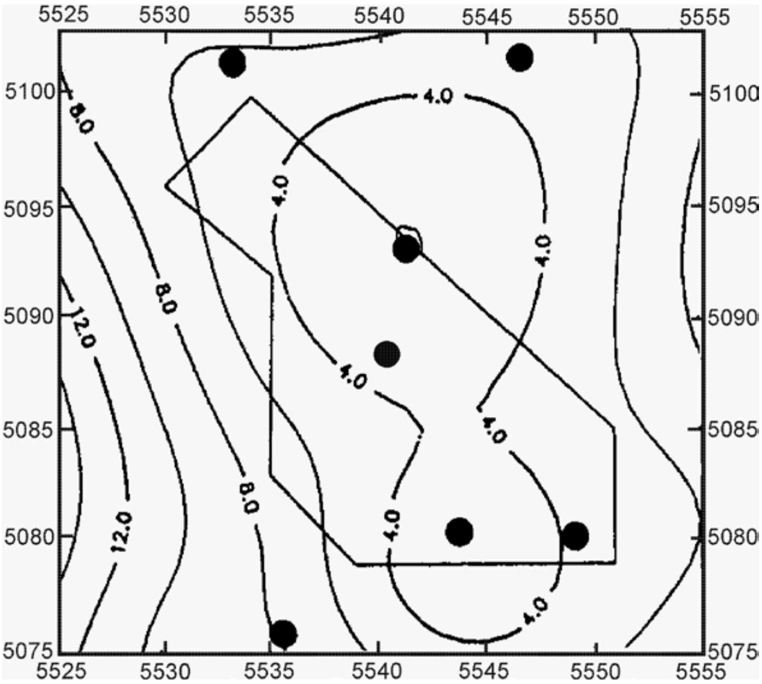


Fig. 7.10 An example of computer modeling of network capability. Isolines of uncertainty of hypocenter determination in km (± 1 standard deviation) are shown for the best of the alternative network layouts.

Several methods for direct computer calculation of optimal network configuration (layout) are described in the literature (e.g., Kijko, 1977; Rabinowitz and Steinberg, 1990; Steinberg et al., 1995). However, practical limiting conditions with respect to infrastructure, topography and accessibility usually outweigh such theoretical approaches. "Optimal" layouts calculated with these methods are rather sensitive to initial conditions such as the predicted gain of stations. This often renders results of questionable value. However, some of these programs may be of help in deciding whether to add or remove stations to an existing network (e.g., Trnkoczy and Živčić 1992; Hardt and Scherbaum 1994; Steinberg et al. 1995; Bartal et al. 2000).

A more detailed discussion of these programs is beyond the scope of this Manual. Simple methods usually suffice for our purposes because we want to compare results for various layout options. Determination of network performances in an absolute sense requires a more sophisticated approach. One program which works rather well for relative performance and which can be made available on request is described in IS 7.4: "Detectability and earthquake location accuracy modeling of seismic networks". The program is based on a simplified and uniform attenuation law for seismic waves in a homogeneous half space or in a single- or double-layer ground model. The software uses estimated uncertainties in the P- and S- wave velocities in the model and in the P- and S-phase readings. The software requires as an input the predicted sensitivity of the seismic stations in the network based on measured seismic noise amplitudes at the sites.

No matter what modeling work is carried out, choosing a seismic network layout always involves making good, educated guesses based on experience.

7.2 Investigation of noise and signal conditions at potential sites
(P. Bormann; version 2002)

7.2.1 Introduction

The general factors affecting seismic site quality and suitable site selection procedures have been discussed above. This sub-Chapter discusses specifically the instrumental measurement of seismic noise and signals for optimal site selection, discusses specific features of noise records and spectra from different noise sources and gives recommendations for carrying out such measurements. In the following we discriminate between:

- reconnaissance noise studies prior to station site selection;
- comparison of noise and signal conditions at existing permanent stations;
- searching for alternative sites in a given network.

Examples for each case are based on data from noise surveys in Iran and Germany.

Many sites in a wide area usually have to be inspected and measured during reconnaissance noise studies, sometimes covering an entire country. Carrying out such a survey within a reasonable time and reasonable cost often dictates making measurements with short-period instruments. These are easily and quickly deployed, require less care than long-period or broadband sensors for thermal shielding and underground tilt stability, and yield stable records immediately after installation and useful high-frequency spectra from a few minutes of recording. Many potential sites can then be measured within a day and thus quickly give a

good idea of their suitability depending on surface geology, topography, distance from potentially disturbing noise sources, etc.

However, short-term measurements using short-period seismographs do not allow judgement of the level of long-period noise (T > 3 s). They are also not very suitable for assessing seasonal or diurnal variation of seismic noise. Furthermore, it is highly unlikely that during the short time windows of measurements, any signals from real seismic events will be recorded which would allow comparison of signal-to-noise-ratios (SNR) at different sites. This is important because sites with the lowest noise are not necessarily the sites with the best signal-to-noise ratio. Signal amplitudes may vary by a factor of three or more, depending on local conditions (see Figs. 4.34 to 4.36).

Nevertheless, short-period and short-term noise measurements are sufficient to get an idea of the high-frequency (f > 0.3 Hz) background noise and to assess the potential influence of various types of man-made noise sources. It is also possible to assess the daily noise variability and to scale and compare measurements at the more remote sites by using a reference station at the nearest main source of man-made noise (town, factory, railway line, high way, etc.), which records throughout the investigation. In this way, we can get a reliable idea of the relative suitability of different potential sites for the frequency range of small local, regional and teleseismic events (0.3 Hz < f < 30 Hz).

Existing permanent recording sites with stable recording platforms and reasonable shielding against environmental influences allow long-term comparative measurements of both seismic noise and signals in a much broader frequency band. These will give a more reliable assessment of the suitability of sites for event detection and location and also for a variety of other seismological tasks, such as source mechanism studies, tomographic studies of the Earth´s structure or the use of very long-period normal modes.

If some of the sites within a seismic network are significantly noisier than others, one should look for alternative sites. For a broadband network, the measurements at alternative sites must be made with the same type of broadband sensors and with every precautions for stable installation and appropriate shielding against wind, weather and direct sunshine. The recording time at each site should be long enough to ensure proper stabilization of the sensor after installation (a few hours to days). Additional days or weeks of recording are needed for assessing diurnal noise variability and relative SNRs for local and teleseismic events.

7.2.2 Reconnaissance noise studies prior to station site selection

7.2.2.1 Offsite assessment of expected noise levels and measurement of instrumental self-noise

Field measurements should always be preceded by offsite studies (see 7.1.2). They help locate the most promising sites and most likely noise sources, help speed up the measurements and reduce the risk of unwanted surprise in the field and final assessment.

When geologic, environmental, climatic, settlement and infrastructure conditions indicate that sites may have very low levels then only high-performance short-period seismographs with very low instrumental self-noise should be used for noise measurements (see 5.6). The level of self-noise should be measured before going into the field and compared with the global

New Low Noise Model (NLNM) (see Fig. 5.21). The seismometer noise should be at least 6 dB below the minimum local seismic noise for the entire pass band of the sensor. The signal pre-amplification has to be set high enough to ensure that very low-level ambient noise is well resolved. The resolution of the data acquisition unit should be set at about 18 dB (3bits) below the minimum local seismic noise over the pass band of the seismograph. Clearly, the frequency response of the seismograph must be known or has to be determined beforehand (see 5.7 and 5.8 and well as the exercises EX 5.1 to 5.5).

Fig. 7.11 shows the combined frequency response of an SS-1 seismometer and an SSR-1 recorder used in field measurements for site selection in NW Iran.[1)] The sampling rate was 200 Hz using a 6^{th} order low-pass filter with corner frequency f_c = 50 Hz in order to avoid spectral aliasing (see 6.3.1). The filter reduces the seismograph gain between f_c and the Nyquist frequency f_{Ny} (half of the sampling frequency) in such a way that very small seismic background noise signals no longer may be resolved above the least-count digitizer noise. Correcting the noise spectrum for the decrease in seismograph gain for $f > f_c$ results in an *apparent* increase of noise power between f_c and f_{Ny}. This is clearly to be seen in Fig. 7.12. Here, therefore, we consider only noise spectra up to 1/4 or 1/2 of the sampling frequency.

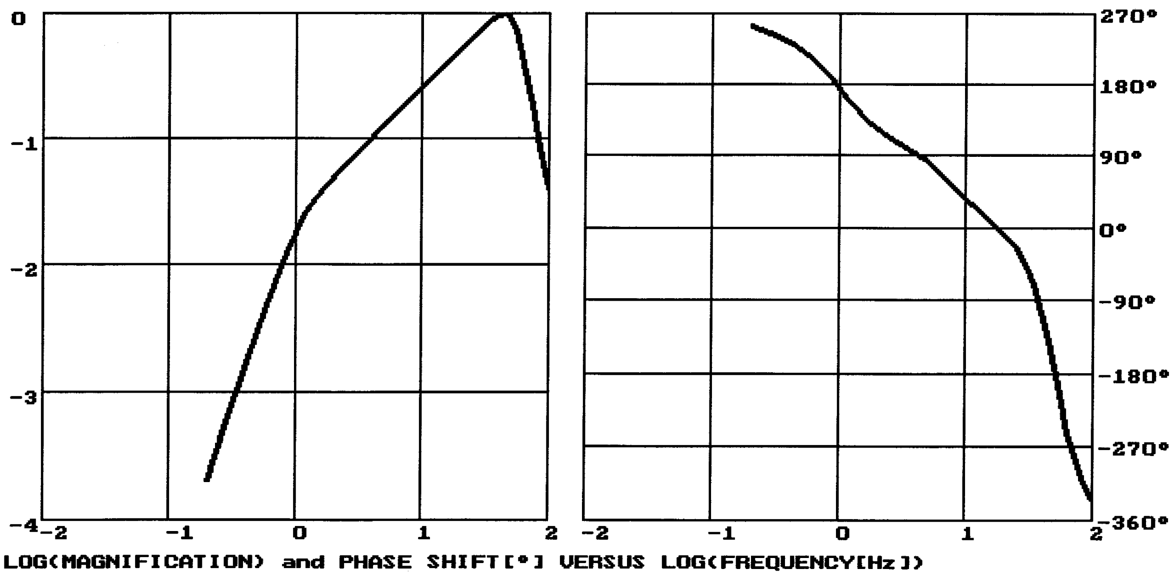


Fig. 7.11 Amplitude and phase response curves for the seismometer-recorder combination SS-1/SSR-1 as used in field measurements in NW Iran (see Figs. 7.12 to 7.21). The response is proportional to velocity between about 1 and 50 Hz.

[1)] The data in Iran have been collected as part of a joint project between the International Institute of Earthquake Engineering and Seismology (IIEES) and UNDP (Ref. No.

IRA/90/009). The data relates to the seismic noise measurements at potential station sites for the Iranian National Seismic Network (INSN). The authors thank Prof. M. Ghafory-Ashtiany, President of IESSS, for the technical and staff support provided and for his kind permission to publish part of the data in this Manual.

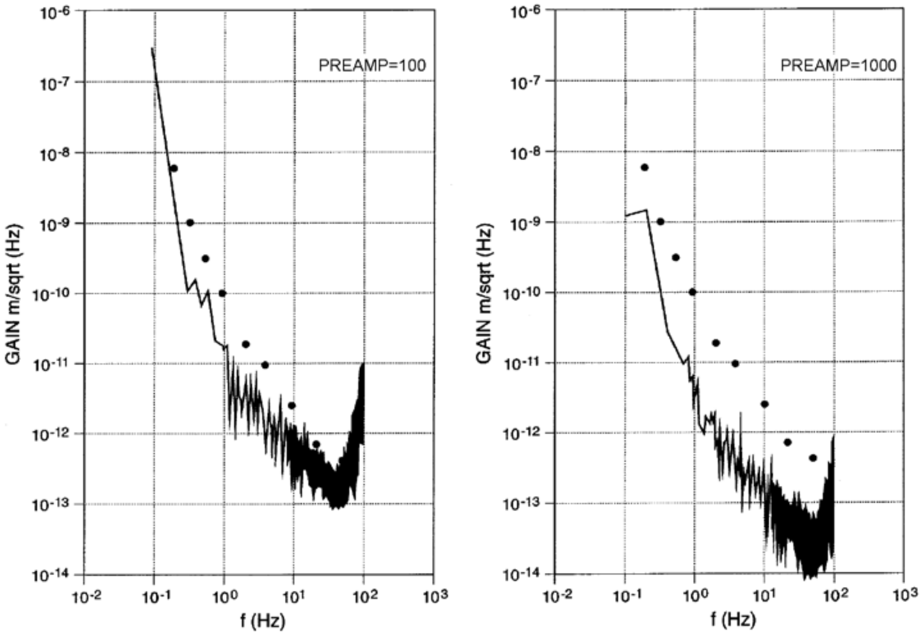


Fig. 7.12 Comparison of the average values (•) of the ground displacement spectrum of seismic noise recorded at the quietest site found during a noise survey in NW Iran with the equivalent displacement spectrum of the combined instrumental self-noise of the Kinemetrics SS-1 seismometer and SSR-1 data logger at a pre-amplification level of 100 times (left) and 1000 times (right). One order of magnitude difference in the amplitude spectra corresponds to 20 dB difference in the respective power spectra. In this case only the higher pre-amplification allows the resolution conditions to be met at the quietest sites in the area under investigation. Current data loggers using 24 bit digitizers connected to high output seismometers generally cover the dynamic range down to and below the low noise model. Nevertheless the use of lower output seismometers, e.g. short-period geophones, still require switchable pre-amplifications in the range of 10 to 100.

7.2.2.2 Sensor installation, measurements and logbook entries in the field

Potential measurement and reference sites should be pre-selected before going into the field, based on geologic and road maps and taking into account other significant aspects or findings from preceding offsite studies. The selections may be changed during the field inspection. Essential points to be considered in field studies have already been outlined in section 7.1.3. The following complementary rules should be observed:

- take daily synchronization of the internal clocks of the data loggers used in the field and at the reference site if they have no common time reference such as GPS-controlled clocks.
- keep a log-book;

- note carefully all relevant features which characterize the measurement sites (local geology and topography, compact or weathered rock outcrop, soil type, vegetation cover, distance to settlements or industry, main roads, power lines);
- note the environmental conditions during measurement (weather, wind, rain, insolation) and the occurrence time of any transient events that might have influenced the noise record (e.g., wind gusts or cars, trains or people passing by at what distance);
- mark the position of any measurement site in your road and/or geological map;
- take representative photographs of each measurement site and sensor installation;
- whenever possible, position the seismometer directly on a flat outcropping rock surface and level it with its three adjustment screws. Unusually-long adjustment screws can be fitted to help level the sensor on rough rock surfaces (proper counter-locking of the screws ensures sensor stability);
- in the case of well-binding (clayish) soil, screw long-leg tripod adjustments directly into the soil. Alternatively, position the seismometer on a thick solid rock plate placed firmly on the ground after removing any loose gravel or vegetation (Fig. 7.13). This may be the only reliable solution when making three-component noise measurements if three individual sensors are used requiring identical installation conditions. It may also work well on rough rock surfaces as long as a nearly horizontal stable three-point support of the plate can be found. A rock plate is not necessary if the three components are mounted in the same package, e.g. for Mark L4C-3D seismometers (see DS 5.1).

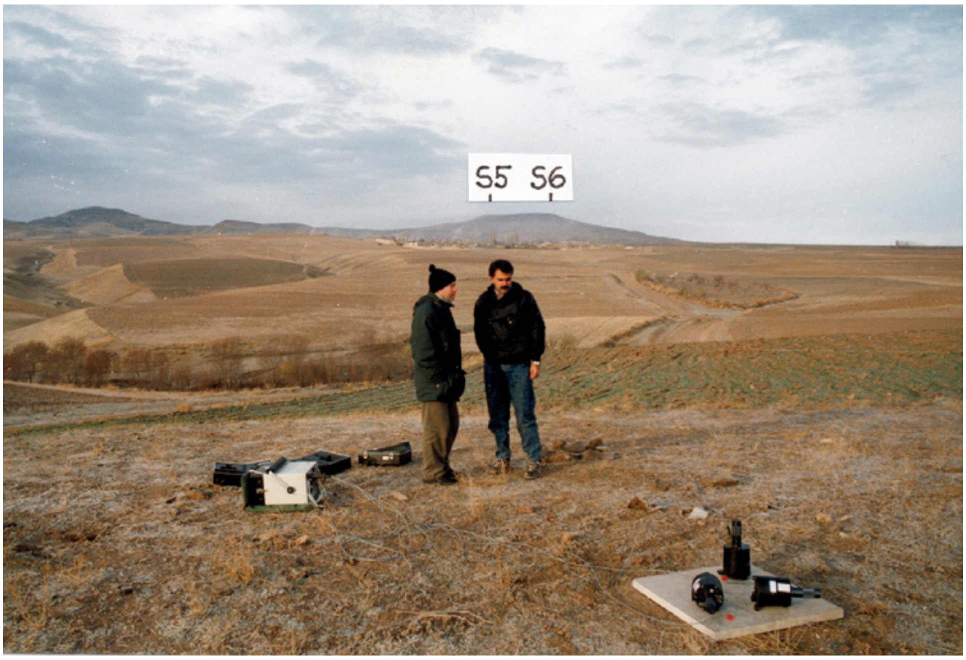


Fig.7.13 Temporary three-component reference installation in NW Iran on a leveled marble plate placed on unconsolidated ground. Two other measurement points on the horizon using outcropping hard rock are marked. The noise at the latter sites was close to the NLNM.

- in the case of wind, rain or snowfall, try to find shielding on the lee-side of a rock-face (Fig. 7.14) or bury the sensor in the ground and cover it with a tightened sheet or blanket or with a box;

- if test measurements show that noise levels are comparable for all three components in the area under investigation it is sufficient to continue the survey using only vertical component recordings. This is usually the case in isotropic noise fields, i.e. in the absence of distinct localized noise sources.
- set up at least one continuously-recording reference station in the study area in order to assess the influence of diurnal noise variations on the measurements made at different sites and at different times of the day. The reference station can be used to scale the noise records at the other sites (see Fig. 7.15).

Fig. 7.14 Hiding with the noise recording equipment on a windy day with snowfall in a small cave on the lee-side of a rock cliff. Surface recordings under adverse weather conditions of the noise level at this site in NW Iran were close to the best sites in good weather.

- take comparative measurements at different distances are recommended to assess the reduction of noise with distance from transient sources (such as nearby road or railway traffic). Measurements on different soil conditions may also be needed if the noise also depends on the lateral impedance contrast of adjacent rock formations (see Figs. 7.16 and 7.17).
- if, at low-noise sites, the ground displacements are of the order of nm (10^{-9} m), do not stand or walk close to the sensors during the recordings. Stay at least 10 m away, remain sitting down, and keep absolutely quiet (see Fig. 7.18).
- stay several hundreds of meters away from large power lines or transformer houses. Otherwise you may get strong induction currents in the seismometer's measurement coils or record 50 to 60 Hz vibrations that are typical of large transformers or heavily loaded power lines (see Fig. 7.19).

7.2.2.3 Case study of noise records in the frequency range 0.3 Hz < f < 50 Hz

Fig. 7.15 shows the daily noise variation at a reference site in a town in NW Iran. The noise between night and day time varies by about 20 to 30 dB around 1 Hz and by about 50 dB around 10 Hz because of the site's proximity to a main road and poor underground conditions. Fig. 7.16 shows the large dependence of noise records and spectra on the geological underground conditions and remoteness from villages and traffic roads in the area around one of the reference stations in NW Iran .

Note that noise spectra should not be determined unless the related time domain records have been inspected and any non-representative spurious or transient events have been removed. The analysis and assessment of noise conditions should never be made on the basis of the calculated spectra alone but always in conjunction with the related time-domain records.

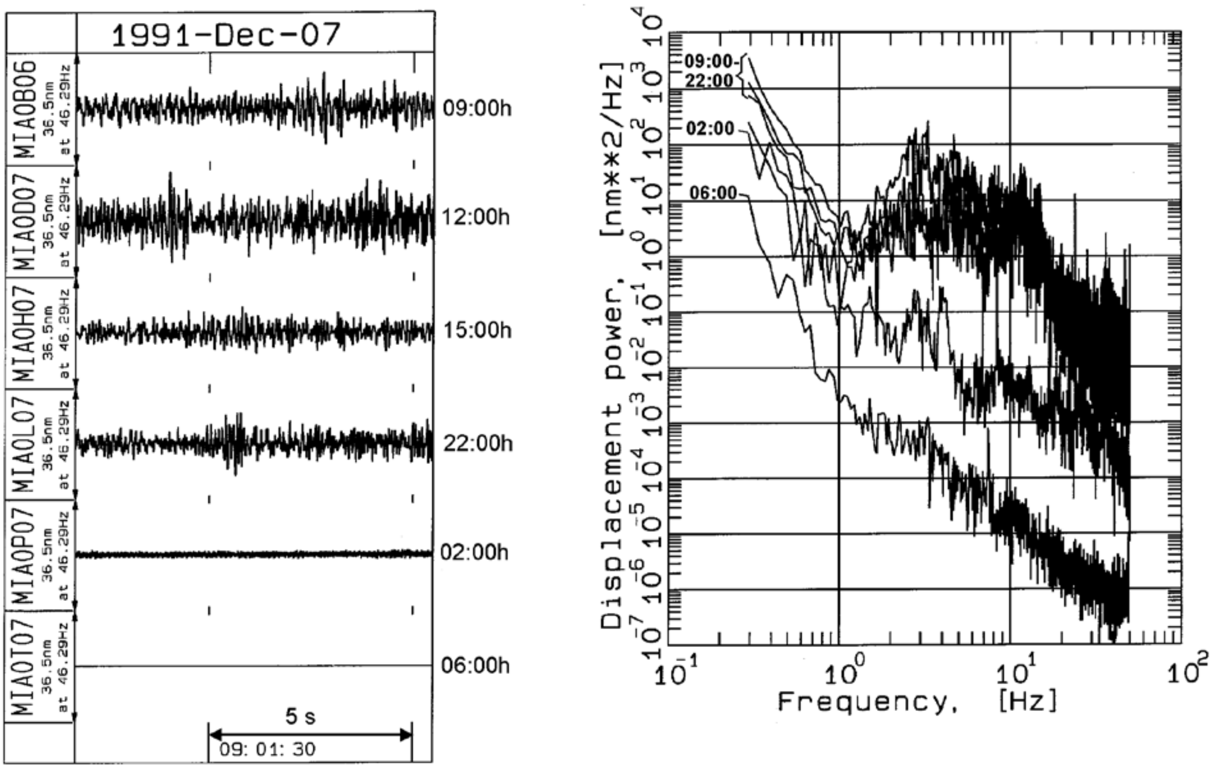


Fig. 7.15 Comparison of relatively quiet sections of vertical component noise records (left; without strong transients) and related power spectra (right) at a reference site in a town in NW Iran. The measurements were made at different times of the day.

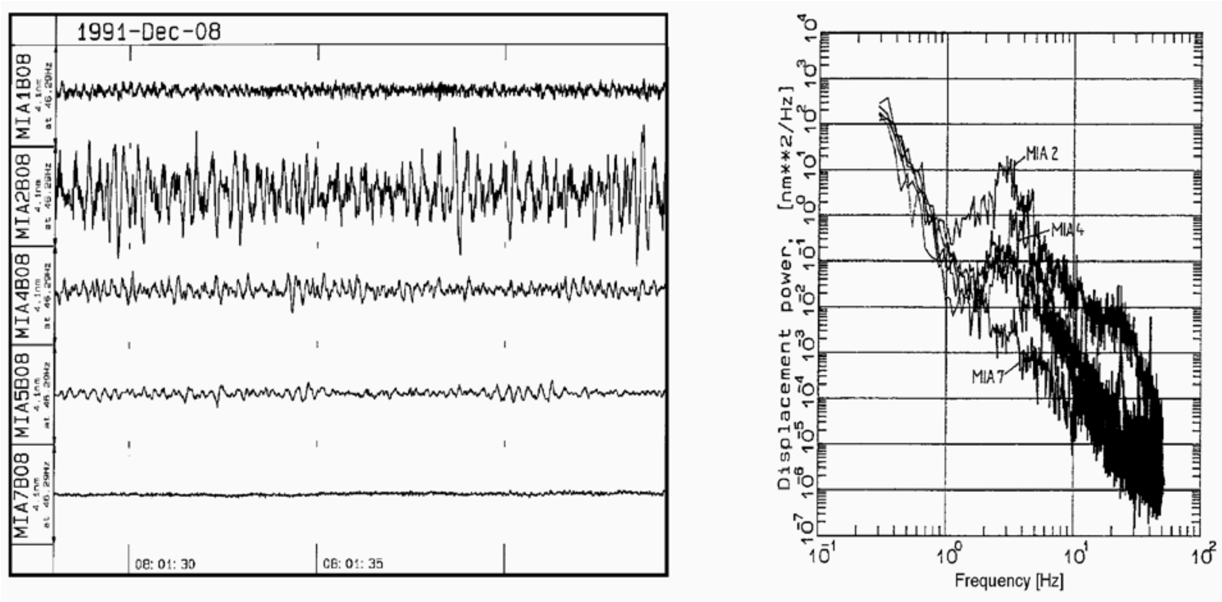


Fig. 7.16 Noise recordings (left) and related power spectra (right) at different sites in NW Iran. From top to bottom: 1) unconsolidated Miocene terrace, 2) unconsolidated Alluvial valley fill, about 2 km away from the main road, 3) as for 2) but some 5 km away from main road; 4) outcropping volcanic hard rock near the road in a valley (with no nearby traffic at the time of measurement, 5) volcanic hard rock surface near a mountain pass road. The noise at MIA 7 is around 1 Hz very close to the global New Low Noise Model (see 4.1) and at 10 Hz only about 14 dB above it.

Fig. 7.17 shows a two minute noise record (left) and the related power spectra (right). The large amplitudes at the beginning are due to a truck and car passing by on the bumpy country road at some 100 to 400 m distance (documented by photograph and time check). Accordingly, for frequencies f > 7 Hz, the noise power of the first minute of the record is 10 to 20 dB higher than for the background noise after the transient is over.

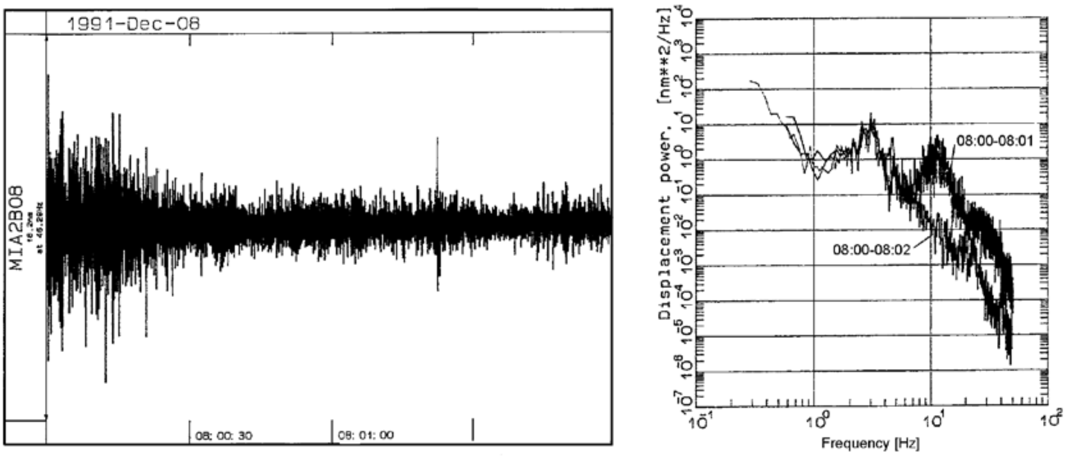


Fig.7.17 Noise record and related spectra for the first minute (transient) and second minute (background noise). The transient is due to a truck passing by at several 100 m distance from the recording site.

Fig. 7.18 shows a recording at a remote low-noise hard rock site. The first segments are very noisy because people were "stretching their legs" only a few meters away from the sensors. This man-made noise stopped abruptly at 13:06:15 hours when they were asked to sit down and not move. Comparing the related noise power spectra for these two different record segments shows amplitudes 20 to 30 dB lower for the unspoilt ambient noise. Therefore, all members of a noise measurement crew must be instructed to stay away from the sensors and keep very quiet during measurements.

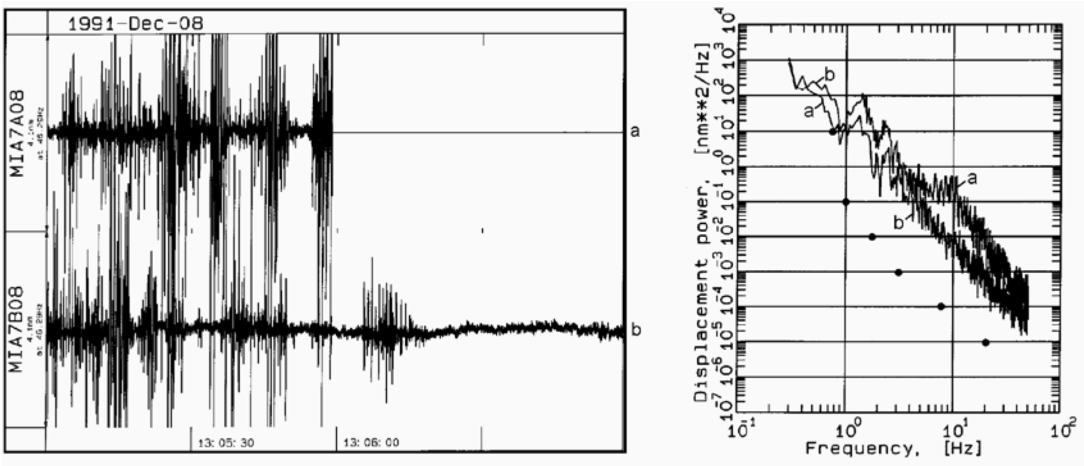


Fig. 7.18 Noise records (left) and related power spectra (right) at a remote low-noise hard rock site in NW Iran. The large, impulse-like amplitudes in the first part of the record are due to the movement of team members near to the sensors. Note the much lower noise (dots in the spectrum) after they were asked to "sit down and be quiet".

Measurements near power lines and transformer houses likewise may significantly spoil the records. The recordings shown in Fig. 7.19 were made near a quiet countryside village. For frequencies below 13 Hz, the noise amplitudes are roughly the same in the vertical and horizontal components. At higher frequencies, surprisingly, the horizontal records are extremely noisy. The related power spectra show strong, almost monochromatic, noise peaks around 13, 30 and 50 Hz in the horizontal components. (Note that the spectral calculation stopped at the seismometer's upper corner frequency of 50 Hz; see Fig. 7.12). According to the notebook entry and site photograph the record was made only about 30 m away from a transformer house and power line. The strong monochromatic high-frequency noise peaks are probably due to strong electromagnetic induction in the horizontal measuring coils by the AC current frequency of 50 or 60 Hz and its lower harmonics (30 and 13 Hz). However, experience at other sites shows that large transformers and heavily loaded power lines may also vibrate at 50-60 Hz.

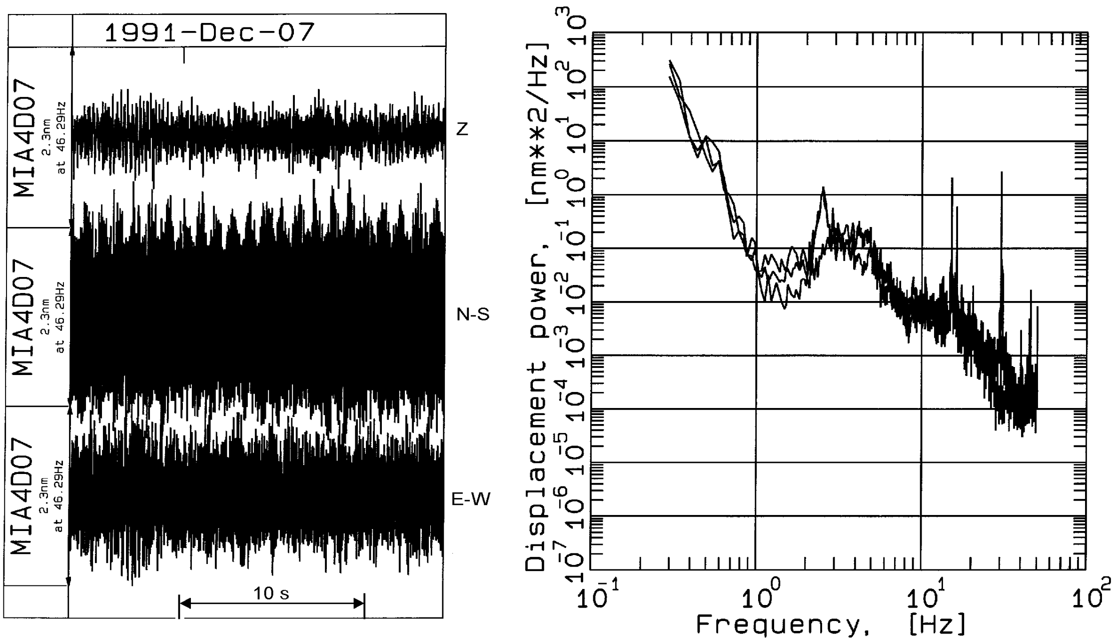


Fig. 7.19 Noise records and related power spectra near to a transformer house and power line. Note the monochromatic spectral lines around 13, 30 and 50-60 Hz, either induced by the AC current frequency and its lower harmonics and/or caused by the vibration of the transformer.

Another experiment demonstrates the attenuation of truck-traffic noise with distance from the road and the influence of the acoustic underground impedance on the recorded spectra. In two different cases, one sensor was placed at the foot of an asphalt-covered road embankment while the other one was installed about 1 km away from the main road in the countryside. In the first case, the underground consisted of wet alluvial coastal plane deposits; in the second case, outcropping competent Cretaceous tuffaceous sandstone, i.e. a rock with a much higher acoustic impedance. The recordings were made simultaneously and the time segments analyzed when a heavy truck was passing by on the main road. On the wet alluvium the vibrations caused by a truck were recorded on the road embankment with very strong amplitudes for almost 30 seconds. Frequencies between 0.3 Hz and 20 Hz were strongly excited. Although power spectral amplitudes at 1 km distant were generally 20 to 30 dB lower, high frequencies were still clearly visible in the record and the spectrum (Fig 7.20).

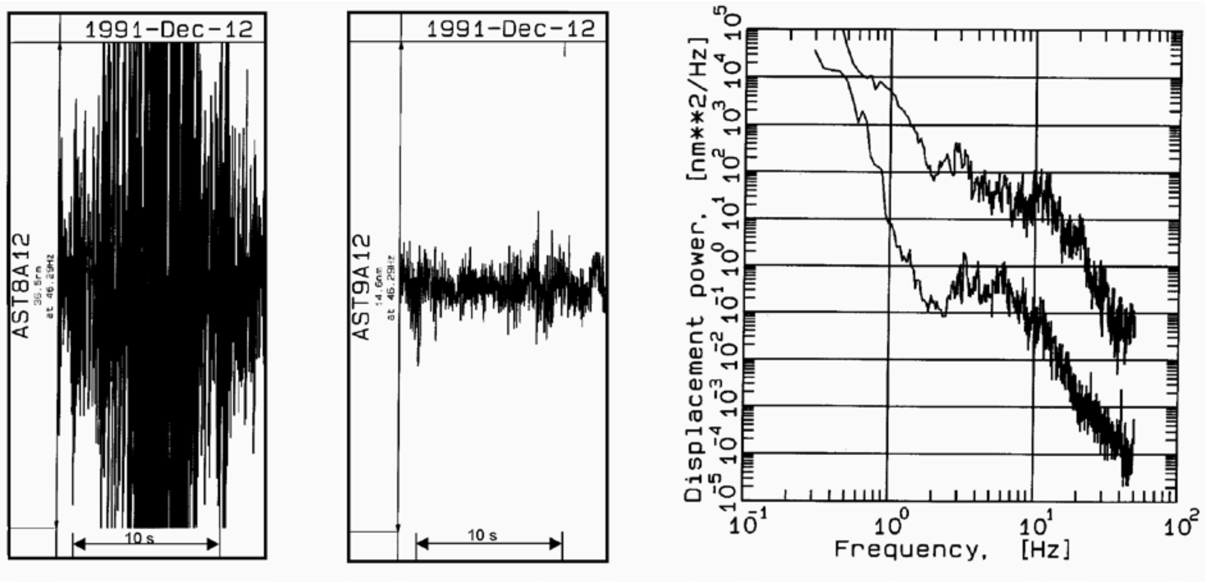


Fig. 7. 20 Comparison of seismic records and related noise spectra made at the time of passing of a heavy truck: Left: record near the road embankment; middle: record made about 1 km away from the road in the countryside (middle); right: noise power density spectra. Underground: wet Alluvial coastal plain deposits. (Note that the noise amplitudes in the left panel have been reproduced with only 40 % of the magnification in the central panel).

In contrast, Fig. 7.21 shows the records made at another section of the road embankment consisting of broken rock overlaying outcropping competent rock. A strong increase in noise amplitudes above the general background level was observed for about 5 s only, i.e., when the truck was close to the site. The general noise level, even at the time of the passing truck, was 20 to 30 dB lower than on the alluvial embankment. Also, at the broken/compact rock road embankment, spectral amplitudes for frequencies between 0.3 and 1.5 Hz were about the same as 1 km away in the side valley on the outcropping compact sandstone. On the other hand, high frequency amplitudes generated by the truck are no longer visible in the record at the hard rock site 1 km away from the main road and reduced by 20 to 30 dB in the power spectrum.

In summary, these examples show what one can expect for noise reduction with distance from main traffic roads or other sources of man-made noise, and their dependence on underground conditions. This may help guide reconnaissance field measurements for appropriate and accessible sites. The examples also illustrate the usefulness of comparing noise records in the time domain with the related power spectra in order to better identify the kind of noise sources and understand their appearance in the records.

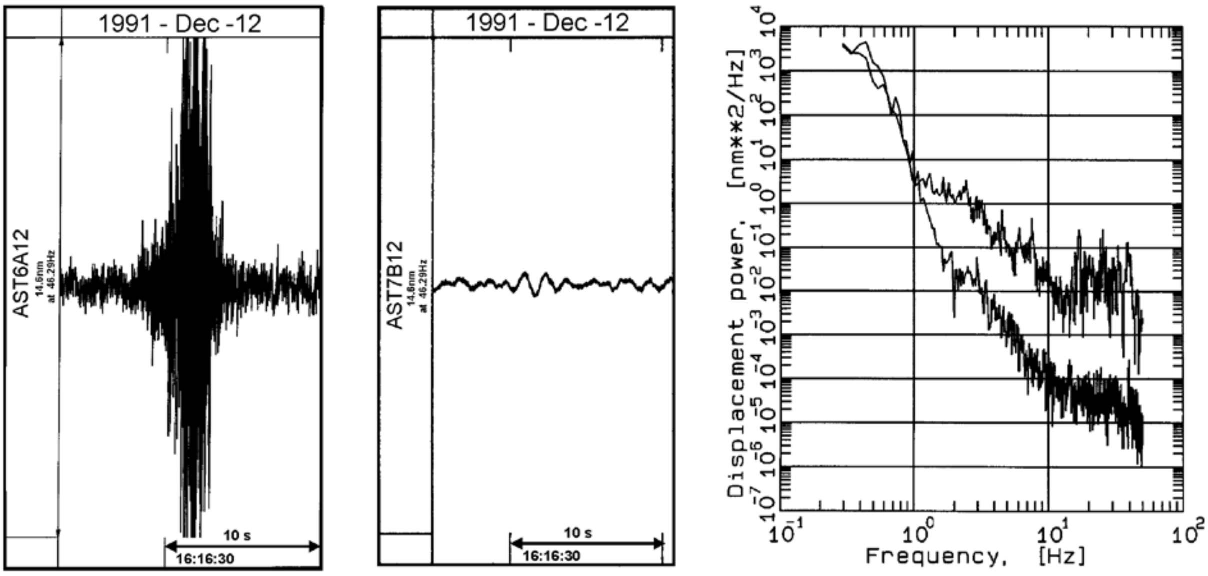


Fig. 7.21 As Fig. 7.20, except that records were made near a broken rock embankment of a main road and on outcropping compact tuffaceous sandstone, 1 km away in a side valley, respectively.

7.2.3 Comparison of noise and signals at permanent seismological stations

7.2.3.1 Introduction

Existing permanent seismological stations have historically been established by different institutions for different reasons and have often been installed under different underground and environmental conditions. The stations were usually operated independently, each reporting their own data readings to national or international data centers. Modern methods of data communication make it easy to link these stations, to merge them into virtual networks (see 8.4.3), to exchange waveform data in real time and to perform joint data analysis at local, national or regional data centers. The overall network performance and quality of results strongly depends on the local conditions at the individual stations. One crucial parameter is the detection threshold. This is mainly (but not exclusively) controlled by the noise conditions at the sites. High noise conditions at some stations reduces their contribution to event detection, discrimination and location accuracy of the network, may bias average network magnitude estimates and may result in inhomogeneous completeness and accuracy of earthquake catalogs. Therefore, when setting up new seismic networks or linking already existing stations into a network, a priority task should be to investigate and compare the signal-to-noise conditions at the various stations, and to find alternatives for inferior sites. Such decisions may have far-reaching consequences and involve significant cost and so should not be based on just a few short-term noise measurements in a limited frequency band. Noise measurements should be taken over at least several days, but preferably over weeks or even months, in order to get a clear understanding of the diurnal and seasonal variability of seismic noise in the full frequency band of interest for the operation of the network. Moreover, one should determine the signal-to-noise ratio (SNR) for events from different distance and azimuth ranges and compare this at existing and possible alternative sites. It is vital that all records should be made with equipment having an identical instrument response.

This is demonstrated using data from the German Regional Seismic Network (GRSN) (see Fig. 8.15). Originally the GRSN consisted of 12 sites in western Germany. Several permanent stations in eastern Germany were subsequently added to the network. The GRSN now consists of 16 digital broadband stations equipped with STS2 seismometers (see DS 5.1), 24-bit data loggers and a seismological data center at the Gräfenberg BB array center (GRFO) in Erlangen. The network covers the whole territory of Germany with a station-spacing between 80 km and 240 km. The stations are located in very different environments: e.g., near the Baltic Sea coast (HAM and LID, now BSEG; RGN); up to distances of about 700 km away from the coast (FUR); within cities (BRNL, HAM) or up to about 10 km away from any major settlement, industry or busy roads. The underground varies from outcropping Paleozoic hard rocks in Hercynian mountain areas (BFO, BRG, CLL, CLZ, GERES, MOX, TNS, WET), sedimentary rocks in areas of Paleozoic (BUG, IBBN) or Mesozoic platform cover (GRFO, STU) to unconsolidated Pleistocene (glacial) deposits (BRNL, HAM, FUR, LID, RGN). The seismometers are installed either at surface level (CLL, CLZ, HAM, IBBN, RGN, WET), in shallow vaults just a few meters below the ground surface (BUG, FUR, GSH, TNS), in boreholes (GRFO, 116 m), or in bunkers, tunnels or abandoned mines between 20 and 162 m below surface (STU, MOX, BSEG, BRG, RUE, BFO). More details about these stations and their equipment can be found on the Internet at http://www.szgrf.bgr.de/station_map.html, and http://www.seismologie.bgr.de .

Seismic background noise at GRSN stations varies in a wide range between the upper and lower bounds of the new global noise model (see Fig. 7.27). The noise conditions at the GRSN have been investigated in detail in the frequency range from 10^{-2} to 40 Hz by Bormann et al.(1997).

7.2.3.2 Data analysis

Continuous recordings at all stations were systematically screened at different times of the day (0, 6, 12 and 18 hrs UT) in order to reveal diurnal variations and their site dependence.Records were also monitored throughout the year in order to identify periods of minimum and maximum noise level and their seasonal variations. Respective record sections and related power spectral densities (PSD) were plotted together and checked for transient signals from seismic or other spurious events.

Data of the GRSN are acquired at a sampling rate of 80 Hz for most stations and 20 Hz at the more noisy stations. For most of the routine noise analysis, the 80 Hz data were re-sampled at 20 Hz. The Power Spectral Density (PSD) was calculated using a subroutine from the program SEIS89 (Baumbach 1999). It implements, in a somewhat modified form, an algorithm recommended as a standard for the calculation and presentation of noise spectra by the Ad Hoc Group of Scientific Experts (1991). The modification allows the use of segments of data larger than 512 samples, thus permitting the analysis of more long-period noise. The digital time series containing background noise are divided into a number of half-overlapping record segments, normally of 4096 samples. The power spectra are then calculated for each segment (after removing the mean and tapering the ends of each segment with a sine-cosine window) and then averaged over eight segments in order to reduce the variance of the PSD estimate. Accordingly, the presented power spectra are representative for noise records of about 15.4 min duration in case of 20 s.p.s. and of about 3.8 min duration for 80 s.p.s.. All spectra are corrected for the instrument response. The power spectra are presented in units of displacement power spectral density in nm^2/Hz. A lower frequency limit is imposed such that the longest period which can be analyzed using this procedure is one sixth of the segment length.

According to Fig. 7.48 in section 7.4.4, STS2 seismographs have a self-noise which is below the global New Low-Noise Model between about 10^{-3} Hz and 10 Hz. According to Wielandt and Zürn (1991), they can resolve the noise at BFO, which is one of the quietest seismic stations in Germany, for frequencies below 30 Hz. Thus, instrumental and/or digitization noise can potentially affect the noise estimates at the best sites only at frequencies above and below this range.

Essential results of the analysis are presented below. Figs. 7.22 - 7.37 are reproduced from Journal of Seismology, Vol. 1, 1997, pp. 357-381, "Analysis of broadband seismic noise at the German Regional Seismic Network and search for improved alternative station sites" by P. Bormann, K. Wylegalla and K. Klinge, Figures 2, 4, 6-7, 9, 11-15, 17-20 and 22; © 1997(with kind permission from Kluwer Academic Publishers).

7.2.3.3 Results

Fig. 7.22 shows an example of high-pass filtered short-period Z-component records of seismic background noise from 15 stations of the GRSN. Amplitudes differ by more than one order of magnitude. Noise amplitudes on vertical and horizontal recordings were about the same at any given station. Therefore, only spectra from Z-component records are considered. In long-period records, however, horizontal noise is sometimes significantly larger (e.g., for stations RGN and BSEG in Fig. 7.23), due to the high tilt sensitivity of long-period horizontal seismometers (see 5.3.3).

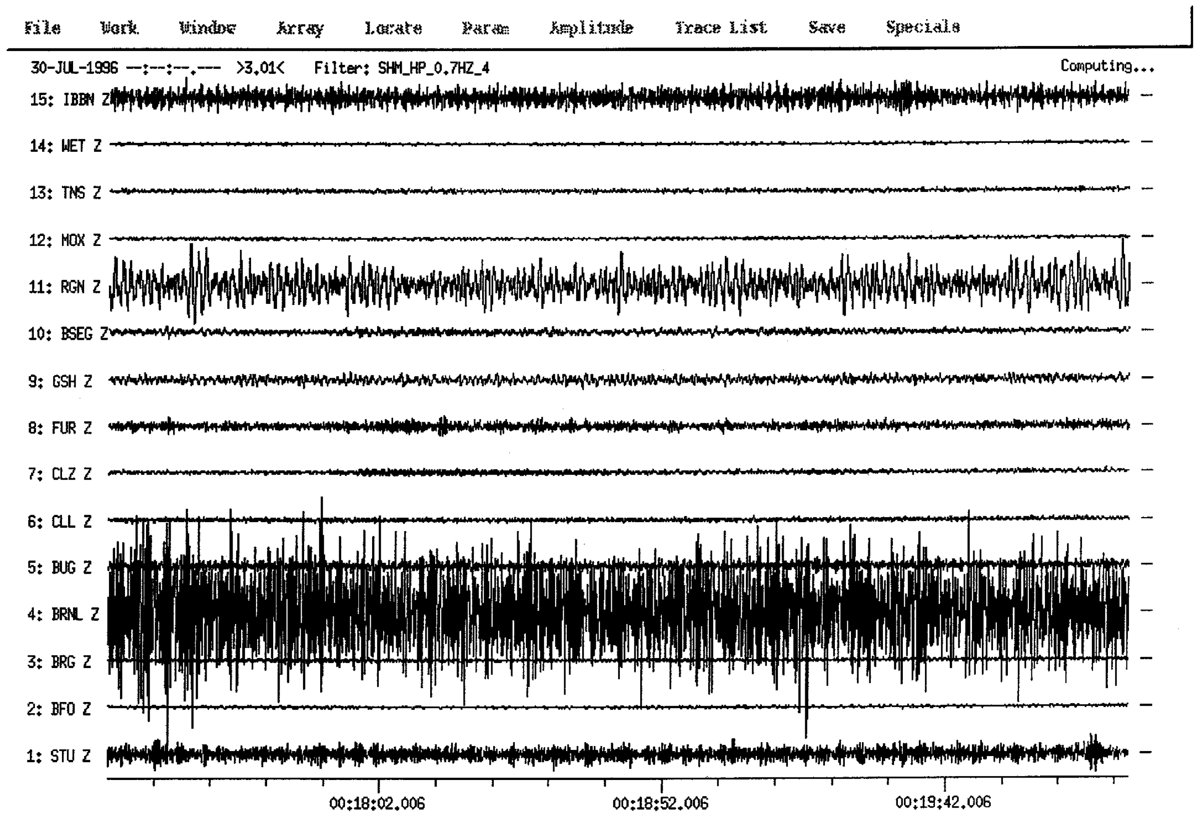


Fig. 7.22 High-pass filtered (f_c = 0.7 Hz) Z-component noise records of GRSN stations on July 30, 1996, at night time (from Bormann et al., 1997).

On very calm days at stations with very good environmental shielding (e.g., BFO, GRFO, TNS in Fig. 7.23), horizontal long-period noise might be equal to or only somewhat stronger than in vertical components. On stormy days with high wind pressure fluctuations and related tilts, however, the noise power in near-surface horizontal recordings might be 20 to 30 dB higher than in vertical ones. When the sensors are installed sufficiently deep in boreholes (as GRFO; 116 m below surface) or in mines (as BFO; 162 m below surface) this difference will be much less, even during stormy days.

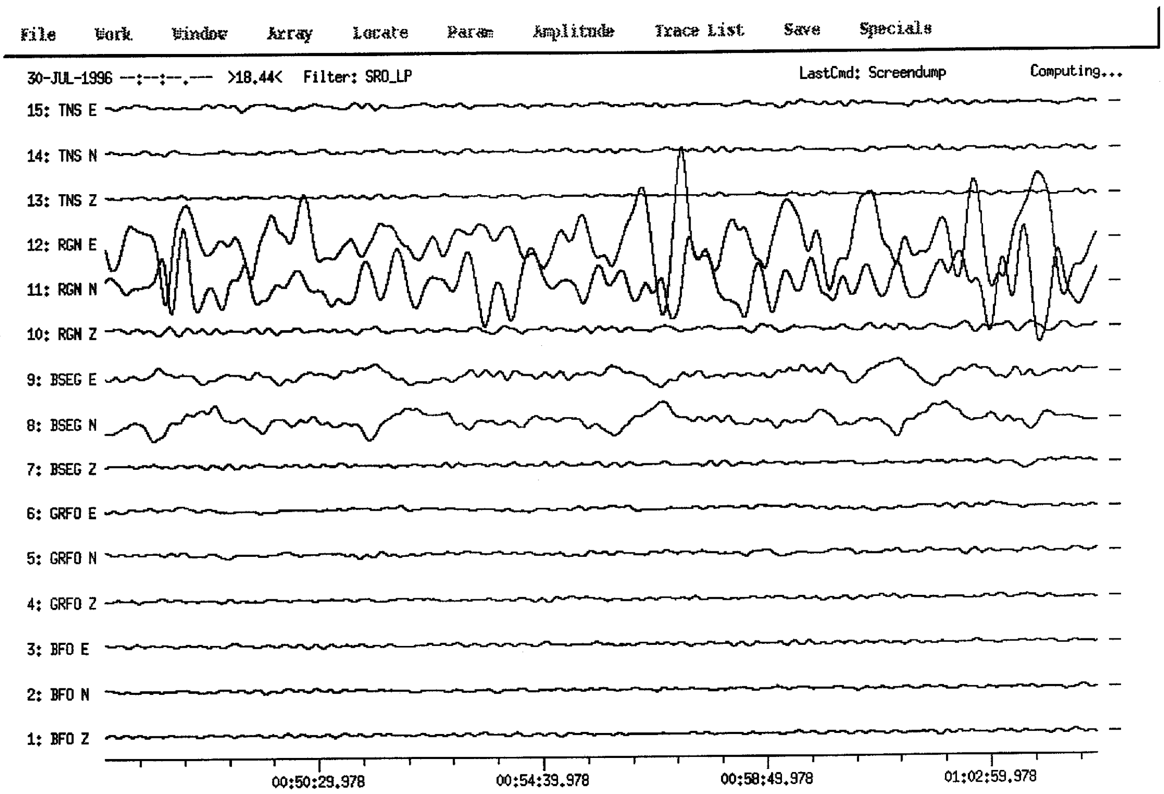


Fig. 7.23 Three-component recordings at five GRSN stations after applying a long-period SRO filter characteristic (from Bormann et al., 1997).

Differences in the displacement PSD at the GRSN stations are most obvious for frequencies above 0.5 Hz. They may reach about 60 dB (Fig. 7.24) and are due to the varying proximity to man-made noise sources and differences in underground conditions. The stations BRNL (Berlin Lankwitz) and HAM (Hamburg) proved to be the worst sites. For longer periods (T > 2 s) the differences in noise level between the GRSN stations are much less pronounced; less than 10 dB in most cases. However, over a long period of time (Fig. 7.25) the noise power variability at individual stations of the GRSN proved to be smallest (and seasonally independent) around f = 1 Hz (about 5 to 10 dB variation only). It is larger between 2 to 10 Hz (up to about 20 dB) and largest for the secondary ocean-storm microseism peak around 7 s period (30 to 40 dB). Microseisms only occur episodically and with seasonally varying intensity (strongest at the time of winter storms). At periods around 20 s, the range of noise power variations still reaches 20 to

30 dB. This is equivalent to variations in the magnitude threshold for Ms determinations of up to 1.5 magnitude units.

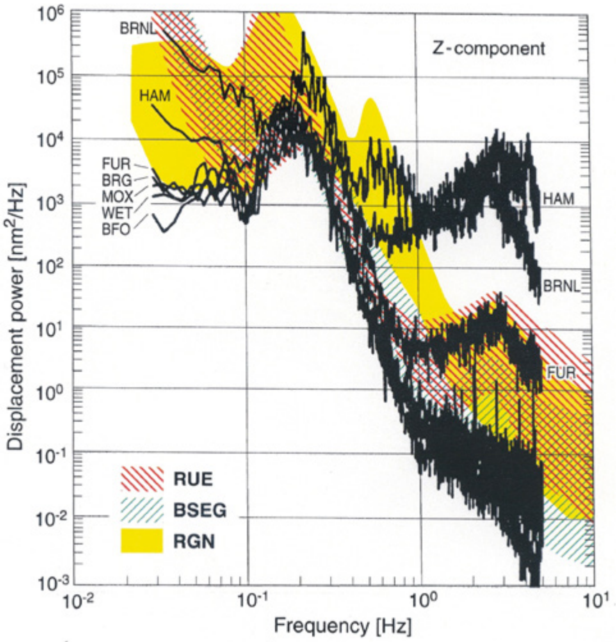


Fig. 7.24 Displacement power density spectra at selected GRSN stations determined from noise records on the morning of April 13, 1993. For comparison the ranges of noise power observed at the new sites BSEG, RGN and RUE are given as shaded areas (from Bormann et al., 1997).

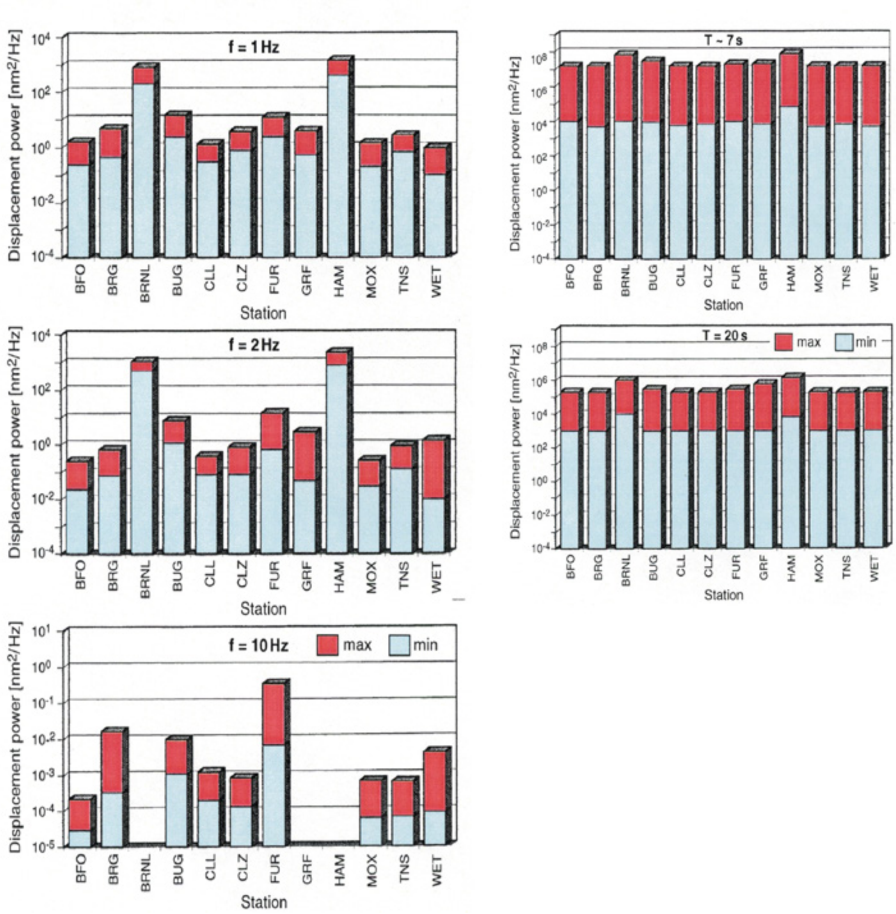


Fig. 7.25 Comparison of the minimum and maximum levels of short-period and long-period seismic noise power observed at GRSN stations (modified after Friedrich, 1996; from Bormann et al., 1997).

Fig. 7.26 shows record sections of only 1 minute duration and with identical gain for one of the quietest and one of the noisiest days observed during a year at each of the stations MOX and HAM. The amplitudes of secondary ocean-storm microseisms with periods of about 6 to 7 s, on the noisy day, are at HAM only about twice as large as at MOX despite HAM being much closer to their origin along the European North Atlantic coastline. On the other hand, the high-frequency noise at HAM is always much larger than at MOX. The corresponding displacement power spectra for the quietest day at MOX (May 23) and the noisiest day at HAM (January 13) during 1993 are compared in Fig. 7.27 with the global New Low Noise Model (NLNM) and New High-noise Model (NHNM) according to Peterson (1993).

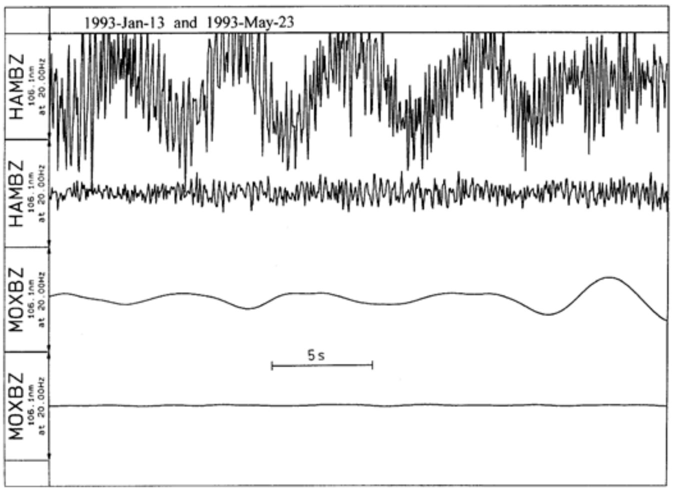


Fig. 7.26 Comparison of record segments with largest (13 January) and lowest seismic background noise (23 May) observed in 1993 at stations HAM (upper two traces) and MOX (lower two traces) (from Bormann et al., 1997).

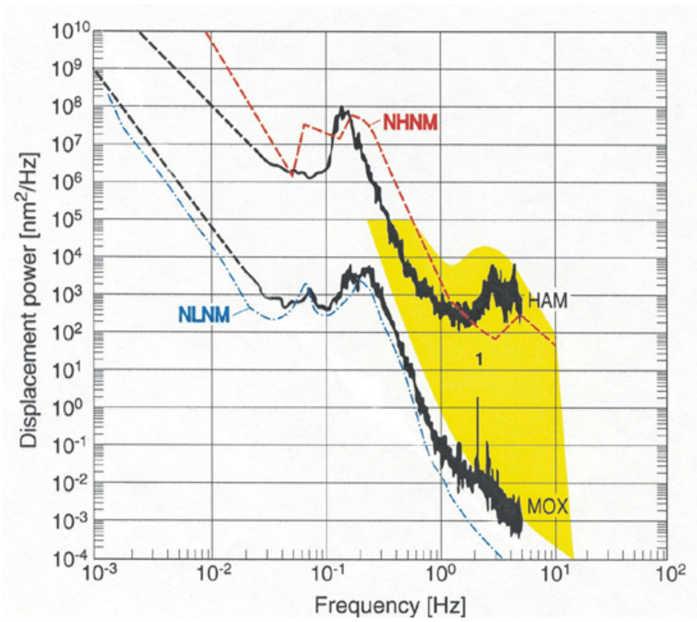


Fig. 7.27 Spectra for the noisiest day observed at HAM (January 13) and the quietest day at MOX (May 23) during 1993. The NHNM and NLNM according to Peterson (1993) are shown for comparison. The shaded area (1) covers the range of short-period noise power calculated by Henger (1995) for all GRSN stations on March 1, 1994 (modified from Bormann et al., 1997).

The diurnal variations of man-made noise have also been investigated at all stations of the GRSN. The variations are very distinct (20 to 30 dB) at the stations BRNL, BUG and FUR, i.e. at sites in densely populated areas and with thick unconsolidated subsoil. They are much less (< 5 to 10 dB) at stations on hard rock in smaller and less busy towns (such as BRG and CLZ) or even at several km distance to the nearest villages (CLL, MOX and TNS).

Due to the large differences in noise conditions at the GRSN stations, the capability to detect and locate events with at least 3 stations was rather inhomogeneous over German territory. The detection thresholds ranged between Ml = 1.5 and 3. Since the network was supposed to detect and localize all local events with Ml ≥ 2, more suitable sites had to be found for some stations. This was particularly true for BRNL and HAM. The search for more appropriate alternative sites focused on areas not too far away from these stations in order to preserve the general configuration of the GRSN.

7.2.4 Searching for alternative sites in a given network

7.2.4.1 Geological and infrastructure considerations

We consider here two case studies for replacing the seismic stations BRNL and HAM.

BRNL was located on the courtyard of the Geophysical Institute of the Free University of Berlin, about 12 km from the city center. The station underground consists of about 290 m unconsolidated Cenozoic sediments overlaying a thick sequence of Mesozoic sedimentary rocks. These unfavorable underground conditions, together with high population and nearby traffic density, made this station one of the noisiest in Germany. An alternative site had to be found in the wider surroundings of Berlin.

In the area of Berlin, the base of the Permian Zechstein subdivision is between about 2600 m and 4000 m below sea level. The pre-Permian basement is block-faulted with different vertical movements between adjacent blocks during post-Permian times. This mobilized the overlying plastic salt deposits of the Zechstein subdivision and resulted in the formation of dozens of salt-pillow structures, up-doming the Mesozoic sequences above. In a few cases, salt diapirs pierced through the post-Permian deposits to the present surface. The largest of these halokinetic structures exists beneath the small town of Rüdersdorf (Fig. 7.28) about 25 km east of the city center of Berlin. It was exposed by Pleistocene glacial erosion, thus forming the northermost natural outcrop of Middle Tertiary limestones in Germany which has been mined for hundreds of years. Logistically, Rüdersdorf is easy to reach and has all the power and telecommunication connections needed for a GRSN station. The open-cast development stretches E-W and is about 0.5 to 4 km away from the eastern segment of the busy "Berliner Ring Autobahn" (motor highway). Despite the proximity to town and highway and the continuing surface mining in the quarries of Rüdersdorf, this area was considered to be the most promising alternative for the station BRNL both from a seismo-geological and logistical point of view. This was subsequently confirmed by measurements (see 7.2.4.3).

Hamburg is situated in the NW of the North German-Polish Depression. The regional geological conditions are similar to those around Berlin although the depression is much deeper here. The unconsolidated sediments above the basis of Tertiary are about 1.5 km thick beneath the station. HAM was situated about 12 km away from the city center but rather near (< 1 km) to different segments of the dense highway network. Accordingly, the noise conditions were the worst of all the seismic stations in Germany. The most promising alternative site was on an outcropping, partially mined, salt diapir in the town of Bad Segeberg, about 50 km NNE from the center of Hamburg, not too close to either the North Sea or Baltic Sea, easily accessible and with suitable infrastructure and communications facilities. There are Quarternary unconsolidated sediments, about 100 to 400 m thick, and Cretaceous and Triassic sedimentary rocks at a few hundred meters depth, adjacent to the diapir. Fig. 7.29 shows a schematic cross section through the former castle hill and the upper few hundred meters of the diapir of Bad Segeberg.

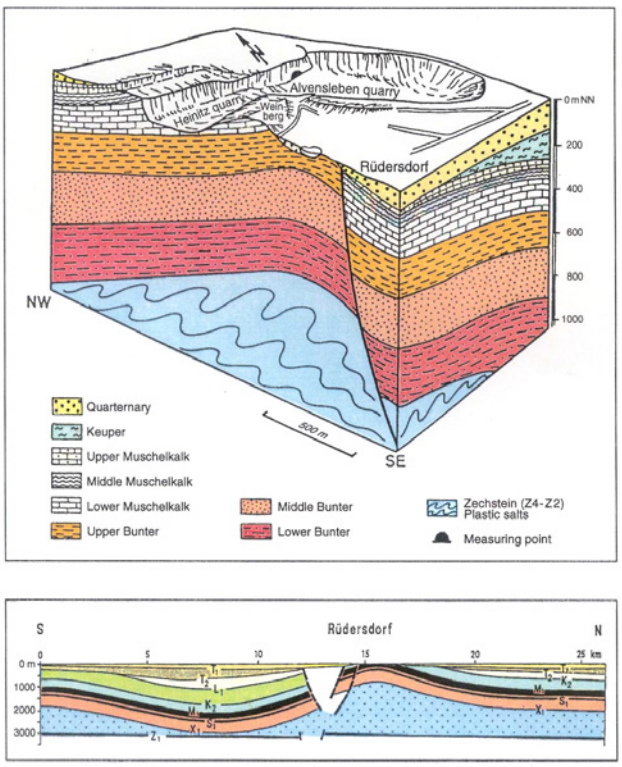


Fig. 7.28 Cross sections through the salt-tectonic up-doming at Rüdersdorf at local (above) and regional scale (below) (from Bormann et al., 1997).

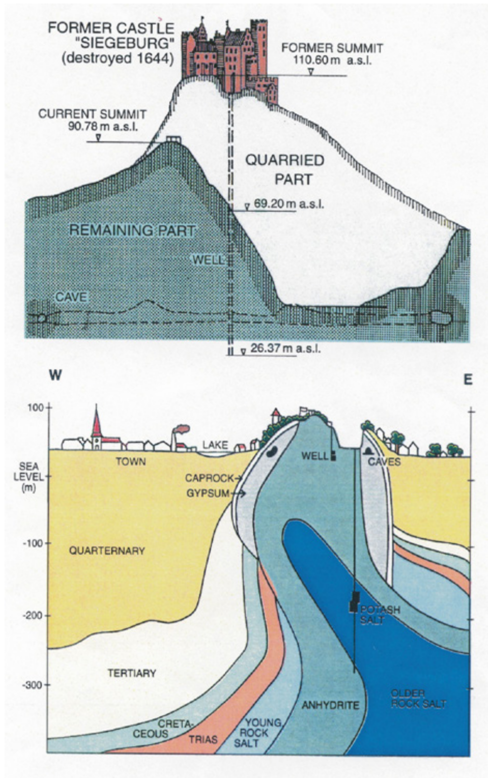


Fig. 7.29 Cross-section through the former castle hill of Bad Segeberg (above) and the related geological profil of the Permian salt diapir (below) (from Bormann et al., 1997).

7.2.4.2 Recording conditions and data analysis of temporary noise measurements for alternative permanent broadband stations

Identical very broadband STS2 seismometers were used with PDAS digital data loggers for comparative measurements of seismic background noise at BRNL and with their potential alternative station sites RUE and BSEG. The data were sampled at 100 Hz. The seismometer at RUE was placed in a small tunnel in the quarry in order to reduce the influence of temperature variations and to enable stable broadband recordings. The tunnel was about 10 m long, with 55 m of limestone overburden, and the site was 2 to 3 km away from the highway and the village of Rüdersdorf. At BSEG, the STS2 was installed in a gypsum cave within the diapir caprock of Bad Segeberg, about 20 to 30 m below the surface. The cave is only a few hundred meters away from the town center of Bad Segeberg.

In both cases the instruments were placed directly on a levelled hard rock surface. No additional thermal or pressure shielding was provided during the temporary measurements apart from the manufacturer´s standard metallic sensor platform with cover hood. Therefore, in the data shown below, the long-period noise at RUE and BSEG is higher than it would be in a good permanent installation. Note that in contrast to temporary noise measurements with short-period seismometers, broadband sensors require about one day to adapt to the environmental conditions and find a stable zero position. Meaningful data can only be acquired after this.

For several days, continuous noise and signal measurements were carried out at BSEG and RUE parallel to HAM and BRNL, respectively. Data sampled at 100 Hz. were used for the determination of displacement noise power between 0.1 and 50 Hz and re-sampled 20 Hz data were used for the range 0.03 to 5 Hz. The PSD subroutine described in 7.2.3.2 was used, with a basic record length of 4096 samples. The average power spectrum was determined using 25 consecutive segments with 50% overlap. Thus the spectra are representative for noise records of 8.87 min and 44.37 min length depending on whether they are based on data sampled at 100 or 20 Hz.

7.2.4.3 Results of noise and signal measurements at BRNL and RUE

Fig. 7.30 shows unfiltered 5-minute broadband segments of noise recordings at BRNL and RUE taken around noon and around midnight. Fig.7.31 shows the noise power at both sites in the frequency range 0.03 to 50 Hz.

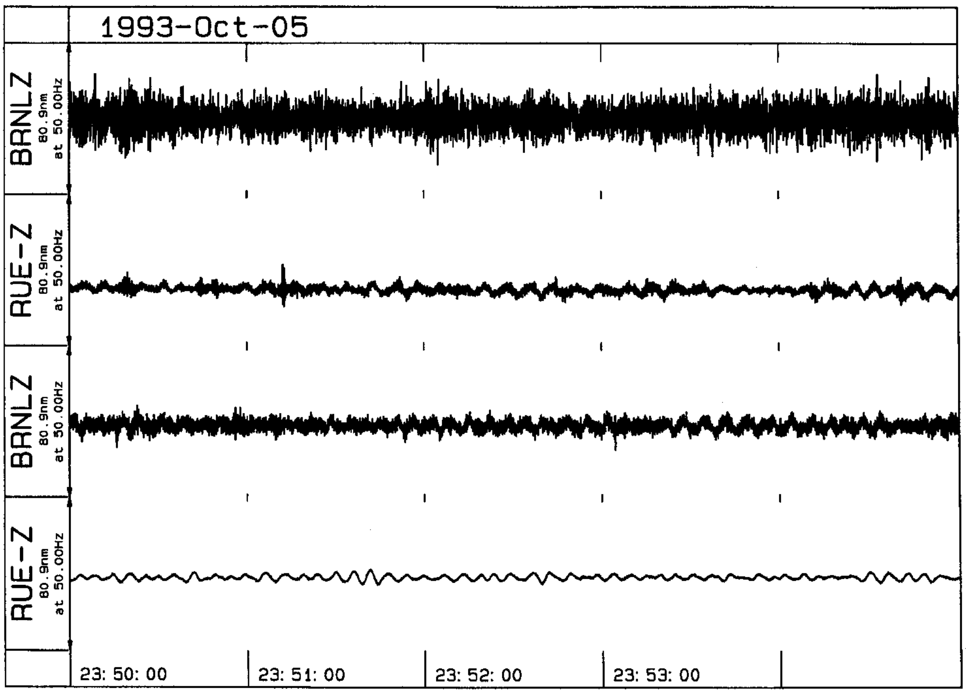


Fig. 7.30 Unfiltered Z-component broadband records of seismic noise with identical resolution at BRNL and RUE. Upper traces: 11:50 - 11:55 UT; lower traces: 23:50 to 23:55 UT (from Bormann et al., 1997).

The comparison reveals that:

- the noise above 1 Hz at BRNL is some 15 to 25 dB higher than at RUE, both at day- and night-time;
- between 1 and 5 Hz the night-time noise is less than the day-time noise by about 10 dB at BRNL and by about 6 dB at RUE;
- below 0.5 Hz, BRNL has about the same noise power level as RUE with negligible diurnal variation at both sites;
- a range of different, spatially distributed random noise sources such as nearby traffic seem to dominate the short-period noise during day-time at both sites. This results in a rather high and "smooth" noise spectrum without any dominating spectral lines at BRNL and only a few sharp spectral lines at RUE (e.g. at f = 8, 10, 16 and 32 Hz);
- during night-time, when the traffic noise is reduced, several sharp spectral lines become dominant for f > 5 Hz at both BRNL and RUE. These are probably due to specific noise sources such as machinery rotating with constant frequency (and their lower and higher modes).

The last of these observations is clearly related to activity in the Rüdersdorfer quarry. Mining and stone crushing machinery are operating there throughout the day. Despite the generally lower noise level at RUE compared to BRNL, it is meaningful only to record at RUE low-pass filtered data (f_c = 5 Hz) sampled at 20 Hz. According to Fig. 7.24 the noise power at RUE is comparable with that at station Fürstenfeldbruck (FUR), a site of intermediate quality. A better result is not achievable with a near-surface installation in the surroundings of Berlin.

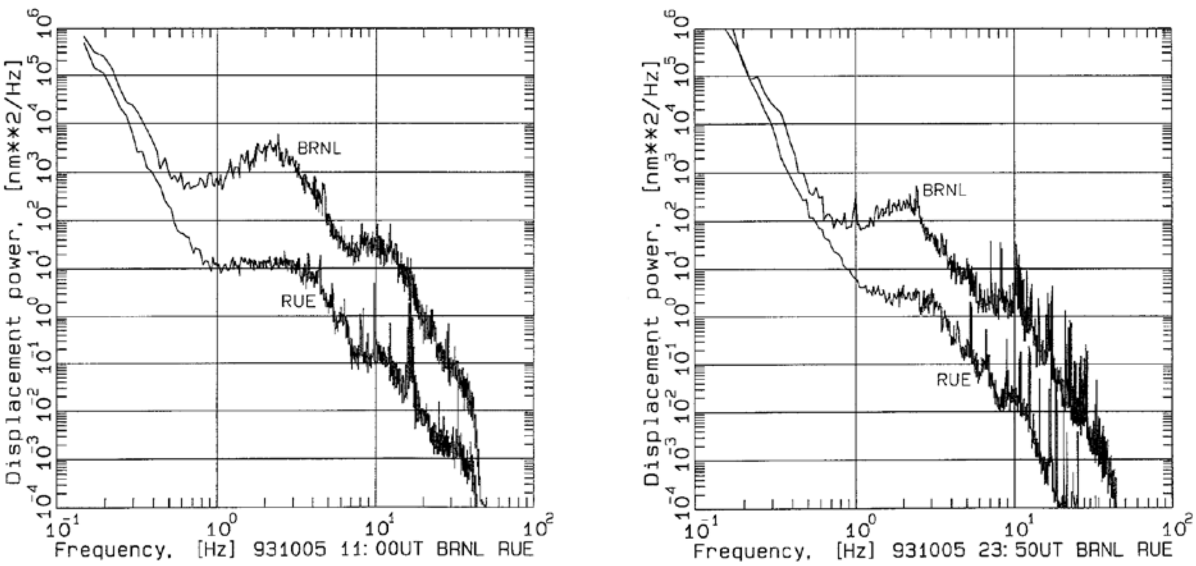


Fig. 7.31 Power spectra of seismic noise in Z-component broadband records at BRNL and RUE around noon (left) and midnight (right) (from Bormann et al., 1997).

Fig. 7.32 presents the broadband (top) and band-pass filtered (from 0.5 - 5 Hz, bottom) Z-component records at BRNL and RUE of a nearby event at approximately the same distance. In both cases the event is not visible at BRNL but is clearly recorded at RUE with several distinct wave groups. The spectral signal-to-noise ratio (SNR) of this event is ≤ 1 at BRNL and varies between 3 and 30 at RUE for 0.5 Hz < f < 7 Hz. This is a significant improvement of recording conditions. As a consequence, station BRNL was closed and its equipment permanently moved to RUE.

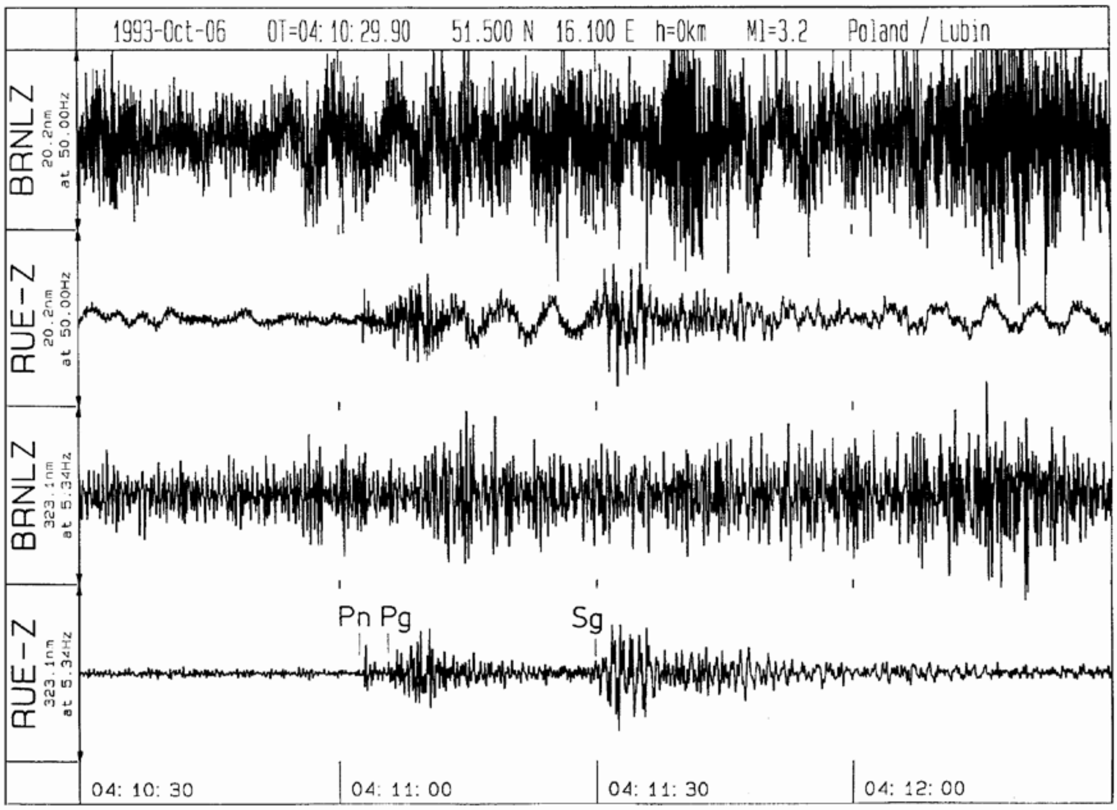


Fig. 7.32 Unfiltered broadband (upper two traces) and band-pass filtered (f = 0.5 - 5 Hz; lower two traces) Z-component records of a near seismic event in Poland at BRNL (D = 214 km) and RUE (D = 191 km) (from Bormann et al., 1997).

7.2.4.4 Results of noise and signal measurements at HAM and BSEG

Fig. 7.33 shows an example of day-time and night-time noise records at HAM and BSEG with identical resolution and Fig. 7.34 shows the related power spectra. The comparison, including that with spectra from other days and with Fig. 7.24, shows that:

- diurnal variations in seismic noise are remarkably small (≤ 10dB) at HAM. The cause is very intense traffic and industrial activity in this busy large harbor town that does not vary much between day and night time.
- diurnal variations are significant (about 10 to 20 dB) at BSEG above 1.5 Hz but negligible below 1 Hz;
- between 0.5 and 40 Hz the noise power at BSEG is about 20 to 50 dB smaller than at HAM;
- for medium-period ocean storm microseisms (around 3 to 5 s period) the noise power is reduced by about 10 dB at BSEG;

- there is sometimes larger long-period noise at BSEG compared to HAM. This mainly non-seismic noise was significantly reduced after final installation and the level is now comparable with other good GRSN sites;
- noise conditions at BSEG above 1 Hz are only slightly inferior (≤ 10 dB) to good hard-rock sites of the GRSN.

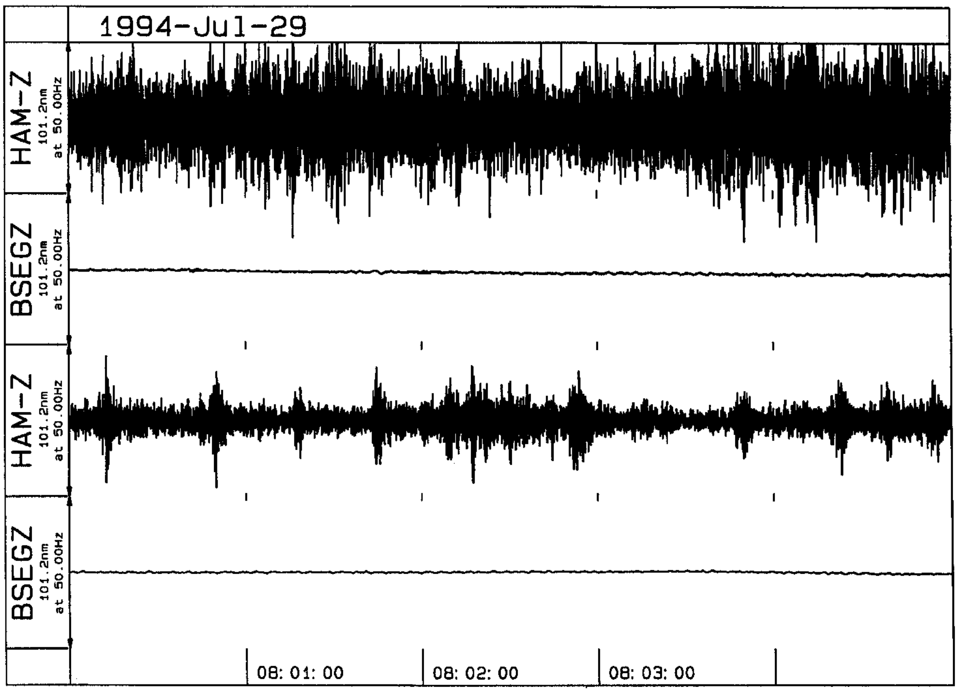


Fig. 7.33 Five minutes of unfiltered Z-component broadband records at HAM and BSEG on July 29, 1994 at 8:00 UT in the morning (upper two traces) and after midnight (lower two traces) (from Bormann et al., 1997).

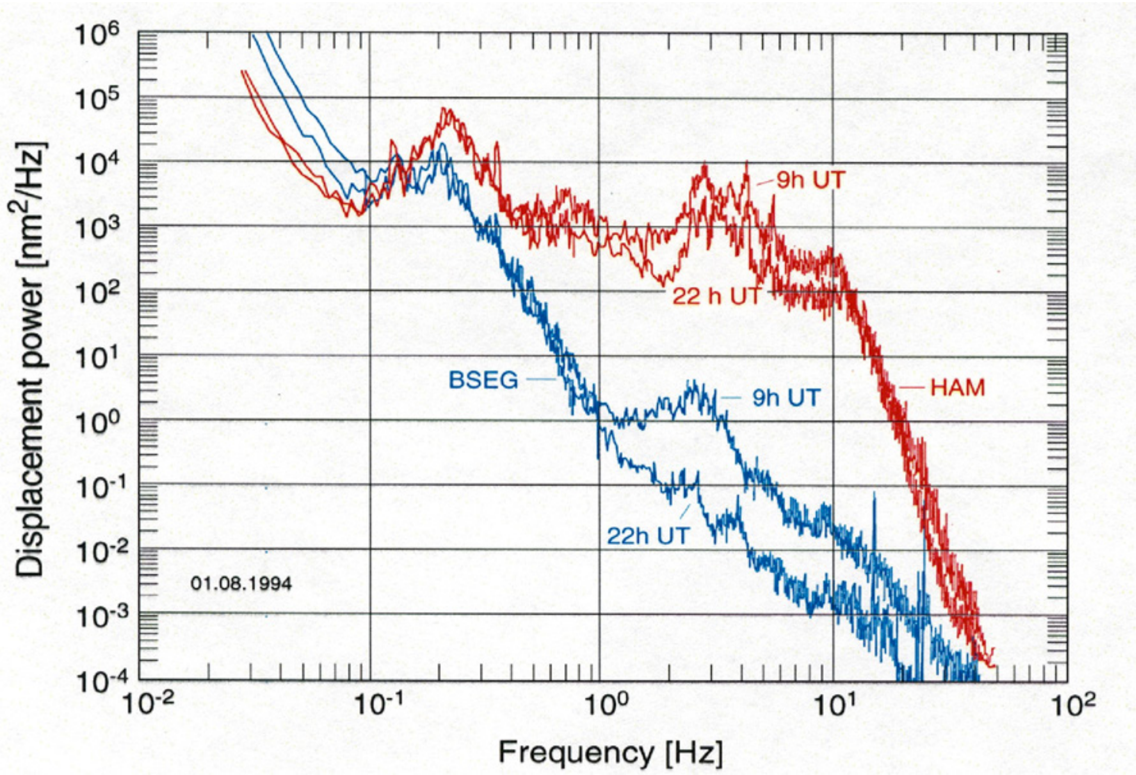


Fig. 7.34 Noise power spectra at HAM (upper two curves) and BSEG (lower two curves) determined from Z-component records on August 1, 1994, around 9 h UT and 22 h UT, respectively (from Bormann et al., 1997).

Fig. 7.35 shows the Z-component broadband and short-period records at BSEG and HAM of a teleseismic event in Iran. The event was not recognizable at HAM but was recorded very well at BSEG. In contrast, the SNR for the P-wave onsets in long-period filtered records (Fig. 7.36) was comparable at HAM and BSEG since the P-wave wavelengths are > 50 km and therefore much larger than the size of the noise-reducing velocity anomaly of the diapir structure at Bad Segeberg.

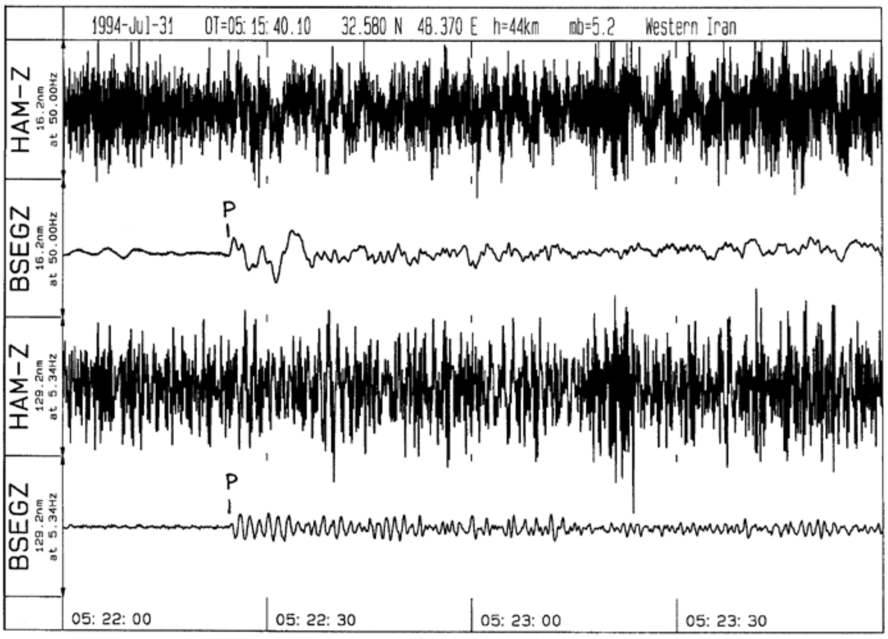


Fig. 7.35 Z-component records of an earthquake in Iran (distance about 3800 km) at HAM and BSEG. Upper two traces: unfiltered broadband records; lower two traces: band-pass filtered with f = 0.5-5 Hz (from Bormann et al., 1997).

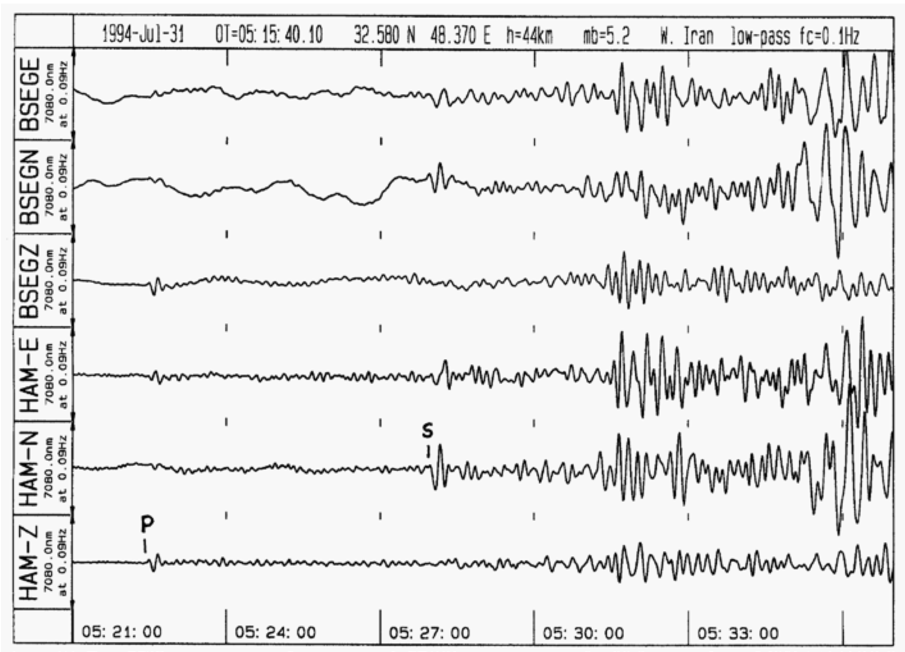


Fig. 7.36 Low-pass filtered (f_c = 0.1 Hz) long-period 3-component records at BSEG and HAM of the Iran earthquake (from Bormann et al., 1997).

Two more examples of relatively weak (mb = 5) earthquakes recorded at about 76° and 150° distance are shown in Fig. 7.37. Although the record traces for HAM have been reproduced at a resolution 10 times lower than the BSEG records the noise amplitudes are still much larger. The P and multiple PKP onsets (including depth phases) can be picked easily in the short-period filtered records of BSEG but not at HAM.

BSEG has now replaced HAM as a permanent GRSN station. Together with RUE, this has significantly improved the GRSN network detection and location performance for events in the northern part of Germany.

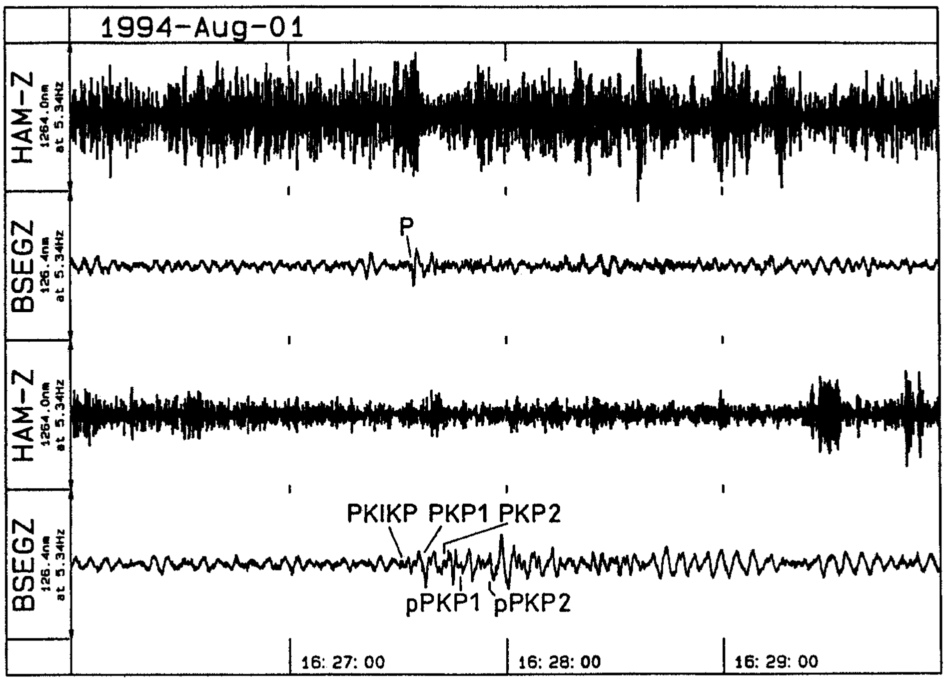


Fig. 7.37 Short-period band-pass filtered Z-component recordings (f = 0.5 - 5Hz) at HAM and BSEG. Upper two traces: P-wave onset of a Kurile Islands earthquake on 01.08.94 (D = 76.2° to HAM, mb = 5.0); lower two traces: PKP-wave group from an earthquake in the Tonga Islands on 30.07.94 (D = 150.1° to HAM, mb = 5.0) (from Bormann et al., 1997).

7.2.4.5 Causes of spectral noise reduction at RUE and BSEG and conclusions

Bormann et al. (1997) estimated quantitatively the reduction of noise amplitudes when traveling from a medium with a low acoustic impedance to a medium with higher acoustic impedance through a sharp impedance discontinuity. Taking into account the best available values for P- and S-wave velocities as well as the densities of the various rock and sedimentary formations in the area of BSEG and RUE, it was estimated that a noise power reduction of about 18.5 dB for BSEG and of 15.6 dB for RUE would be due to the lateral impedance contrast of the anomalous geological bodies at these two sites with respect to the surrounding unconsolidated Quarternary sediments. This would explain about half of the noise power reduction observed at BSEG with respect to HAM (some 30 to 40 dB between 1 and 15 Hz). The remaining reduction of about 10 to 20 dB at BSEG can be accounted for by the distance of BSEG (≈ 40 km) from the seismically noisy city of Hamburg.

For the noise power reduction observed at RUE with respect to BRNL (about 15 to 25 dB in the same frequency range), about 15 dB can be explained by the impedance contrast of the Rüdersdorf anticline. The change in distance to Berlin is less effective (RUE is about 20 km from the city center) because of the noise generated at a busy highway near RUE and ongoing production activity in the quarry.

Below 0.5 Hz, the effect of noise reduction due to these anomalous geological bodies is negligible because their near-surface diameter is then of the order of or smaller than the wavelength of the long-period noise. Large halokinetic, diapir or anticline structures do exist in many other parts of the world with dominating young soft sediment cover (e.g., around the Caspian Sea; west of the Zagros Mountains in Iran; in the USA). A systematic search and use of such structures (or of other anomalous local hardrock outcrops) as sites for permanent seismic recordings is recommended as a way to achieve significant short-period noise reduction. Otherwise, one has either to settle for rather bad noise conditions for near-surface installations or go for expensive borehole installations (see 7.4.5).

7.3 Data transmission by radio-link and RF survey

(A. Trnkoczy, 2002)

7.3.1 Introduction

Radio links are often used for data transmission in a seismic network. Radio links offer seismic data transmission in real time, are continuous, independent, often robust to damaging earthquakes, and usually involve a reasonable cost (see also IS 8.2: Seismic data transmission links used in seismology in brief).

However, experience shows that the most frequent technical problems with radio frequency (RF) telemetry networks originate in the RF links themselves. This is often the result of a non-optimally designed RF system. Many seismic networks in the world experience unreliable and noisy data transmission. There are even reports of some complete failures. This Chapter gives some general advice on how to design a seismic telemetry system, covering VHF (usually 160 - 200 MHz for seismology) and UHF (usually around 450 MHz for seismology) frequency band FM modulated links, as well as spread spectrum (SS; around 900 MHz or 2.4 GHz) RF data transmission and satellite . The need for a professional RF survey will be explained.

The UHF and VHF frequency bands are still the most frequently used. Spread spectrum and satellite links are becoming more popular in seismology.

7.3.2 Types of RF data transmission used in seismology

Most of today's RF telemetry seismic networks use the VHF or UHF frequency band. Both bands can be used for frequency modulated (FM) analog signal transmission or digital data transmission with a variety of modulation schemes. Both usually use standard 3.5 kHz bandwidth "voice" channels. It is much easier to obtain permission for these than for special channels with a higher bandwidth. Direct connection distances of up to 150 km (100 miles) are possible with less than one Watt RF power transmitters, if topography permits.

Unfortunately, the VHF band is almost completely occupied in most countries. It is therefore very difficult or even impossible to get permission to use this band. The band is also more susceptible to interference from other RF users and therefore is rarely used for new seismic networks.

Until very recently, the UHF band has been the most popular. But it is now becoming difficult to obtain permission for new frequencies within this band in many countries.

Spread spectrum RF telemetry is a new and increasingly popular alternative in seismology. These links operate at frequencies around 900 MHz or 2,4 GHz. Spread spectrum RF links do not use a single carrier frequency but instead use the entire frequency band dedicated for such links. Many users use the same frequency band so the corresponding transmitter and receiver must identify each other to discriminate from other users using special codes.

The practical advantages of spread spectrum links are that often no permission is needed for their operation and that they are very robust against RF interference (the technology was first developed for defense purposes for just this reason). There are limitations, however, because the maximum RF power of transmitters is defined by national regulations, varies greatly, and. dictates the maximum practical connection distance between a transmitter and a receiver. This may impose severe limitations on the wider use of spread spectrum links for seismology. In Western European countries where the limit is 100 mW, connections are only possible up to 20 to 30 km. Direct connection distances around 100 km can be achieved using stronger transmitters (up to 4W) only in the countries that allow them.

Satellite links are becoming more popular in seismometry and undoubtably represent the future for seismic data transmission. Costs are still a hindrance to the widespread implementation of this technology but these will surely come down.

Most of the commercially available satellite links are of the high throughput type. Usually they are purchased as 110 kHz bands in the GHz frequency range (e.g., Ku-band: 11 to 14 GHz). Frequently, the smallest available bandwidth (and consequently the baud rate) is much higher than usually required for a seismic station or even for a small seismic network. This makes satellite links relatively expensive for small networks. Prices for one 110 kHz band are currently around several hundred dollars per month (1998).

If the size of the network and the total bandwidth required is equal to or slightly smaller than any multiple of the available bandwidth increments, the cost of satellite data transmission may be more acceptable. This is easier to achieve in large national or regional seismic networks. The number of seismic data channels that can be transmitted in a 110 kHz frequency band depends on several parameters: the sampling rate; the number of bits per data sample (dynamic range); whether single direction (simplex) or bi-directional (duplex) links are used; the overhead bits required for error detection, forward error correction (FEC), and link management.

One of the important issues which varies from country to country relates to the central satellite recording site (the hub). In some countries, where the communication market is open, a seismic network owner may have its own 'private' hub directly at the central recording site. The cost of equipment for such a local hub varies from $80,000 to about $200,000 (in the year 2001). In countries with a more restricted communications market only a shared hub owned by a communications company may be available. In this case, not only is the cost of satellite communications higher but there will be additional costs for the communication links from the shared hub to the seismological central recording site. These usually use leased lines and the costs can be significant, particularly if the distance involved is large. Cost analysis of different satellite systems is complex and the prices vary significantly from country to country. A very careful cost analysis is recommended before making any final decision about satellite links.

A practical problem with satellite links is the relatively high power consumption of the equipment installed at a seismic station. In most cases, we must consider at least 50W power consumption for the data transmission equipment at each site. This significantly exceeds the power consumption of RF equipment traditionally used in seismology, including spread spectrum transmitters. It creates the need for large arrays of solar panels at stations without mains power and for bigger back-up batteries for a given station autonomy.

Nonetheless, the costs of satellite communications are constantly decreasing thanks to increasing liberalization in the communications market which will encourage the use of satellite links. No other communication system has the potential of satellite links for high reliability at the most remote and distant seismic stations.

7.3.3 The need for a professional radio frequency (RF) survey

The design of VHF, UHF or spread spectrum RF telemetry links in a seismic network is a specialized professional technical matter. Practice shows that guesswork and an approach based on "common sense" usually lead to problems or even complete failure of a project. The following misunderstandings and oversimplifications are commonly encountered:

- the amount of data that must be transmitted in seismology is often underestimated. Seismology requires a much larger data flow (baud rate) than most other geophysical disciplines, for example several orders of magnitude more than meteorology;

- the required reliability for successful data transmission in seismology is also frequently underestimated. Missing data due to interruptions on the links, excessive noise, spikes, and data errors are particularly destructive for networks operating in triggered mode and/or having any kind of automatic processing. With old paper seismograms and analog technology, spikes, glitches, interruptions and other 'imperfections' are relatively easily "filtered out" by the seismologist's pattern recognition ability during the analysis. However, the same errors, if too frequent, can make the results of an automatic computer triggering and/or analysis totally unacceptable;

- a false comparison with voice RF channels is made frequently. People try to verify a seismological RF link between two points using walkie-talkies. If they can communicate, they expect that transmission of seismic data will also be successful. Note that voice channels allow a much lower signal-to-noise ratio while still being fully functional because human speech is highly redundant. Also, the RF equipment parameters in walkie-talkies and in seismic telemetry are very different, making such "testing" of RF links meaningless.

- another wide-spread belief is that the "line of sight" between transmitter and receiver is a sufficient guarantee for a reliable RF link. This may or may not be true. It is only certain for very short links up to about 5 km length with absolutely no obstructions between the transmitter and the receiver (such links may occur in some small local seismic networks). Fading, i.e., the variation of the intensity or phase of an RF signal due to changes in the characteristics of the RF signal propagation path with time, becomes a major consideration on longer links. The real issues in link reliability calculations are the equipment's gains and losses, RF signal attenuation based on Fresnel ellipsoid obstruction, and the required fading margin. The resultant reliability of the link can then be expressed as a time availability (or probability of failure or time unavailability) as a percentage of time in the worst month of the year (or per year). During 'time unavailability', the signal-to-noise ratio at the output of the receiver is lower than required, or the bit error rate (BER) of digital data transmission link is higher than required. Many parameters are involved in the RF path analysis including transmitter power, frequency of operation, the various losses and gains from the transmitter outward through the medium, receiver antenna system to the input of the far end receiver and its characteristics. In link attenuation calculation, the curvature of the Earth, the regional gradient of air refractivity, the type of the link regarding topography, potential-wave diffraction and/or reflections, time dispersions of the RF carrier with digital links, processing gain and background noise level with spread spectrum links, etc. all play an important role.

We strongly recommend having a professional RF survey during the seismic network planning procedure. IS 7.1 provides the information on what preparation is needed if an RF survey is purchased as a service along with the seismic equipment.

7.3.4 Benefits of a professional RF survey

The benefits of a professional RF survey are:

- it ensures that the links will actually provide the desired reliability, which has to be decided beforehand. During the RF survey, the design parameters of the links in a network are varied until the probability of an outage in the worst month of a year drops below the desired value. This may require additional investment in equipment, but it will prevent unreliable operation or may save some money by loosening the requirements where appropriate;
- it guarantees the minimum number of RF repeaters in a network. This results in a direct benefit to the user in having less equipment, fewer spare parts, and in cheaper and easier maintenance. There will also be lower instrumental noise in the recorded signals for FM analog networks and a better BER performance for digital networks. Note that in most designs for analog FM telemetry, every additional repeater degrades data quality to some extent and always decreases the network reliability;
- It will determine the minimum number of licensed frequencies required in a network without sacrificing data transmission reliability. Note that the required number of different carrier frequencies in VHF and UHF telemetry can be significantly smaller than the total number of the links in the network. This prevents unnecessary pollution of RF space in the country. Use of fewer frequencies also benefits the user since they are easier to obtain and fewer different RF spare parts are required;
- the robustness of the entire seismic network to lightning threat is significantly increased by a proper RF layout, for example, one should always avoid repeaters which relay data from many seismic stations because any technical failure of the repeater will result in severe data loss;
- reduced power consumption can be achieved by calculating the minimum sufficient RF output of the transmitters. This results in less pollution of RF space in the country. The user also benefits from lower power consumption at remote stations;

- minimizing the heights of antenna masts and the minimum gains of the antennae has potential for cost saving.

7.3.5 Radio-frequency (RF) survey procedure

An RF survey usually considers the RF equipment to be used, a topographical profile from each transmitter site (remote seismic station) to each receiver site (central recording site or repeater), local RF path conditions, and the desired reliability of the link. It is based on decades of experience of transmission statistics from all over the world and computer modeling using specialized software. Field RF measurements are rarely performed because they are expensive and time-consuming and they are often less reliable than calculations. RF transmission conditions vary with time (diurnal, seasonal, weather dependent), vary unpredictably and within climatic zones. Theoretical calculations include the full statistics of these variations whereas practical one-time measurements suffer from unpredictable variations in fading. However, even if no measurements are planned, a communications expert still has to visit all potential seismic sites during the site selection procedures to assess local topography and to check for the existence of potential RF obstacles which may not be evident from topographic maps.

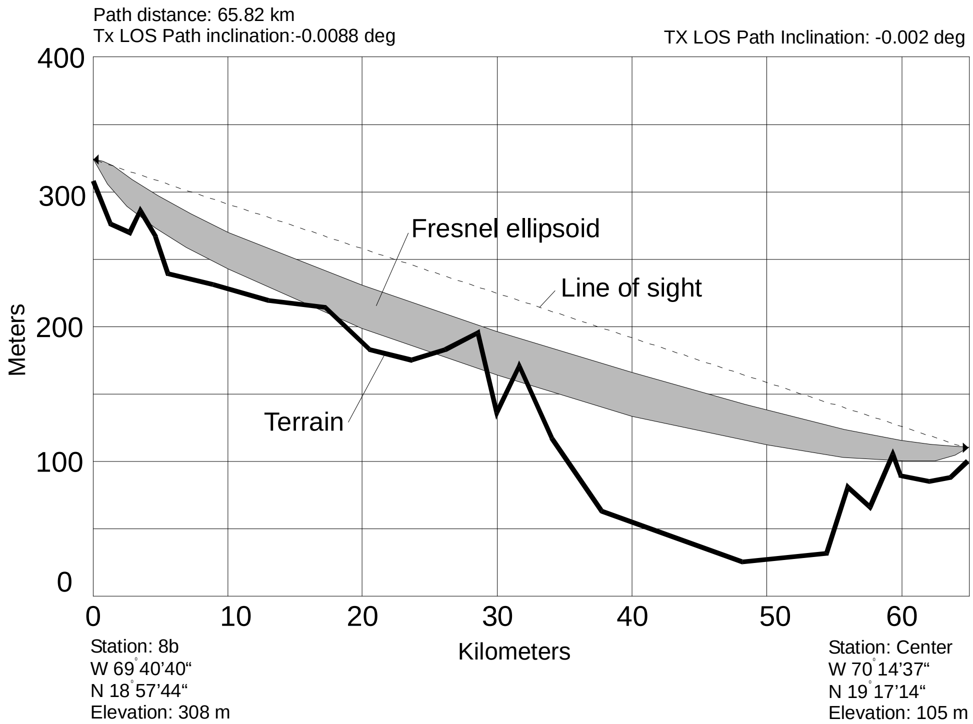
If the RF link calculation based on a given set of input parameters does not give the desired reliability, some of the input parameters must be changed. We can change topographical profile by either repositioning stations or by introducing a new RF repeater. We can change the antenna type and/or increase their gain. We can increase antenna mast height or increase transmitter output power (seldom effective) or we can change the RF equipment completely (significantly more powerful transmitters and/or more sensitive receivers).

Topographic profiles are usually taken from 1:50.000 scale topographical maps. In most cases, many more profiles than stations available in the network are taken and links calculated before we determine the final RF layout of a network. A great deal of this work can be done before fieldwork starts, but profiling is always needed during the fieldwork.

The result of an RF link calculation is shown in Fig. 7.38 with input parameters on the left and output parameters on the right. The figure intentionally shows an example where there is a "direct line of sight", but the profile doesn't guarantee acceptable link operation. Note the curved path of the first Fresnel ellipsoid where the RF energy actually travels from the transmitter to the receiver. This curvature is mostly due to the regional gradient of air refractivity. In the example, this ellipsoid hits the mountain ridge and causes a significant loss of energy or possibly link failure.

For analog VHF or UHF telemetry it is usual to regard a time availability of about 99.95% (equivalent to about 15 minutes of outage of each link per month) in the worst month as being marginally acceptable and 99.99% as good. If we use an RF repeater between the seismic station and central recording site, we have to increase the required reliability of individual sections to give the required reliability for the entire link.

In digital data transmission, the bit error rate (BER) is used as a measure of data link reliability. BER strongly depends not only on physical reliability of the RF link but also on error detection and error correction methods used in the RF equipment (modems). For example, one-directional (simplex) links are generally far less reliable than bi-directional (duplex) links, even if the RF links themselves are of the same quality in terms of RF signal to noise. This is because duplex links allow repeated transmission of corrupted data blocks until they are received without error whereas simplex links result in corrupted data, unless forward error correction (FEC) methods are used. Due to the complexity of the problem, a precise targeting of desired BER is usually beyond the scope of seismic network projects.



Frequency: 900 Mhz
Distance: 65.82 km
Antenna height TX: 18 m
Antenna Height RX: 18 m
TX antenna type: Yagi
RX antenna type: Yagi
Effective isotropic radiation power: 38.0 dB
TX power: 30 dBm
TX antenna gain: 10 dB
TX connector loss: 0.05 dB
TX line loss: 2 dB
RX antenna gain: 10 dB
RX connector loss: 0.05 dB
TX site totals - gain/loss: 40.0/2.0 dB
RX site totals - gain/loss: 40.0/2.0 dB
RX threshold level: -110.0 dB
Profile: K =4/3, F = 0.6*F1

Free space path loss: 128.21 dB
Diffraction loss: 0.0 dB
Total system loss: 132.2 dB
Total system gain: 50.0 dB
Unfaded receiver
signal level: -82.16 dBm
Fade margin: 27.8 dB
Outage: 23412 sec/year
Time availability: 99.926 %

Fig. 7.38 Result of an RF link calculation with input parameters on the left and output parameters on the right.

Something similar is the case for spread spectrum links where another factor complicates the situation. Spread spectrum receivers incorporate so-called "processing gain". These receivers are capable of resolving very weak RF signals, which may even be a few dB below the RF noise at the receiver site. However, the problem is that the amplitude of the RF noise at the receiver site is generally unknown. Note that every new spread spectrum transmitter increases the background noise in the band of operation of the spread spectrum system and since this band is open to the public, it is difficult to predict its actual noise. Consequently we will not know exactly the sensitivity of a receiver, resulting in a less reliable estimate of the link availability.

Specialized spread spectrum measuring equipment is extremely expensive. The algorithms which are used to resolve the sub-noise level RF signals in the receivers also present a problem. They are mostly proprietary and therefore not generally accessible. Both facts significantly reduce the practicality of measurements of the reliability of spread spectrum links for seismological purposes.

Fortunately, some spread spectrum equipment manufacturers provide special software which allows easy but approximate link reliability measurements for the transmitters and receivers to be used in the seismic system. Taking into account a safety margin due to temporal variation of RF transmission conditions, one can successfully use these measurements for an approximate estimate of link quality. However, it is difficult to relate these proprietary 'reliability scales' to standard parameters like probability of link outage or BER. Nevertheless, classical RF signal attenuation calculations still give valuable information about RF energy propagation over a given topographic profile. These results, combined with measurements using manufacturer's proprietary 'reliability scales' and practical experience, suffice in almost all seismometric projects.

The cost of a professional RF survey is generally around a few percent of the total investment in a new seismological network. Practice shows that its benefits are well worth the investment. An RF survey is a major step toward the reliable operation of any future telemetry seismic network.

7.3.6 The problem of radio-frequency interference

While spread spectrum links are fairly robust, radio-frequency interference between a VHF or UHF seismological system and other RF users is quite a common and difficult problem in many developing countries. In some countries, the lack of discipline in RF space causes unforeseen interference. In others, insufficient maintenance of high-power communication equipment results in strong radiation from the side-lobes of powerful transmitters that may also interfere with seismological links. Army facilities, particularly if they operate outside civil law, especially some types of radars, frequently interfere with seismological links. The risk of interference is very high if seismic stations are installed at sites which are also used for other high power RF communication equipment (see IS 7.2). Extensive use of walkie-talkies can also cause problems.

In some developing countries, the use of RF spectrum analyzers, which can frequently reveal the origin of interfering signals, is prohibited for security reasons, particularly for foreigners. In any case, interfering RF sources may appear only very intermittently and so are difficult to detect.

Note that RF interference problems due to indiscipline in RF space are generally beyond the control of a seismic equipment manufacturer and/or foreign RF survey provider. They can only be solved, or at least mitigated, by involving local RF communication experts during the very early phases of network planning. These people are familiar with the real RF conditions in the country and can provide better advice than any foreign expert. If a new seismic network experiences interference problems, only very tedious and time consuming trial-and-error procedures (swapping frequencies of the links or even VHF/UHF bands, changing antenna orientation and polarization, or even re-positioning of stations or repeaters) may help. However, the results are unpredictable. One should also be aware that the allocation of frequencies may change in future and disturbances remedied today may reoccur later.

7.4 Seismic station site preparation, instrument installation and shielding

7.4.1 Introduction and general requirements (A. Trnkoczy; version 2002)

When installing a seismometer inside a building, vault, or cave, the first task is to mark the orientation of the sensor on the floor. This is best done with a geodetic gyroscope although a magnetic compass will often suffice. The magnetic declination must be taken into account. A compass may be deflected, showing a false reading, when inside a building so the direction should be taken outside and transferred to the site of installation. A laser pointer may be useful for this purpose. When the magnetic declination is unknown or unpredictable (such as in high latitudes or volcanic areas), the orientation can be determined with a sun compass. Special requirements and tools for sensor orientation in boreholes are dealt with in 7.4.6.2.

To isolate the seismometer from stray electric currents, small glass or perspex plates should be cemented to the ground under its feet. The seismometer can then be installed and tested. Broadband seismometers should be wrapped with a thick layer of thermally insulating material. The exact type of material does not seem to matter; alternate layers of fibrous material and heat-reflecting blankets are probably the most effective. The edges of the blankets should be taped to the floor around the seismometer. Further information on suitable and proven thermal insulation for broadband seismometers, including illustrations, can be found in 7.4.2.1, 7.4.4.2 and 5.5.3. One has to be aware that electronic seismometers generate heat and so may induce convection in any open space inside the insulation. It is therefore important that the insulation fits the seismometer tightly.

For the permanent installation of broadband seismometers under unfavorable environmental conditions, they should be enclosed in a hermetic container. A problem with such containers (as with all seismometer housings) is that they cause tilt noise when they are deformed by barometric pressure. Essentially three precautions are possible: either the base-plate is carefully cemented to the floor, or it is made so massive that its deformation is negligible, or a "warp-free" design is used, as described by Holcomb and Hutt (1992) for the STS1 seismometer (see DS 5.1).

To prevent or reduce corrosion in humid climates, desiccant (silica gel) should be placed inside the container, including inside the vacuum bell, of an STS1 seismometer. Broadband seismometers may also require some magnetic shielding (see 5.5.4).

Civil engineering work at remote seismic stations should ensure that modern seismic instruments can be used to their fullest potential by sheltering them in an optimal working environment. Today's high dynamic range, high linearity seismic equipment is of such quality and sensitivity that seismic noise conditions at the site and the environment of the sensors have become much more important than in the past. Apart from site selection itself, the design of seismic shelters is the determining factor in the quality of seismic data acquisition.

Seismic vaults are currently the most common for new seismic stations (see 4.2). They are the least expensive but suffer more from seismic noise because of their near-surface installation. Alternatives include seismic installations in abandoned mines, in specially constructed tunnels (see 7.4.3) and in boreholes (see 7.4.5 and 7.4.6). These have the advantage of high temperature stability and significantly reduced surface and tilt noise because of the significant overburden. The low tilt noise is of particular importance for long-period and broadband seismometers because of their high tilt and temperature sensitivity (see 7.4.4, 5.3.3 and 5.3.5). A variety of factors must be considered before the optimal technical and financial solution for a seismic installation is found. These include the type of monitoring or research to be carried out, the kind of equipment to be installed, existing geological and climatic conditions, already existing potentially suitable structures and sites, available construction materials or alternative technical solutions, accessibility of and available infrastructure/power supply at the station.

Various solutions can be employed with equal success. Much depends on potential future upgrades of the instrumentation and site, what working conditions are desired for maintenance and service personnel, and, of course, on the funds available. Because of these diverse considerations, no firm design and civil engineering drawings are provided in this document. Instead, the general requirements that must be satisfied are described in detail so that, e.g., in the case of seismic vaults, any qualified civil engineer can design the shelter for optimal performance, taking into consideration local conditions in a given country and at a specific site.

7.4.2 Vault-type seismic stations (A. Trnkoczy; version 2002)

This section describes the general conditions to be considered when constructing seismic vaults. A vault for seismic data acquisition and transmission equipment should satisfy the following general requirements:

- provide adequate environmental conditions for the equipment;
- ensure the proper mechanical contact of seismic sensors with bedrock;
- prevent seismic interaction between the seismic shelter and the surrounding ground;
- mitigate seismic noise generated by wind, people, animals, and by potential noise sources within the vault;
- ensure a suitable electric ground for sensitive electronic equipment;
- provide sufficient space for easy access and maintenance of the instruments.

These requirements will be discussed in detail below. A design example of a seismic vault for a three-component short-period (SP) station together with its upgrade for broadband (BB) and potentially very broadband (VBB) seismic sensors will be given, complemented by some technical hints at the end of this section. Other examples of vault-type seismic shelters are given in 7.4.4.3 . Detailed installation guidelines for BB and VBB stations on can find in Uhrhammer et al. (1998). Alternative vault designs of typical 'classic' seismometer vaults are given in Figures 4.5b-e of the old MSOP (Willmore, 1979; also accessible on the IASPEI website http://www.iaspei.org/projects/NMSOP.html via the link Manual of Seismological

Observatory Practice (1979 Edition)). Some recent complementary comments have been added by the Editor in the inserted box below.

Complementary comments on seismometer installations in vaults and on piers (2011)

Several NMSOP-1 users asked to specify somewhat more in this section how to “decouple” best the place or pier on which a seismometer is installed in a vault or in a building from ambient and human disturbances. The editor asked two experts. There answers see below:

Amadej Trnkoczy on 15.06.2011

Regarding the vault design my opinion has always been the same: dig the vault until you reach a good bedrock, then put as little as possible fine concrete on it to make a flat surface big enough to put a seismometer or seismometers on it. Build around the vault as small and as light as possible 'housing', the best is none. Just a firm (strong wind!), water tight cover over the vault and that is it. In this case there is no structure/soil or structure/seismic pier interaction possible since there is practically no 'structure'. The problem is solved.

Generally modern seismic instruments are so sensitive that there should be no housing for people to live or work close to them. To my opinion there is no way to decouple a seismic pier from human activity so close to it. Also such housings may cause problem during windy periods.

In old times, when sensors were much less sensitive, this was allegedly possible using several different methods (like "mechanical dampers", or separate foundation for the housing and for the pier, etc). I would not recommend such approaches for regular seismic stations of a seismic network today.

Thomas Forbriger on 27.06.2011

“Decoupling” is probably meant to avoid noise on the pier caused by forces excerted on the external surface of the vault. Most effective decoupling should always be achieved by underground installations in solid rock and good coupling of the pier to bedrock. Better decoupling as provided by overburden competent rock probably cannot be achieved by any other measures.

Explicit decoupling from the housing in above-surface installations may be an issue in sedimentary settings (loose soil). In such cases you should avoid mechanical coupling of the pier to the walls of the above-surface building. There should always be a gap in between with the pier being only coupled to the ground (if possible on bedrock). This will however not avoid noise coupled to the ground surface outside the building which can be significant for long-period observations in above-surface installations.

Better focus on good coupling of the pier to bedrock.

7.4.2.1 Controlling environmental conditions

Adequate shelter for seismic equipment should:

- prevent large temperature fluctuations in the equipment due to day/night temperature differences or because of weather changes;
- prevent large temperature fluctuations in the construction elements of the vault, resulting in seismometer tilt;
- ensure adequate lightning protection;
- mitigate electromagnetic interference (EMI);
- prevent water, dust and dirt from entering the shelter;
- prevent small animals from entering the shelter.

At very low seismic frequencies and in VBB seismometers, air pressure changes also influence seismometer output. Special installation measures and processing methods can be used to minimize the effect of air pressure. However this issue will not be treated here. For more information see Beauduin et al. (1996).

Mitigating temperature changes

In general, seismic equipment can operate in quite a broad temperature range. Most of the equipment on the market today is specified to function properly between –20 and +50 degrees Celcius. However, this is the operating temperature range – that is, guaranteeing only that the equipment functions at a given constant temperature within these limits.

Temperature changes with time, particularly diurnal changes, are far more important than the high or low average temperature itself. Many broadband seismometers require mass centering if the temperature "slips" more than a few degrees Celcius, although their operating range is much wider. Even small temperature changes can cause problems with mechanical and electronic drifts which may seriously deteriorate the quality of seismic data at very low frequencies. Unfortunately, the practical sensitivity of the equipment to temperature gradients is rarely provided by manufacturers. Very broadband (VBB) seismometers require extremely stable temperature conditions which are sometimes very difficult or impossible to assure in a vault-type shelter. VBB sensors usually require special installations (see Uhrhammer et al., 1998). Short-period (SP) seismometers, particularly passive ones, and accelerometers are much less sensitive to temperature changes.

In general, thermal drifts should be kept acceptably small by thermal insulation of the vault. However, the requirements differ significantly. Maximum +/- 5 deg C short-term temperature changes can be considered a target for passive SP seismometers and force-feedback active accelerometers. To fully exploit the low-frequency characteristics of a typical 30-sec period BB seismometer, the temperature must be kept constant within less than one degree C. To fully exploit a several-hundred-seconds period VBB sensors only a few tens of millidegrees C per month are recommended.

Data loggers and digitizers can tolerate less stable temperatures, i.e., on average, the temperature change would be ten times greater than on a BB seismometer for the same change in output voltage. The best digitisers, for example, change their output voltage less than +/-3 counts in room temperature conditions. If daily temperature changes are less than 1 deg C, their output voltage changes less than +/-1 count (Quanterra, 1994).

Some elements such as some computer disk drives, diskette drives, and certain time-keeping equipment, may require narrower operating temperature tolerances. The most effective way to assure stable temperature conditions is an underground vault that is well insulated (see Fig. 7.39). Underground installations are also the best for a number of other reasons.

Thermal insulation of active seismic sensors is done in two places. First, the interior of the vault is insulated from external temperatures, and second, the sensors themselves are insulated from residual temperature changes in the vault. In the most critical installations, the seismic pier itself is insulated along with the sensors.

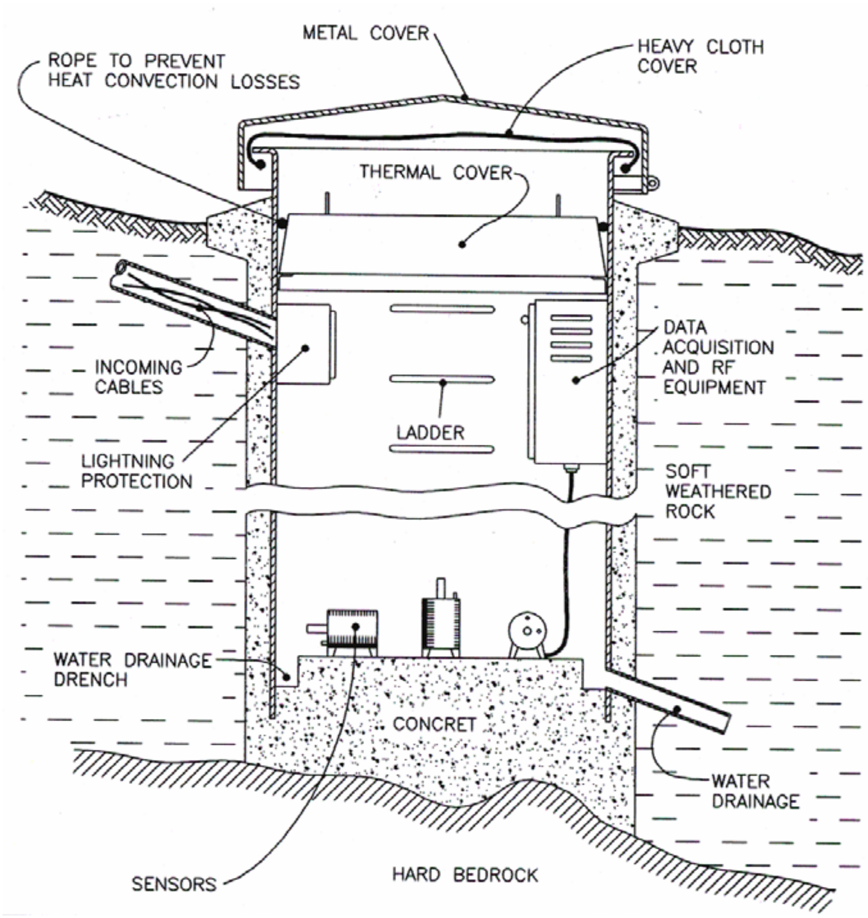


Fig. 7.39 Example of a vault for a short-period three-component seismic station made of a large-diameter metal pipe with thin concrete walls.

Underground vaults are usually insulated with a tight thermal cover made of styrofoam, foam rubber, polyisocyanuratic foam, or other similar, non-hygroscopic insulation material (Fig. 7.39, Figs. 7.41 and 7.42). Such materials are usually used in civil engineering for the thermal insulation of buildings. They come in various thicknesses, often with aluminum foil on one or both sides. This aluminum layer prevents heat exchange by blocking heat transfer through radiation. Thinner sheets can be glued together to make thicker ones. Casein-based glues are appropriate for styrofoam and expanding polyurethane resin is used to glue polyisocyanuratic foam sheets.

In continental climates, a 20 cm (8") layer is considered adequate but in extreme desert climates, up to 30 cm (12") of styrofoam is recommended. In equatorial climates a 10 cm (4") layer is considered sufficient.

There are two thermal cover design issues that are particularly important. Special care must be taken to assure a tight contact between the vault's walls and the thermal cover. If it is not tight, heat transfer due to convection through the gaps can easily be larger than the heat transfer through the thermal cover by conduction. This can undo the insulating effects of the cover. One way to achieve a tight thermal cover is shown in Fig. 7.43. A "rope" is tightly pressed into the gaps between the vault's walls and the thermal cover as well into the wedge-like gap between the cover halves seen in Fig. 7.41. This "rope" can be made of insulating fibers and is usually used for industrial hot water pipe insulation. It is available in different sizes and is inexpensive.

The cover should be placed at or below the depth at which the ground heats up during the day – not on the top of the vault. In desert areas, surface ground temperatures can exceed 80 deg C. At 30 cm (12") depth, temperatures of 50 deg C are not unusual. In such conditions, the thermal cover must be placed 40 - 50 cm (16" - 20") below ground level. A thermal cover of any thickness at the top of the vault, particularly if the vault's rim stands significantly above the surface, has almost no effect.

Fig. 7.40 Interior of a seismic vault made of welded metal sheets. The vault is big enough to accept weak- and strong-motion instrumentation together with data acquisition and transmission equipment.

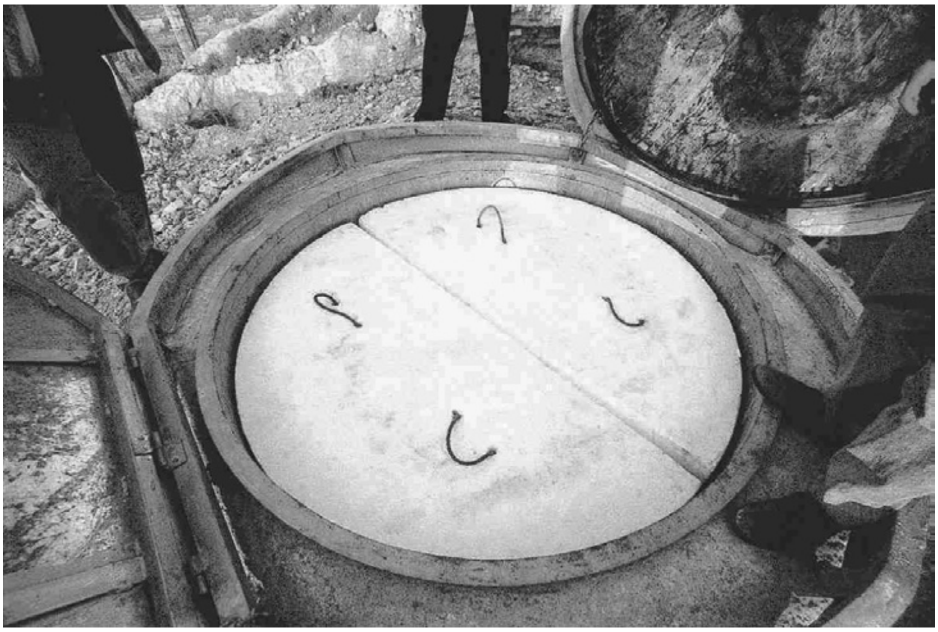


Fig. 7.41 Thermal cover of a seismic vault in two pieces made of thick styrofoam. The gaps between the cover and the vault walls and between both pieces must be tightly sealed.

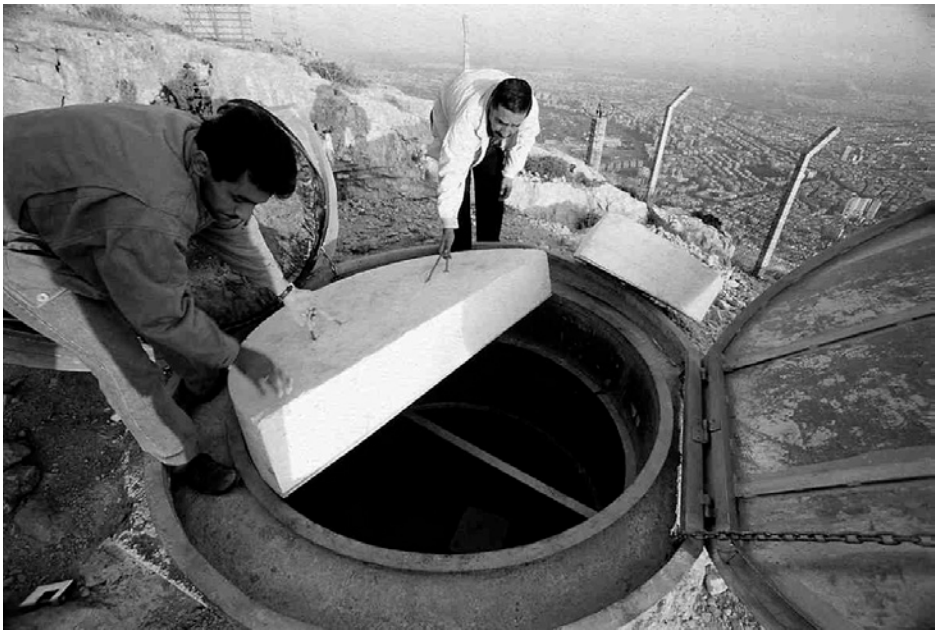


Fig. 7.42 Installing thermal cover in a seismic vault. In climates with large diurnal temperature changes the cover should be positioned lower in the vault where external ground temperature does not change significantly.

If vaults are used for BB or even VBB stations (see Wielandt, 1990), it is advisable to make a second inner thermal cover just above the sensor but below the floor where all other equipment is installed (see Fig. 7.44). Since most maintenance work relates to batteries, data recording, and data transmitting equipment, the thermal- and mechanical-sensitive BB/VBB sensors are not disturbed at all during service visits.

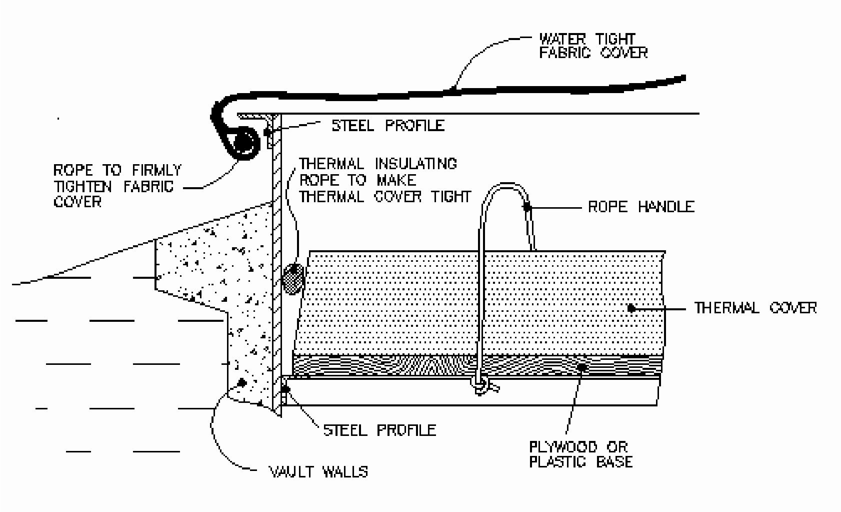


Fig. 7.43 Detail of making a thermal cover effective by filling up the gaps between the cover and vault walls with insulation material and making the vault tight against dust, dirt, and rain during windy periods with a fabric cover.

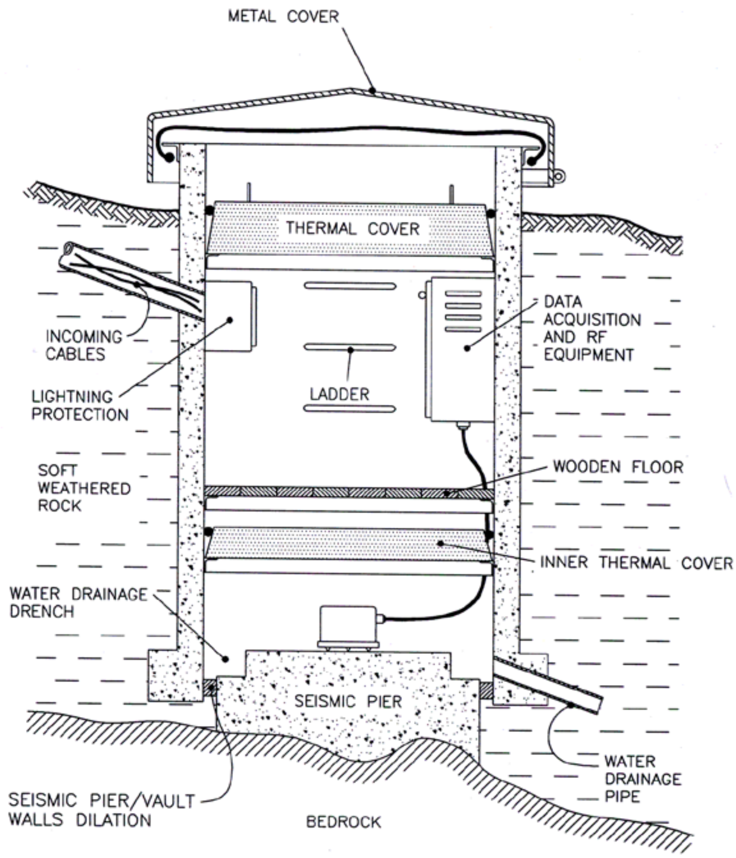


Fig. 7.44 Example of a BB or VBB seismic vault with a separate compartment for sensors and double thermal cover. Usually, the sensor itself is additionally isolated (see. Fig. 7.50). A thermal isolation box is usually put around the sensors to additionally insulate them.

Thermal insulation of the seismic pier itself, together with the seismometer, is the best method of insulation (Fig. 7.45). This method keeps the heat transfer between seismometer and vault interior as low as possible, while at the same time assuring good thermal contact with the thermally very-stable ground. Thus, the thermal inertia of the system is very large, limiting the rate of temperature changes to a minimum.

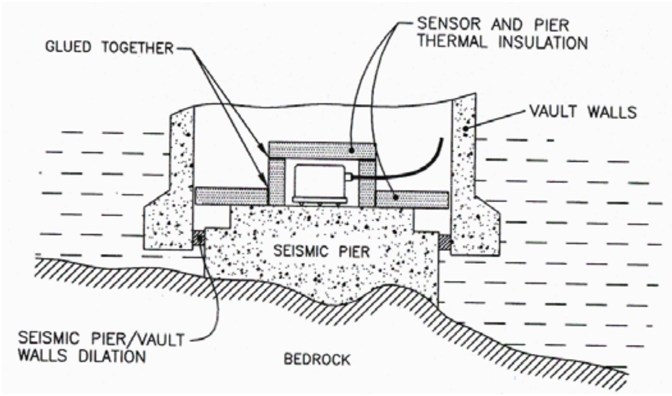


Fig. 7.45 Thermal isolation of a VBB sensor and surrounding seismic pier and mechanical separation of the pier from the vault walls for the most demanding applications.

Thermal tilt mitigation

Special measures are required to prevent thermal deformation and tilt of the seismic pier in a vault to allow the study of extremely low frequency signals with VBB seismometers. Modern VBB sensors, the horizontal components in particular, can detect tilts of a few nanoradians. A human hair placed under the corner of a level football field or an air pressure difference of only 0.1 mbar over a distance of several km would cause such a tilt. According to Wielandt (see section 5.3.3) a tilt of about 10^{-9} rad would result in a noise ground acceleration amplitude of 10^{-9} g in the horizontal components but only of 10^{-11} g in the vertical one.

Homogeneity of the seismic pier and surrounding soil, as well as civil engineering details of vault design are very important. Uhrhammer et al. (1998) recommend the physical separation of the seismometer pier and the vault walls (see Figs. 7.44 and 7.45). This separation assures that minute changes in the dimensions of the vault walls due to temperature change do not tilt the seismic pier. However, since such seismic vaults are not constructed "in one piece," one has to be particularly careful that the contact between the pier and vault walls is still watertight.

The seismic pier should be made of homogenous material and neither it nor the walls of the vault should use any steel reinforcement. Steel and concrete have different temperature expansion coefficients which cause stress and unwanted minute deformation of the structure of the vault if the temperature changes. Steel is unnecessary anyhow because structural strength is practically never an issue except in the very deepest of vaults. Sand aggregates used for concrete should be homogenous, fine-grain, and of uniform size rather than of varying size as in the usual concrete mixture. Uhrhammer et al. (1998) recommend sieved sand with 50% Portland cement. After the pier is poured, the concrete must be vibrated to remove any trapped air.

Lightning protection

Lightning causes most of the damage to seismic equipment around the world and lightning protection is probably the most important factor in preventing station failure. We know of several seismic networks that lost half or more of their equipment less than two years after installation because of inadequate lightning protection. Of course a direct hit by lightning will cause equipment damage despite the best protection. Fortunately, this rarely happens. Most lightning-related damage is caused by induction surges in cables, even when the source is some distance from the station.

Climatic and topographic conditions at a site vary greatly and determine the degree to which one should protect the system from lightning. Tropical countries and stations on top of mountains are the most vulnerable and therefore require the most lightning protection measures.

Lightning protection includes the following measures:

- proper cabling that minimizes voltage induction during lightning;
- proper use of special electronic devices to protect all cables entering the seismic vault from voltage surges;
- a good grounding system since no practical lightning protection measure works without grounding;
- enclose the equipment in a "Faraday cage" either by making a metal shielded seismic vault or a loose mesh of ground metal strips around the vault. This creates an equipotential electric field around the equipment, thus decreasing voltage drops on equipment and cables during lightning strikes.

If any one of these measures is not undertaken, the others become largely ineffective.

The best lightning protection is a metal seismic vault. The exterior of the vault should not be painted so that good electrical contact can be made with the surrounding soil, thereby lowering impedance. If the main cover or any other part of the vault is metal, it should be connected to the vault's walls using a thick flexible strained wire.

In any event it is necessary to protect all cables entering the seismic vault. Many high quality seismic instruments already have internal lightning protection circuitry, but these measures are sometimes not enough for high lightning threat regions. Lightning protection may include gas-discharge elements, transient voltage suppressors (transorbs), voltage dependant resistors, and similar protection components.

The lightning protection equipment of the cables must be installed at the point where they enter the vault. It must be grounded at the same point with a thick copper wire or strip that is as short as possible. The unprotected length of any cable within the vault must be kept to an absolute minimum.

All cables entering the vault must be protected. Voltage surges usually occur in all cables, and leaving a single long cable unprotected is virtually the same as leaving all the cables unprotected.

All metal equipment boxes should be grounded with a thick copper grounding wire or strip (> 25 mm^2 cross-section) to the same point where the lightning protection equipment of incoming cables is grounded. Use a tree-shaped scheme for grounding wires. All these wires should be as short as possible and without sharp turns. All the cables in a vault should be kept to a minimum length. No superfluous cables or even coiled lengths of excess cable are acceptable. These are true lightning catchers.

Telephone and power companies usually install lightning protection equipment for their lines. This should be required of them when arranging these services. Manufacturers of seismic equipment can also provide and install such equipment if asked.

Note that there is never a 100% safe lightning protection system. However, for high lightning risk regions and for expensive and delicate seismic equipment, long years of practice show that investing in an effective lightning-protection system pays off in the long run.

Electro-Magnetic Interference protection

The problem of electro-magnetic interference (EMI) is not normally a very important issue because seismic stations are generally situated in remote rural locations. However, in such regions the main power lines can frequently be of low quality. We recommend using mains power voltage stabilizing equipment in such cases. This equipment usually incorporates EMI filters and voltage surge protection, which further protects seismic equipment from failures and EMI-generated noise. In general, metal seismic vaults protect equipment from EMI very effectively.

Some passive seismometers with moving magnets and separate components generate EMI during mass motion. Since this may influence surrounding sensors, you should not install such seismometers too close together. A minimum distance of 0.5 m (1.5 feet) is recommended. A simple test can assure you that cross talk is insignificant. Disconnect and un-damp one component, move the seismometer mass by shaking it slightly and measure the output of both the other components. There should be no cross-talk.

In addition, seismometers should not be placed too close to the metal walls of a vault. This minimises potential changes in the static magnetic field, which may slightly influence the generator constant of some seismometers.

Data recording equipment with mains transformers should not be installed next to, or on the same pier as sensors. The transformer may cause noise in the seismometer signals either through its magnetic field or due to direct mechanical vibrations at 50 or 60 Hz. The same is true for magnetic voltage stabilizers, if used at the site. Place such equipment in a metal housing for additional magnetic shielding and install it on the wall of the vault.

Water protection

Water entering seismic vaults is probably the second most common cause of station failure. The most effective way to prevent water damage is vault drainage (Fig. 7.46). Use a hard plastic tube of about 3 cm (1") diameter, such as used for water pipelines. The drainage pipe must be continuous and have at least a 3% gradient, particularly in regions where the ground freezes during the winter. If drainage is impossible, as is often the case for deep vaults, water tightness of the vault is of the utmost importance. Note that a high ground water level and porous concrete vault walls more or less guarantee water intrusion.

Water tightness is easy to achieve if the walls of the vault are made of metal welded from plain or corrugated iron sheets or from large-diameter metal tubes, providing the welds are of good quality. If the vault is made of concrete and has no water drainage, the concrete should be of a very good, uniform quality. Water-resistant chemicals should be added to the mix to help keep it water-tight. The concrete must be vibrated during construction to assure homogeneity of the walls.

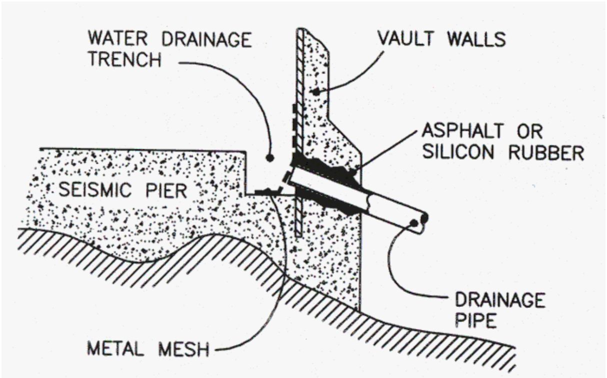


Fig. 7.46 Water drainage pipe and vault trench around the seismic pier.

The bottom of the seismic vault - the seismic pier - is always made of concrete. Once again, use good quality, uniform-aggregate concrete with water-resistant additives. The bottom should have a water drainage ditch (see Figs. 7.39 and 7.46) around the flat central pier on which the sensors are installed. For vaults with external water drainage, the ditch should be at least 5 cm (2") deep and 10 cm (4") wide. For the vaults without drainage, this ditch should be larger (at least 15-cm by 15-cm or 6"x 6") so it can collect more water.

Making the joint between the vault walls and floor requires special care. Use asphalt to seal any cracks by heating the concrete with a hot-air fan and then pouring hot asphalt into them. The cables entering the vault also require special care. They are normally installed in a plastic or metal tube that should fit snugly into the appropriate hole in the vault wall. Use silicon rubber or asphalt to seal any gaps.

In vaults designed for VBB seismometers whose seismic pier is mechanically separated from the walls, water tightness represents a special challenge. Once again use soft asphalt to make the gap between the walls and the pier watertight.

The upper rim of the vault must be at least 30 cm (1 foot) above the ground. At sites where a lot of snow is expected, this should be higher, up to 60 cm (2 feet). Slush is particularly troublesome with regard to keeping vaults watertight. Where possible, the surrounding terrain should descend radially from the top of the vault.

One practical measure is to create a small "overhang" at the top edge of the vault (see Fig. 7.43). This ledge should be about 5 cm (2") out from the vault wall. A thick, watertight fabric cover can be hooked over this metal edging. The cover is pulled tight to the vault by rope and prevents water from entering the vault during windy, rainy periods. It also protects against dust and dirt and provides some additional thermal insulation.

To minimize the danger of equipment flooding, install all equipment, apart from the sensors, on the wall of the vault or on a raised platform.

Protection from small animals

At first glance the issue of small animals may seem amusing. However, animals frequently use seismic vaults as dwellings. We have seen some very strange "seismic" records caused by ants, grasshoppers, lizards, and mice. Worse, such animals can cause severe damage to cables and other plastic parts of the equipment.

Tight metal (particularly effective), fabric or thermal vault covers usually prevent animals from entering the vault from above. Plastic tubes for cables and drainage should be protected by metal mesh. Placing metal, wool or glass shards in the free space in these tubes also helps. Insecticides can be used to drive away ants and other insects.

In extreme circumstances, animals may be deterred from chewing cables and other equipment by applying paints developed to prevent animal damage to trees.

7.4.2.2 Contact with bedrock

Good contact between seismic sensors and bedrock is a basic requirement. Soil and/or weathered rock layers between the sensor and the bedrock will modify seismic amplitudes and waveforms.

The depth of bedrock and the degree of weathering of layers beneath the surface can be determined by shallow seismic profiling of the site, by drilling (most often too expensive), or by actually digging the vault. Only rarely will a surface geological survey provide enough information about the required depth of the seismic vault (except where the bedrock is clearly outcropping).

If you choose not to carry out a shallow seismic profile, then expect surprises. You will need to dig until you reach bedrock, and that can sometimes be very deep; a vault may have to be repositioned and re-dug if weathered bedrock is extremely deep. These risks make the cost of shallow profiling a wise investment.

A definition of "good" bedrock is necessary when digging vaults without a seismic profile. Unfortunately, the definition is fairly vague, especially because some recent studies show that even a site with apparently hard, but cracked, rock may still have significant amplification compared to true solid bedrock. As a rule of thumb, "good" bedrock is rock hard enough to prevent any manual digging. If profiles are available, P-wave velocities should be higher than 2 km/s.

Seismic vaults are on average 2 to 6 m (7 to 20 feet) deep. At sites where the solid, non-weathered bedrock is outcropping, the required depth is defined solely by the space required for the equipment. One meter (3 feet) or even less may be adequate if the requirements regarding temperature changes associated with the local climate allow. On some highly weathered rock sites, the required vault depth may exceed 10 m (30 feet). In some places a reasonably deep seismic vault can not reach bedrock at all and a borehole installation would ideally be required. Vaults are sometimes still used in such cases for financial reasons. More details on borehole installations are given in 7.4.5.

7.4.2.3 Seismic soil-structure interaction and wind-generated noise

The ideas behind the design and construction of seismic stations have greatly evolved in the last few decades. The increased sensitivity of seismometers and the complexity of seismic research, based more and more on waveforms, require very quiet sites and distortion free records. Sixty years ago, seismic stations were usually situated in houses and observatories. Sensors were installed on large, heavy concrete piers, mechanically isolated from structural elements of the buildings, sometimes well above the ground (see Figure 4.2 in the old MSOP; Willmore, 1979; or http://www.seismo.com/msop/msop79/sta/sta.html via link "Examples of stations"). Scientists increasingly observed that the interaction between surrounding soil and civil engineering structures in such installations substantially modified seismic signals during seismic events, particularly if the site was on relatively soft ground. Structures swinging in the wind also caused undesired seismic noise, and strong unilateral wind load or insolation on a building's walls or the rock face of seismometer tunnel entries caused intolerable drifts in long-period or VBB records.

Further evidence arose (Bycroft, 1978; Luco et al., 1990) that every structure at a site modifies seismic waves to some extent. Therefore, today's seismic stations are mostly ground vaults jutting only a few decimeters (about a foot) above ground level. All buildings, antennae and other masts are positioned well away from the vault to minimize the interaction.

In theory, there is no modification of the seismic signal by the soil-vault structure interaction if the vault's average density (taking into account the empty space in the vault) equals the density of the surrounding soil. However, seismic station design is never based on calculated average densities. The most important factors are that:

- the design is not too heavy, particularly if the surrounding soil is soft;
- all potential buildings and masts are placed away from the seismic vault;
- the vault rises above ground level as little as possible to minimize wind-generated seismic noise.

7.4.2.4 Other noise sources

We recommend that seismic stations are fenced, despite the fact that fences usually represent a significant expense. There are a few exceptions, such as stations in extremely remote desert or mountain sites. The fence minimizes seismic noise caused by human activities or by animals that graze too close to the vault. It also contributes to the security of the station.

The optimal size of the fence depends on several factors:

- density of population around the site and human activity close to the station;
- potential agricultural and other activities in the near vicinity;
- the probability of animal interference;
- general seismic noise amplitudes at the site (qiet stations require a bigger fenced area);
- seismic coupling between ground surface and bedrock. Non-consolidated surface ground and seismometers installed on good bedrock allow a smaller fence. A very deep vault has a similar effect.

The smallest recommended fenced area is 10 x 10 m (30 x 30 feet). In the worst case, a fence could be 100 x 100 m (300 x 300 feet). A height of about 2 m (6 - 7 feet) should be sufficient. Light construction with little wind resistance is preferable so that wind-generated seismic noise is minimized.

The equipment and the vault itself can also generate seismic noise. Equipment that includes mains transformers or rotating electromechanical elements like disk drives, diskette drives, cooling fans, etc. should be installed on the vault wall rather than on the seismic pier.

If the vault cover is not firmly fixed to the vault, it can swing and vibrate in strong winds, which can totally ruin seismic records. Be sure that the cover is very firmly fixed to the top of the vault, as its own weight may not be sufficient to prevent vibration in strong wind. When closed and strongly shaken by hand, there should be no play whatsoever between the vault and the cover. If there is, it will cause seismic noise during strong winds.

If a seismic station uses an antenna mast, place it well away from the vault to prevent seismic noise being generated by the antenna swinging in the wind. The required distance is usually between 5 and 50 m, depending on a number of factors such as:

- the maximum expected wind speed and the probability of windy weather at the site (the higher the speeds and the more often they appear, the greater the required distance);
- the antenna's height (the higher the antenna mast, the greater the required distance);
- the vault's depth (the deeper the vault, the smaller the distance);
- the degree of seismic coupling between sensors and antenna base (strong coupling requires larger distances); and
- general seismic noise at the site (very quiet sites require larger distances).

7.4.2.5 Electrical grounding

A grounding system is required for the proper functioning of electronic equipment. Grounding of equipment and cables keeps the instrument noise low. It is also a prerequisite for lightning-protection equipment and for interference-free RF telemetry. The grounding system design is usually a part of the RF link design in telemetry seismic systems.

A ground impedance below 1 ohm is usually desired. Generally, a radial star configured system, of five to six "legs" with 15 to 20 m (45 - 60 feet) length each, is required for a grounding system (see Fig. 7.47). The total length of the required grounding metal strips depends strongly on climate and local soil type and its humidity. The strips, made of zinc plated iron or copper, 3 x 30 mm (1/8" x 1.5") in cross-section, should be buried from 25 to 35 cm (~1 foot) deep in the soil. In dry regions they should be deeper. The strips should be straight. No sharp turns (around rocks, for example) are allowed because this decreases *lightning protection* efficiency as a result of increased inductivity of the grounding system.

In arid regions, high deserts, or completely stony areas, longer and thicker strips are required. In these cases, a different approach to grounding and lightning protection is sometimes taken by trying to obtain an electric equipotential plane all around the station during lightning strikes. Grounding impedance is no longer the most important issue. High lightning threat regions and very dry or rocky ground usually require a specially-designed grounding system.

In seismic vaults without metal walls, bury a loose mesh made of grounding strips around the vault and connect them to the rest of the grounding system. The grid dimension of this mesh should be around 60 to 100 cm square (~2 to 3 feet square).

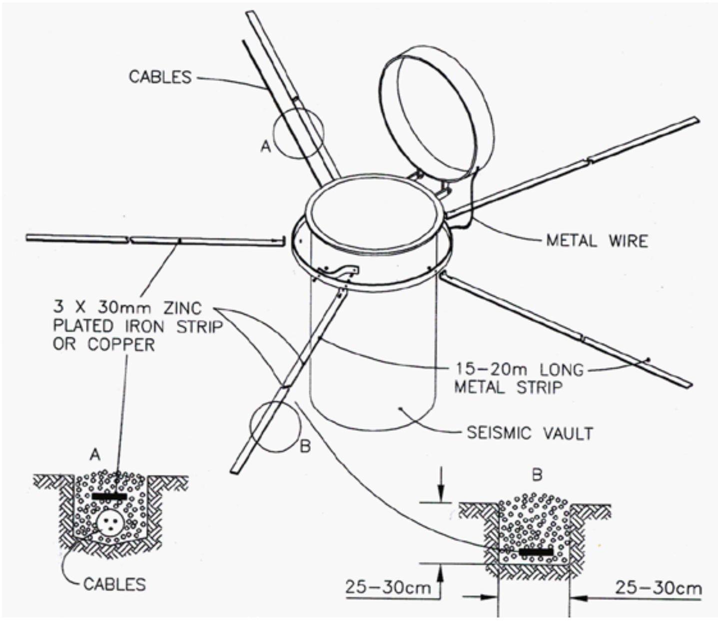


Fig. 7.47 An example of a seismic station grounding system. Note that its dimension depends on local soil humidity conditions.

At seismic stations with RF data transmission and antenna masts, the star-configured grounding system should be centered on the antenna mast, not on the seismic vault. The seismic vault should be included in one of the legs of the grounding system. One of the grounding strips must be laid exactly above the cables connecting the antenna mast and seismic vault (see Fig. 7.47, detail A). This ensures a minimum voltage drop along the cables during lightning strikes and therefore a minimum induced voltage surge in the cables.

The antenna mast itself should be grounded and equipped with a lightning protection rod. Its highest point should be at least 1 m (3 feet) above the highest antenna or solar panel installed on the mast.

Note that any grounding system requires periodic service checks because contacts between the metal parts may slowly corrode. It is recommended that the grounding impedance of the system be checked once every two years. Regular maintenance visits should always include a check of the lightning protection system and equipment and replacement of any burnt-out elements. For more on lightning protection see http://www.protectiongroup.com/Home.

7.4.2.6 Vault construction

Seismic vaults can be made with metal walls. Plain iron sheets or corrugated iron can be welded together, or pieces of large-diameter metal pipes can be used. We recommend zinc-plated metal for durability. It is not necessary to make metal vaults very strong and heavy. Water tightness is relatively easy with this design.

If the vaults are made from thin sheet metal (a few mm), then pour relatively thin, 15 - 20 cm (6 - 8") concrete walls around the metal to add strength. The quality and homogeneity of this concrete does not need to be high because water tightness is not a problem. Locally-available sand aggregates can be used in most cases. Such vaults, however, may cause problems if deformation and tilts of the vault due to external temperature changes are important.

The walls can also be made of only concrete – in which case it is easiest to make the vault rectangular. Note that the quality of the concrete must be good to make the vault watertight, as explained earlier. Apart from very deep vaults, strength is not a problem and therefore no steel reinforcement is needed.

At sites where accessibility allows, vaults can be made of the prefabricated concrete pipe sections used in sewerage systems. They are cheap and can be obtained in different diameters and lengths. In deeper vaults you can simply stack them to the required depth of the vault. Care must be taken to ensure that the joints between sections are watertight.

The bottom of the seismic vault – the seismic pier - is always made of high-quality, watertight concrete. Special requirements must be fulfilled for VBB sensors. More details are given in 7.4.2.1 above.

The depth of seismic vaults is determined by seismo-geological parameters. Apart from providing adequate space to put all the equipment, the diameter is primarily a matter of the desired ease of installation, maintenance and service.

For three-component stations with single component sensors, between 1 and 1.5 m^2 (10 to 15 square feet) of space on the seismic pier is required. Less space is needed for three-component seismometers, three-component accelerometers, or a single component sensor. If the vault contains (or will contain in future) three-component weak-motion and strong-motion sensors, about 1.5 - 2 m^2 (15 - 20 square feet) is required.

We have found that a minimum vault diameter for installation and maintenance is 1.4 m (4.5 feet). If the vault is deeper, a 1.5 to 1.6 m (5 to 5.5 feet) diameter is recommended. Deep vaults (> 4 m (13 feet)) require a diameter of at least 1.6 to 1.7 m (5.5 to 6 feet). Vaults deeper than 1.2 m (4 feet) require a ladder.

7.4.2.7 Miscellaneous hints

Vault cover design

A seismic vault cover should have the following:

- at least 5% slope so that water drains quickly;
- vertical siding all around that extends at least 15 cm (6") below the upper rim of the vault to prevent rain from entering in windy conditions;
- a mechanism which firmly fixes the cover to the ground and a lock to mitigate vandalism;
- handles for easy opening and closing;

- be painted a light color, preferably white, that will reflect as much sun as possible, particularly in hot and dry desert regions.

The metal cover and thermal insulation cover of the vault should not be too heavy. They should be designed in such a way that a single person can open and close the vault smoothly and easily. Otherwise, maintenance visits will require two people in the field. For large vaults, the cover can be designed in two parts, or a simple pulley system may help.

Alternative materials

As material for a vault cover, metal is less appropriate in very hot and very cold climates as it becomes difficult to handle under extreme temperature conditions. UV light-resistant plastic or water-resistant plywood is a better alternative in dry regions. Plywood also has lower thermal conductivity, which improves thermal insulation, and less weight, making handling the cover easier.

Mitigating vandalism

Experience shows that, apart from political instability in a country, most vandalism of seismic stations is driven by people's curiosity. Therefore we believe that a large sign with a short and easy-to-understand explanation of the purpose of the station and posted at the entrance to the fenced area, may significantly mitigate vandalism.

Fixing seismometers to the ground

In regions where earthquakes with peak accelerations of 0.5 g or more can occur, seismometers must be firmly fixed to the seismic pier, a common practice with strong-motion sensors. Obviously, sensitive seismometers are clipped during very strong earthquakes. However, they should not shift or move during such events otherwise, the sensors will not be properly orientated for the recording of aftershocks .

7.4.3 Seismic installations in tunnels and mines (L. G. Holcomb; 2002)

Abandoned mines have been used for many years as ready-made quiet sites for installing seismic instrumentation. In some cases, active mine tunnels have proven to be successful, even though they may be somewhat noisy as a result of mining activity during the workday.

Existing tunnels in solid rock provide a low-cost, ready-made and accessible facility that often provides nearly ideal conditions for the installation and operation of high sensitivity seismic sensors. The bedrock in a mine tunnel is usually already exposed, providing an excellent firm foundation on which to install standard surface instruments. If unventilated, as is usually the case for abandoned mines, a mine tunnel provides an essentially constant-temperature environment that is ideal for seismic sensors. Depending on its thickness, the overburden above the mine tunnels provides isolation of the seismic sensors from the seismic noise that is always present at the surface of the Earth.

Obtaining permission to use an abandoned mine property may be difficult, even for non-working mines, because the operational organization or the property owners may quite understandably be reluctant to allow access because of legal liability. Access to working mines is usually even more difficult because the additional equipment and personnel involved in station activities tend to interfere with mining activities.

Mines are usually concentrated in mineralized zones. It is therefore unlikely that an existing mine will be found near the location of a proposed seismic installation. Tunnels are sometimes constructed solely for the purpose of the installation of seismic sensors. Digging tunnels in hard rock is a very expensive endeavor because tunneling on a small scale is highly labor-intensive.

In many respects, a tunnel installation is very similar to a surface vault installation. A poured concrete floor or pier is usually constructed on the rough bedrock floor of the tunnel to provide a flat and level surface on which to install the sensors. Despite the improved temperature stability found in a tunnel, it is still necessary to provide adequate thermal insulation around the sensors themselves in order to reduce thermally generated noise. Some type of air pressure variation reduction system is also necessary for long period sensors because the air pressure varies in underground tunnels. Usually, this is accomplished in the same manner as it is in a surface installation although sometimes an effort is made to seal off all or parts of the tunnel itself. Sealing a volume enclosed by natural rock walls is difficult because most tunnel walls are riddled with fractures.

However, there are significant differences between surface vault installations and tunnel sites. Rockfall is a real hazard in a tunnel installation. Both personnel and instrumentation must be protected at the actual location of the instruments and along access routes. Another hazard is the build up of harmful gasses (bad air) underground if the tunnel is not adequately ventilated.

The presence of water and high humidity levels in most underground passages is a common problem in tunnel installations. It is very difficult to keep instrumentation dry and the wet environment is frequently unpleasant to work in. The high humidity slowly corrodes the contacts in delicate electrical connectors, which frequently causes poor electrical contact and intermittent operation. The presence of moisture also slowly degrades the effectiveness of thermal insulation materials, and precautions must be taken to prevent moisture accumulation in the isolation system.

Access to power and communication lines is usually more difficult in tunnel installations, depending, of course, on how far the equipment is placed in the tunnel. Frequently, power and or communication lines must be installed throughout the entire length of the tunnel. In the case of power, this can be quite expensive if long distances are involved; either large diameter cables or a high voltage line coupled with a step-down transformer must be installed to ensure that sufficient voltage is available at the site.

Determining the orientation of an underground sensor is considerably more difficult than in a surface installation. Usually, one must transfer an already known azimuth from outside the tunnel to the installation site using standard surveying techniques. Specially designed gyroscopic systems can be used to determine the orientation underground but they are relatively expensive.

It is more difficult to provide timing to a tunnel site than to a vault. This is particularly true for modern GPS based timing systems because the distance between the antenna (outside thetunnel) and the timing receiver is usually limited. Inline radio frequency amplifiers can be used for long antenna runs. It is preferable, however, to place the GPS receiver near the antenna, e.g., at the tunnel entrance. A serial connection can then be used between the receiver and the recorder either using RS422 (up to 1 km distance) or fiber optic cable. This approach has been used successfully in the Swiss digital seismic network.

7.4.4 Parameters which influence the very long-period performance of a seismological station: examples from the GEOFON Network (W. Hanka, 2002)

7.4.4.1 Introduction

The goal for a very broadband (VBB) station for the GEOFON network is to resolve the full seismic spectrum from high frequency (regional events) to very long period (VLP) (Earth's tides) with sufficient dynamic range. The overall instrument noise should remain below the New Low Noise Model (NLNM, Peterson 1993) throughout this frequency range. The GEOFON project (Hanka and Kind, 1994) aims to achieve this goal at minimum cost. This sets strict limits on costs for instrumentation, vault construction and remoteness of the sites.

It is relatively straightforward to get good station performance in the high frequency and medium-period band since the "only" measures to be taken are to get away from man-made noise sources and the sea shore and find a station site on as hard rock as possible. Good VLP performance is usually much more costly to achieve since adequate instrumentation and vaults with sufficient overburden or borehole installations are necessary. However, there are certain measures which can be taken to optimize the VLP station performance in shallow vaults. The parameters to be taken into account for good VLP performance are:

- Instrumentation
- Installation of instruments
- Vault construction
- Geology
- Depth of burial
- General climate

The influence of these different parameters will be demonstrated in the following case studies from the GEOFON network.

7.4.4.2 Comparison of instrumentation and installation

Which seismometer to choose?

The longer the period of ground motion to be recorded, the larger the potential influence of environmental disturbances, such as temperature and air pressure fluctuations and induced ground tilts on the seismic recording, and the larger the need for effective shielding against them. The instrument currently with the best VLP resolution is the Wielandt-Streckeisen STS1/VBB (Wielandt and Streckeisen, 1982; Wielandt and Steim, 1986). It is widely deployed in the IRIS GSN and GEOSCOPE global networks as well as in some regional networks (e.g., MedNet). The permanent GEOFON network uses mostly Wielandt-Streckeisen STS2 and a few STS1/VBB instruments (see DS 5.1) with comparably good results. Fig. 7.48 shows the resolution of the STS1/VBB and the STS2 in relation to the New Low Noise Model by Peterson (1993).

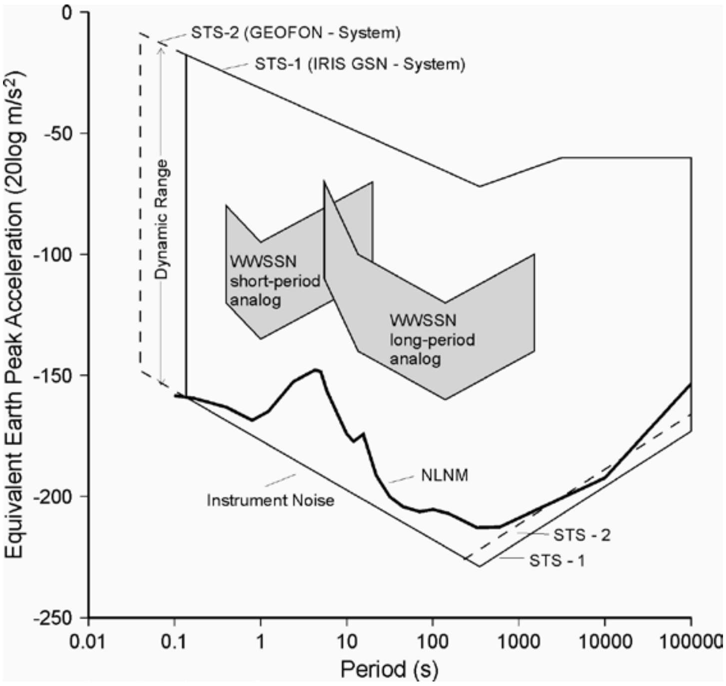


Fig. 7.48 A representation of the bandwidth and dynamic range of a conventional analog (WWSSN short- and long-period) and digital broadband seismographs (STS1/VBB and STS2 with GEOFON shielding, respectively). The depicted lower bound is determined by the instrumental self-noise. The scale is in decibels (dB) relative to 1 m/s^2. Noise is measured in a constant relative bandwidth of 1/3 octave and represented by "average peak" amplitudes equal to 1.253 times the RMS amplitude. NLMN is the global New Low Noise Model according to Peterson (1993).

The more compact, lighter and cheaper triaxial STS2 has a pass band with a slightly higher low-frequency corner (0.00833 Hz instead of 0.00278) and a significantly higher high-frequency corner (dashed lines in Fig. 7.48). Depending on the properties of the recording system, 50 Hz can easily be reached compared to the 10 Hz of the STS1. For nearly all sites on Earth, a properly installed STS2 seismometer will give nearly the same performance as a set of STS1/VBB seismometers. The maximum long-period resolution can only be achieved when the seismometers are properly shielded.

The GEOFON project exclusively uses Wielandt-Streckeisen seismometers. The discussion above and below reflects this fact and is not an endorsement of one make of seismometer over another. Potential instrument purchasers need to establish for themselves what instruments are best suited for their own purposes.

The discussion of the shielding efficiency at GEOFON stations in surface or shallow depth vaults or tunnels in the next Chapter is only based on the VLP channel plots (sampling frequency 0.1 Hz) of STS1 records (original or simulated from STS2 records by recursive filtering). The low self-noise of the STS2 allows us to effectively simulate STS1/VBB records down to tidal periods. Fig. 7.49 illustrates this using the recordings of a tidal wave recorded by an STS1/VBB and an STS2. It is difficult to tell the difference between them.

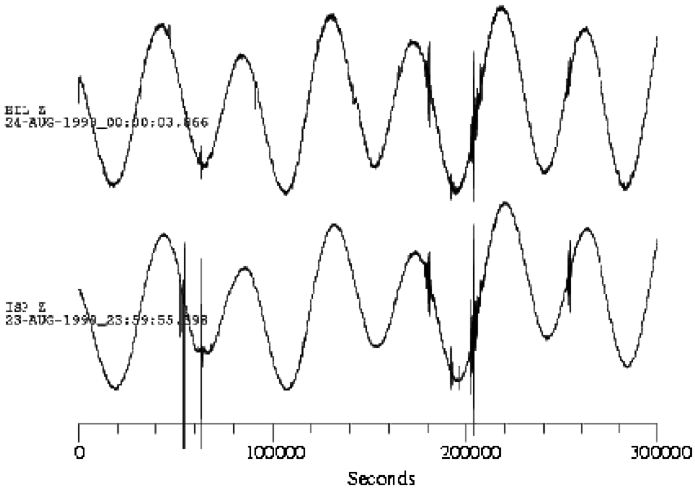


Fig. 7.49 Tidal recordings of STS1/VBB and STS2 do not differ very much when properly installed in a comparable environment. The two traces were recorded in the Eastern Mediterranean in buried vaults in limestone. At the station EIL (Eilat, Israel) an STS2 with additional GEOFON shielding and at ISP (Isparta, Turkey) a set of STS1/VBB are installed.

Installation of an STS1/VBB

Seismometers must be shielded against environmental influences, namely pressure and temperature variations as well as magnetic disturbances. The proper installation of an STS2 to achieve good VLP performance is discussed in detail in the next paragraph. Comments on installing the STS1/VBB are kept short here since this is a well known procedure and is described elsewhere (Wielandt and Streckeisen, 1982, Holcomb and Hutt, 1992).

The three separate STS1/VBB components are supplied with different shieldings: a permalloy helmet as magnetic shield (vertical only), an aluminum helmet and a glass bell jar for evacuation. The feedback electronics are placed in a separate container. There are two basic methods used for the installation of STS1/VBB seismometers. The "conventional" one, also suggested by the manufacturer, uses a plane glass plate which has to be cemented to a plane pier. The second method, introduced by Albuquerque Seismological Lab, uses a warp-free rigid stainless steel base plate (similar to the aluminum one used in the GEOFON STS2 shielding) on which the vacuum glass bells and the metal helmets are installed above the actual seismometer. The second method is faster and easier in practice and gives additional flexibility (see Holcomb and Hutt, 1992).

Installation of an STS2

The STS2 is not supplied with any shielding. All three components and the electronics are contained in a single casing. This casing provides magnetic and pressure shielding to some extent. Nevertheless, temperature shielding is still important in order to obtain longer period signals with a good signal/noise ratio. This is especially important because of thermal convection generated by heat from the electronics. A rather sophisticated shielding (see Fig. 7.50 a) was introduced by Wielandt (1990) for the first STS2 based network, the German Regional Seismograph Network (GRSN). The STS2 was installed on a 10-cm thick gabbro plate covered by an airtight aluminum helmet. Before being covered, the STS2 is insulated with a thermal blanket.

A simpler and more practical approach is used for GEOFON stations (see Fig. 7.50 b). This uses an aluminum casing consisting of a rigid thick base plate (3 cm) and a thinner aluminum helmet with a cylindrical foam rubber insert. As with the gabbro plate, the base plate can not be easily distorted by pressure variations and gives, together with the foam rubber insert, extra thermal stability. In addition, this shielding helps prevent corrosion and is separated from the pier or ground surface by adjustable tripod screws.

The GRSN shielding has extra internal cabling and a socket, whereas the GEOFON casing does not, and the casing is penetrated by the original STS2 cable through a special hole which is made tight with silicon. The GEOFON shielding potentially gives better electrical performance but has worse pressure integrity. The GEOFON shielding is portable and readily available which are problems with the GRSN shielding.

Even better thermal insulation then the one discussed above can be achieved for both installation methods when an additional styrofoam box, completely filled with styrofoam pieces, is used (as shown in Fig. 7.50 b). The box should be tightly glued to the pier or ground surface and the box lid glued to the box walls after filling with the styrofoam beads. Depending on the site conditions, this can give an additional order of magnitude in VLP noise reduction.

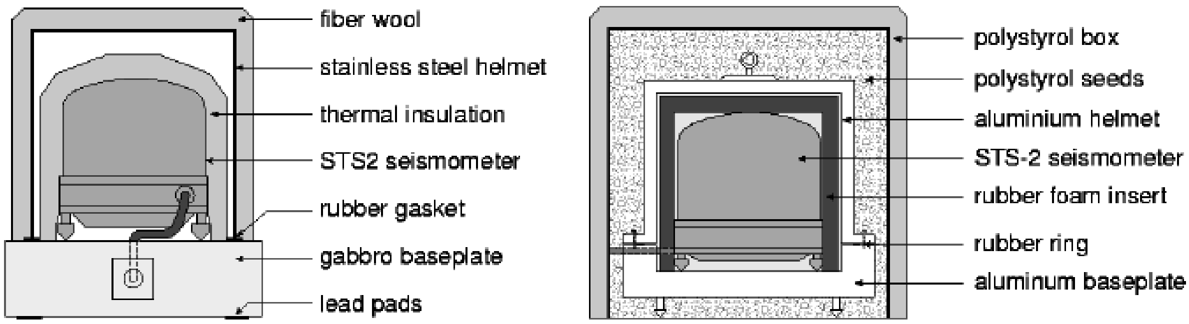


Fig. 7.50 Left: GRSN shielding after Wielandt (see Fig. 5.16 in Chapter 5) and **right:** GEOFON type shielding for the STS2.

Fig. 7.51 shows the substantial LP and VLP noise reduction which can be achieved even by an incomplete GEOFON type shielding (aluminum casing only, no polystyrol box) in the period range from 30 to more than 10,000 seconds. A reduction of about two orders of magnitude in terms of spectral power (one order of magnitude in terms of amplitude) can clearly be seen between 100 and several thousands of seconds and again around 10,000 sec.

The GRSN shielding gives exactly the same result in most cases. It is only in very rare situations - probably in connection with large air pressure variations – that the performance of Wielandt's approach is slightly better at periods of several hundreds of seconds.

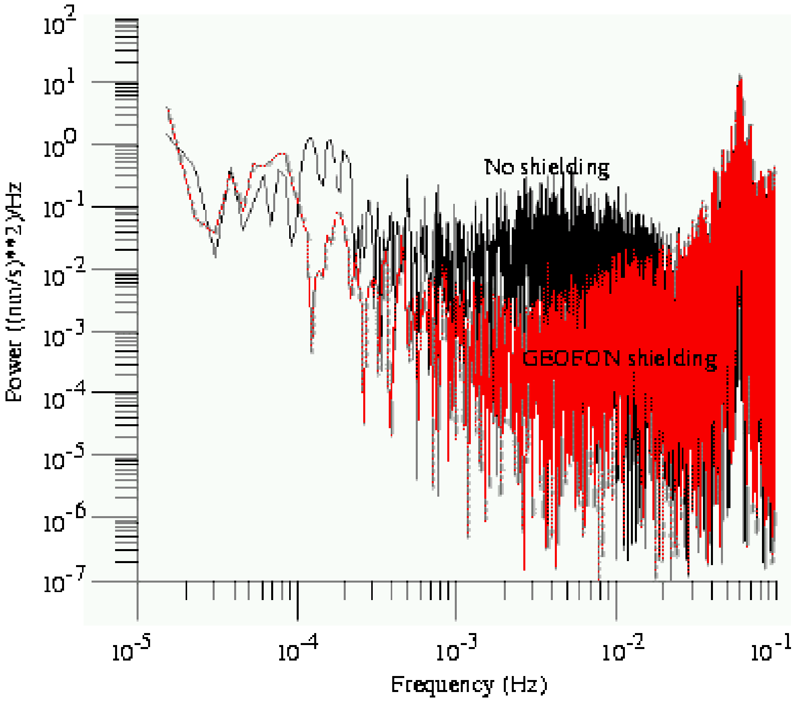


Fig. 7.51 VLP noise reduction achieved by using the simpler version of the GEOFON shielding method (no additional polystyrol box and beads). The relative noise power spectra of the vertical component of two STS2s positioned side-by-side are shown. No instrument correction has been applied. The black spectrum is from the unshielded STS2, the red spectrum from the shielded one.

7.4.4.3 Comparison of vault constructions, depth of burial, geology and climate

The harder the rock and the deeper the vault and the more stable the temperature and air pressure remain in the vault, the better is the VLP performance of a VBB station. In contrast, the shallower a vault is, the greater the influence of the general climate.

Fig. 7.52 shows the scheme of an artificial tunnel vault which is used at several IRIS/USGS installations in cases where no other existing underground facility can be used. The tunnel is about 25 m long and segmented using four doors (air locks). The last chamber contains the large seismometer pier. Since the tunnels are drilled into mountain slopes, depth of overburden is of the order of the tunnel length.

Tunnel vaults

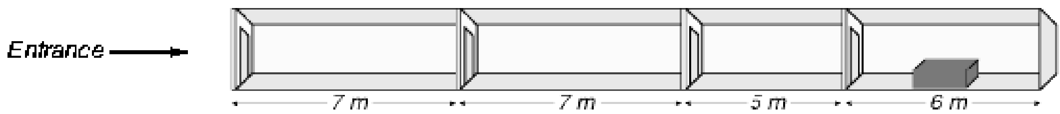


Fig. 7.52 Sketch of an artificial horizontal tunnel construction with different chambers to host a VBB seismological station. This type of construction is widely used within the IRIS/USGS

part of the IRIS GSN network. The total length of the tunnel is approximately 25 m. The construction cost of such a vault can reach up to US$ 100,000 depending on local conditions and infrastructure.

Although the vault construction is identical, the VLP performance at different sites is not. This is shown by the recordings Earth's tides in Fig. 7.53. The tunnel of the IRIS/GEOFON station LVC (Limon Verde, Chile) is built in hard basaltic rock and the traces show remarkably low VLP noise, while at KMBO (Kilima Mbogo, Kenya, also an IRIS/GEOFON site) a soft volcanic conglomerate drastically increases the noise, especially on the horizontal components. Another effect which can clearly be seen on the horizontal components is the large day-night noise variation. The general temperature increase and perhaps also the deformation of surface rocks caused by direct sunshine during the day, as well as stronger winds cause substantially larger VLP noise levels on the horizontals at both sites. This shows that even this kind of sophisticated and expensive tunnel vault construction gives no guarantee of seismic recordings free of environmental influences.

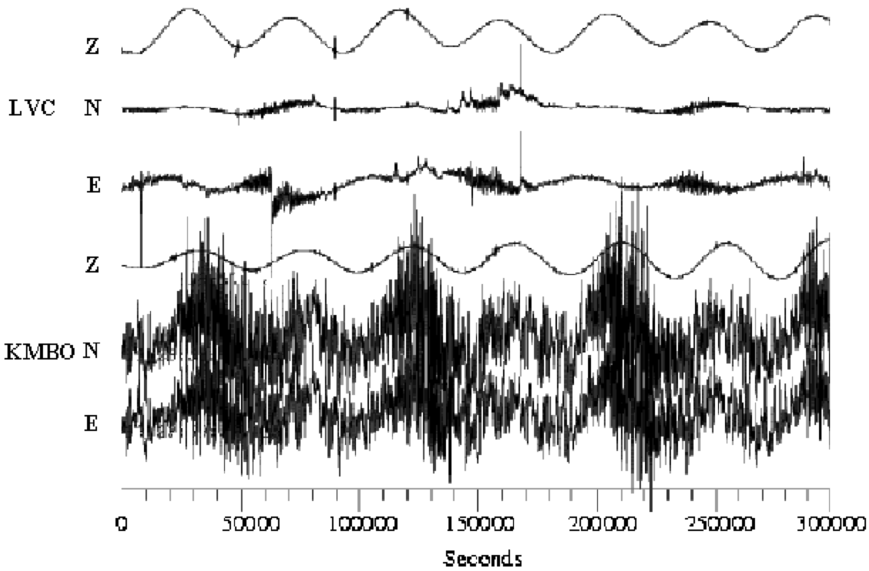


Fig. 7.53 Comparison of two 3-component STS1 VLP traces recorded in identical tunnel constructions but in different geological and climatological environments. LVC (Limon Verde, Chile) is built in hard basaltic rock in a full desert environment, KMBO (Kilima Mbogo, Kenya) is placed in rather soft volcanic conglomerate influenced mostly by a humid tropical environment. Day-to-night temperature gradients are high in both cases.

Shallow vaults
If tunnel vaults are not affordable, other less expensive methods of getting the seismometers sufficiently buried have to be used. Several cases are discussed below.

Fig. 7.54 compares the recordings made at three different stations. The depth of burial is only about 4-5 m in all cases, which is very poor compared to tunnels. Nevertheless, the moderate climate at MORC (Moravsky Beroun, Czech Republic) and at ISP (Isparta, Turkey) gives a relatively good VLP performance. These vaults are build in hard rock and limestone, respectively. The spikes which can be seen mainly on the horizontal traces are due to human activity close to the site. In the arctic climate of KBS (Ny Alesund, Spitzbergen = Svalbard), the more drastic temperature changes cause increased VLP noise level on the horizontals. Here, there are also some spikes caused by local man-made disturbances.

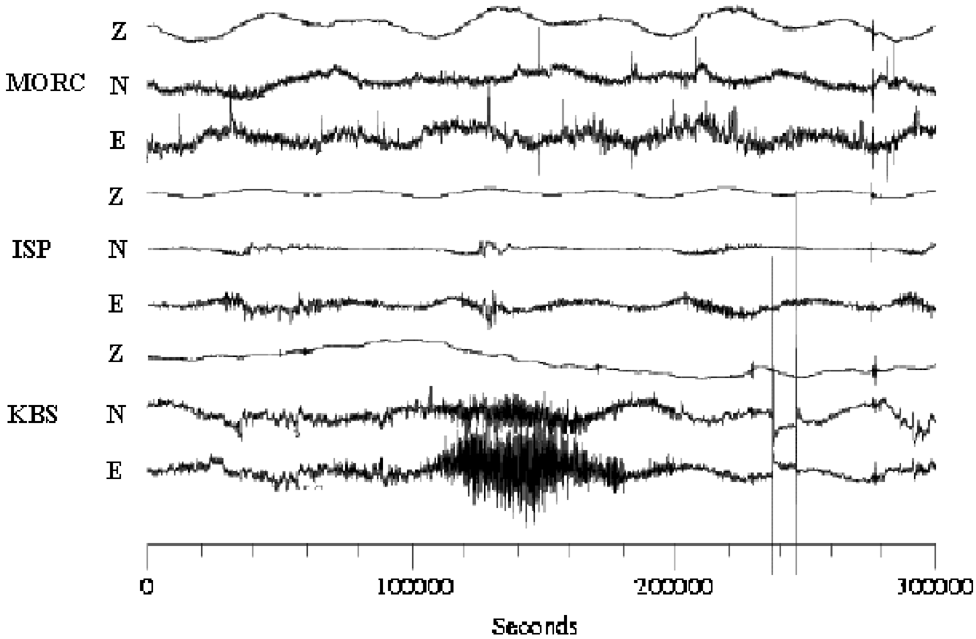


Fig. 7.54 Comparison of three 3-component VLP records in shallow vaults (4 - 5 m). At MORC (Moravsky Beroun, Czech Republic) an STS2 is installed in a 1 m wide borehole in hard rock; in ISP (Isparta, Turkey) and KBS (Ny Alesund, Spitsbergen) sets of STS1/VBB are installed in underground bunker vaults in limestone and weathered rock (permafrost), respectively.

The vaults at KBS and ISP are very similar: about 5 m deep large underground concrete bunkers with large concrete piers for the installation of the STS1/VBB seismometers (see Fig. 7.55 a). The geologies are different: weathered rock in permafrost (KBS) and limestone (ISP). The recording system at KBS is located elsewhere, while at ISP, recording is local in a house built above the vault. A very different construction is used at MORC: a very wide shallow vertical borehole has been drilled into hard rock and a one-meter wide steel tube placed into

it, with a concrete floor on the bottom. The STS2 in GEOFON shielding has been installed on this at about 5 m depth (see Fig. 7.55 b). Here and in the two other examples of construction schemes for STS2 stations (see Figs. 7.55 c and d), a recording room hosting all computer and communication equipment is located above the seismometer vault.

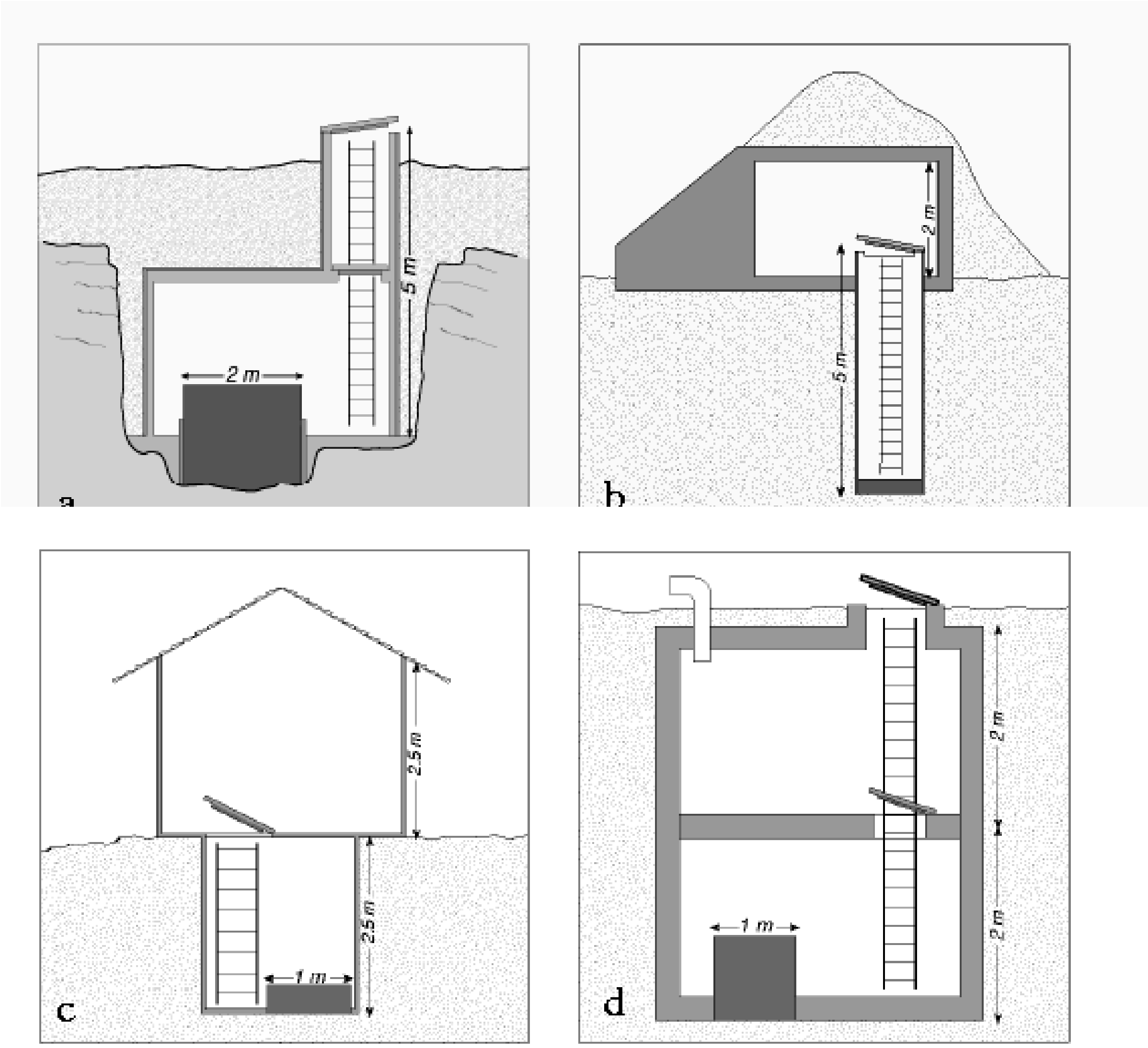


Fig. 7.55 a) Underground bunker vault construction for the installation of a set of STS1/VBB (remote recording); b) "wide & shallow borehole" vault construction for the installation of an STS2; c) and d) simple bunker vault construction schemes for an STS2. The vault constructions b - d allow onsite data recording thanks to the existence of a separate recording room.

Fig. 7.56 shows, again in comparison to MORC, the recordings at shallow vaults in locations near the equator. At PMG (Port Moresby, Papua New Guinea) a two-room underground vault hosts a set of STS1/VBB seismometers. The two-room construction is situated in a sedimentary layer above rock and is comparable in size with the one at KBS and ISP, but shallow (3 m) and with a horizontal entrance into the first (recording) room. UGM (University Gadja Mada, Wanagama, Indonesia) uses a very simple, 2.5 meter deep bunker in limestone (construction after Fig. 7.55 c) with an STS2 and a small open recording hut above. Both show rather similar results to MORC, especially on the horizontals. The extreme large amplitudes at UGM during daytime are caused by human activity close to the station.

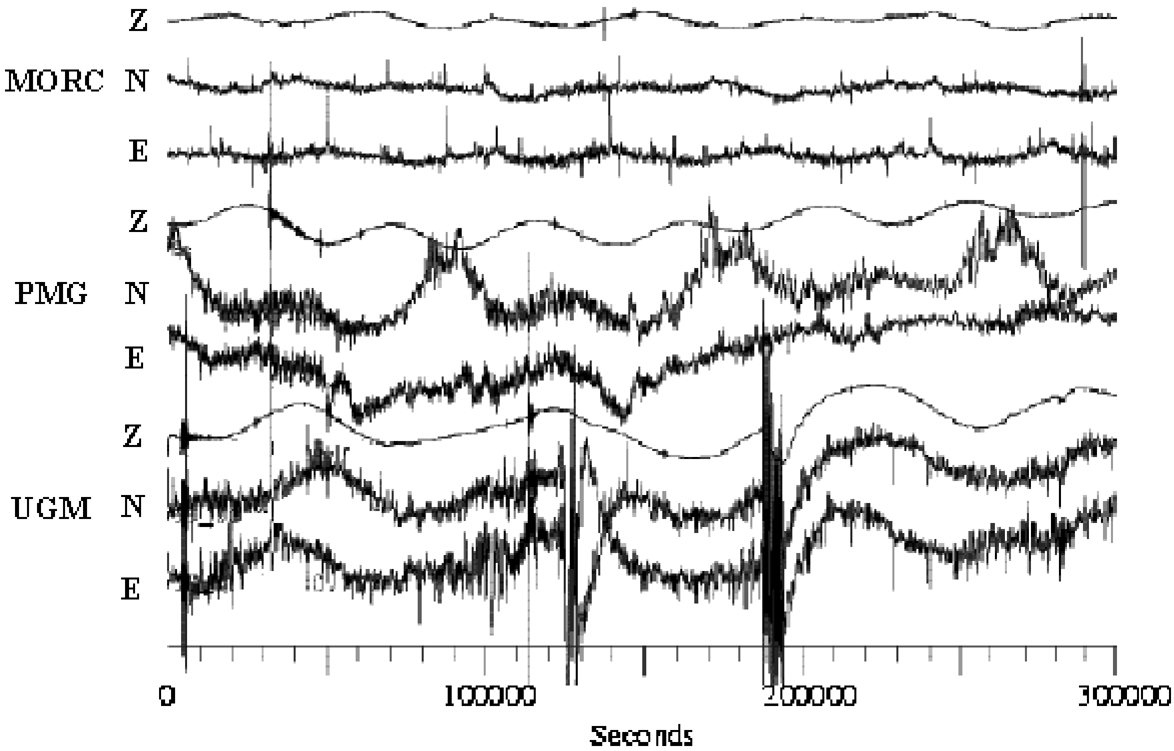


Fig. 7.56 Comparison of three 3-component VLP records from shallow vaults in rock in different climates. Data from two sites close to the equator (Port Moresby, Papua New Guinea, PMG, and Wanagama, Indonesia, UGM) are shown together with data from MORC (same station as in Fig. 7.54).

In principle, the VLP station performance is not so different at both equatorial sites, particularly the horizontal components which are not as good as at a site in a more moderate climate. The instrumentation and construction details do not play any significant role in determining the VLP noise performance.

Surface vaults in moderate climate

The STS2 records in Fig. 7.57 were obtained in a simple above-surface vault on rock (DSB) and a very shallow vault in soft sediments (RGN). Both sites are located in an area with a very moderate climate and close to the sea. Temperature shielding is a little better at RGN due to complete soil coverage on three sides and up to one meter on top. Therefore the general VLP performance - as seen on the vertical components - is better at RGN, but the horizontals show large additional distortions during daytime. These are most likely caused by temperature-induced swelling and related up-bending of the sand hill which is a very typical behavior for sediments (it can also be seen to some extent on the PMG records in Fig. 7.56). This is not the case with rock at DSB. It is remarkable that there is almost no day-night variation on the DSB records although the vault is completely above the surface. This is due to the maritime climate with very small day-night temperature changes.

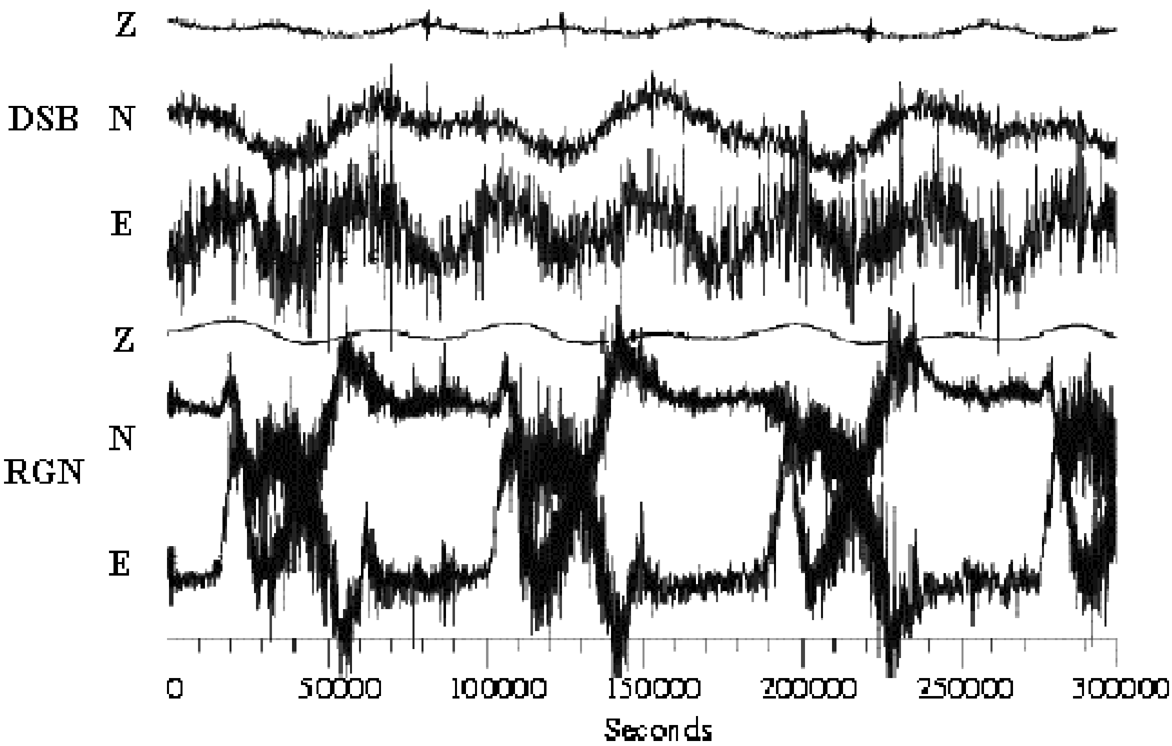


Fig. 7.57 Comparison of two surface vaults in moderate climate on rock and in sediments. At DSB (Dublin, Ireland), a small surface bunker was built in an old granite quarry. At RGN (Rügen Island, Germany), an old one-room military bunker with a thin (< 1m) soil cover on top is used. Both sites host STS2 seismometers with GEOFON shielding.

Surface vaults in arctic climate

The very poor VLP noise performance of surface stations in arctic climates can be seen in Fig. 7.58, where data from two stations in Greenland are shown. Both vaults are located in surface wooden huts built on weathered rock, more or less open to all kinds of atmospheric turbulence in terms of air pressure and temperature changes. The vaults are heated in winter. This results in about the worst conditions one can imagine for VLP noise performance. Earth´s tides are no longer seen very clearly and the daily noise variations are large. However, there is no other choice in these regions. DAG is in one of the most remote places on Earth where it is almost impossible to build an underground vault.

7.4.4.4 Conclusions

The VLP performance of a VBB seismological station is directly dependent on several instrumental and environmental parameters. High quality VBB seismometers, a true 24-bit A/D converter and a continuous multi-stream data recording are essential. In the GEOFON network, only STS1/VBB and STS2 seismometers and Quanterra data loggers are used for this reason. With the appropriate shielding, the VLP performance of the STS2 is not much different from the STS1/VBB. Only in very rare cases at extremely quiet sites can the extra infrastructure, installation, maintenance and financial efforts related to the usage of STS1/VBB sensors be justified. The same is true for vault construction. The construction scheme itself has not much influence on the station performance as long as the depth of burial is deep enough and the environmental disturbances can be reduced to a minimum. With an adequate casing, a seismometer pier is not required to install an STS2 sensor properly underground. The geology plays a very important role. The harder the rock, the lower is the VLP noise at a certain depth since surface tilts caused by atmospheric influences do not penetrate as deep. Sediments show special tilting effects, which reduce drastically the daytime VLP performance of the horizontal components. The shallower a vault is, the more the influence of the general climate. In very moderate climates, e.g., close to the sea, even surface vaults can have a reasonable VLP noise level. In summary: Although the task of establishing a VBB station that is capable of recording with sufficient dynamic range the full seismic spectrum from high-frequency regional events up to the very long-period (VLP) Earth's tides seems to be a very difficult and costly effort, it can be achieved with rather simple means.

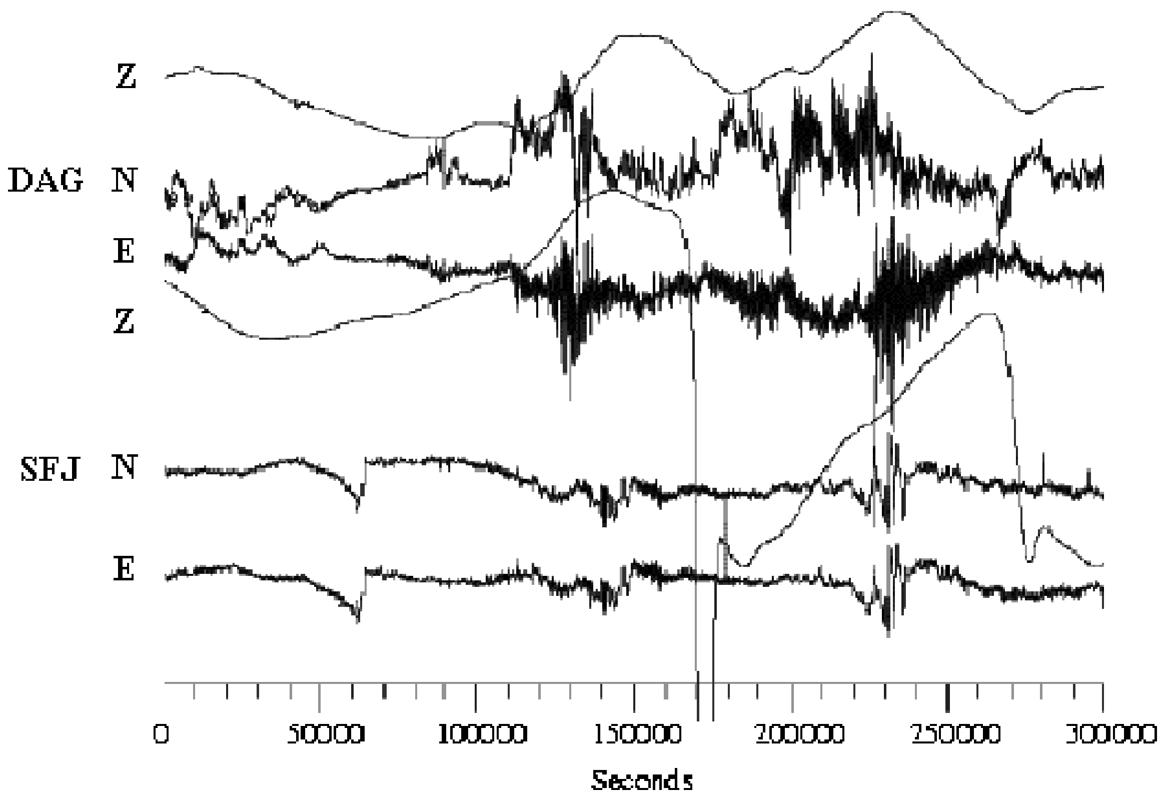


Fig. 7.58 VLP records obtained at two surface vaults on Greenland. At DAG (Danmarkshavn, NE Greenland) a STS2 in GEOFON shielding is installed in a wooden hut on weathered rock close to the sea shore. At SFJ (Sondre Stromfjord, SW Greenland) a set of STS1/VBB is located in a container-like building on top of a mountain. In both cases the geology is weathered rock in a permafrost environment.

More details on the installations made at various VBB stations and the comparison of noise data can be found on the web page http://www.gfz-potsdam.de/geofon/.

7.4.5 Broadband seismic installations in boreholes (L. G. Holcomb, 2002)

7.4.5.1 Introduction

Borehole seismology is a relatively new technology that has developed over the last 30 years or so. In the early years of seismology, installing a seismometer in a borehole was virtually impossible because of the relatively large physical size of instruments. As seismological technology matured, the instruments became smaller and it became more practical to consider borehole installations as alternatives to surface vaults or tunnels. There are several practical reasons for placing seismic instrumentation in boreholes; these include reduced noise levels, temperature stability and reduced pressure variability.

Experience gained over many years of installing both short- and long-period instruments has shown that sensor systems which are installed at depth are usually quieter than those installed at or near the surface of the Earth (see 4.4.). This is why abandoned underground mines are frequently used as sites for low-noise seismological stations. However, abandoned mines are not always found at the desired location of a seismic station. A borehole provides a practical solution to the need to install seismic sensors at depth almost anywhere.

A borehole is also a very stable operating environment in which to operate sensitive instruments because the temperature at depth is very stable and the pressure in a cased sealed borehole is very constant. Temperature changes and pressure variations at frequencies within the pass band of the sensor system are common sources of seismic noise (see 7.4.2.1). Systems installed on the surface or in shallow vaults require extensive thermal insulation systems in order to reduce the influences of temperature to acceptable levels. Similarly, elaborately designed pressure containers are required to eliminate pressure-induced noise particularly at long periods in vertical instruments. Both temperature and pressure considerations have become more important with the advent of broadband instruments because these instruments are sensitive to outside influences over a broader frequency range thereby making it more difficult to sufficiently isolate broadband instruments from extraneous influences. A sealed borehole of only moderate depth provides excellent temperature stability because of the tremendous thermal mass and inertia of the surrounding Earth. Furthermore, most seismic boreholes are cased with steel casing whose cylindrical walls are quite thick; this casing constitutes a quite rigid container, which greatly reduces atmospheric pressure variations within the borehole (assuming that both the top and bottom are sealed).

Boreholes are frequently considered to be expensive, but they sometimes represent the only practical alternative if an abandoned mine is not available. Excavating tunnels purely for seismological purposes into competent rock deep enough to provide sufficiently quiet seismic data is also a very expensive solution (see below). In many cases, a borehole may actually be the cheapest method for achieving an installation at depth unless the local manual labor costs are very low.

One advantage of a borehole installation over a vault is that there can be much less surface equipment on site, especially if no recording equipment is deployed on the site, say in a seismic array or small network. This can significantly save on costs and improve security. These advantages have led, in some cases, to the use of very shallow boreholes, or postholes, which are drilled to depths similar to vaults.

It is impossible to state exactly how much it would cost to construct either a borehole or a tunnel type vault because too many factors are involved. Precise costs will depend on the type

of material in which the facility is constructed, raw material costs, local labor costs, etc.. However, here are some examples of approximate costs that have been encountered in constructing facilities for the IRIS program over the past 5 to 10 years. In Africa, IRIS has excavated three tunnel type seismic vaults that extended 25 to 40 meters horizontally into hillsides. The costs of these three projects ranged from approximately US$ 150,000 to US$ 250,000. For a typical borehole (100 meter deep), project costs range from approximately US$ 25,000 to US$ 200,000 at large landmass sites with boreholes in hard rock being significantly more costly than in soft soil. On the other hand, at small isolated Pacific Ocean island sites, borehole costs are in the US$ 150,000 to US$ 250,000 range.

7.4.5.2 Noise attenuation with depth

The main reason for installing broadband sensors in boreholes is to reduce the long-period tilt noise which plagues horizontal sensors installed on the surface. The question commonly asked by seismologists who are contemplating a borehole installation is how rapidly does the tilt noise decrease with depth and so how deep does the borehole need to be. There is no easy answer to this question because a borehole never eliminates all of the long-period tilt noise however deep it is. In general, the noise attenuation rate (db per unit depth) decreases as the depth increases; most of the noise reduction occurs in the upper parts of the borehole.

Fig. 7.59 illustrates the attenuation of long-period horizontal noise with depth. It shows the relative power spectral density (PSD) noise levels obtained from the simultaneous deployment of four broadband sensors located close to one another at the same site and installed at various depths. The first sensor was installed in a small vault on or near the surface. Three other three sensors were installed in boreholes at depths of 4.3, 89 and 152 m below the surface. The site consists of about 18 m of unconsolidated (soft/weathered) overburden overlying fractured Precambrian granite bedrock. In Fig. 7.59, noise attenuation data points in db relative to the noise level in the surface sensor are plotted for periods of 30, 100, and 1000 seconds. Note the very rapid decay in the noise level over the first few tens of meters followed by a much slower rate of decrease in noise levels at greater depths. Note that, in general, a depth of 100 m is sufficient to achieve most of the practicable reduction of long period noise.

The data in Fig. 7.59 should only be regarded as an example of noise attenuation with depth. Apparent surface noise levels at a particular site are frequently highly dependent on the methods used to install the instrumentation. This is particularly true of noise levels at many surface installations where faulty installation of broadband horizontal sensors causes excessive tilt noise at long periods.

Choosing the optimum depth for a borehole for a particular site involves comparing the cost of drilling the borehole to a given depth against the desired data quality, the anticipated surface noise levels (they are frequently determined by the anticipated wind speeds and wind persistence at the site), and the depth of the overburden at the site. Unfortunately, studies detailed enough to yield the precise relationships between the various factors have never been conducted. Therefore, choosing the depth of a borehole for a particular site usually involves non-quantitative consideration of the various factors involved. Many years of experience has demonstrated that 100 meter deep boreholes drilled at sites with a few tens of meters of overburden overlying relatively competent bedrock will provide a sufficiently quiet environment for installing a high quality borehole instrument. Most broadband IRIS borehole instruments are installed at or near 100 meters depth. Boreholes at sites with more overburden and/or softer lower quality bedrock are sometimes deeper depending on construction costs and anticipated surface noise levels.

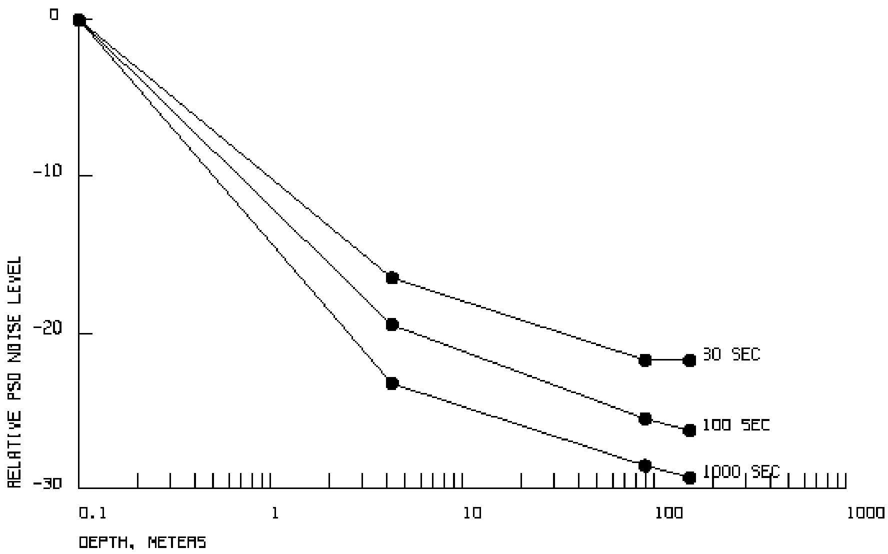


Fig. 7.59 Horizontal surface noise attenuation as a function of depth at three selected periods. The depths were 0, 4.3, 89, and 152 meters.

7.4.5.3 Site selection criteria

There are several criteria for selecting the site for a borehole installation. Ideally, one should select a site at which the surface background seismic noise over the band of interest is as low as possible. However, there are other factors such as accessibility, availability of power, improved network configuration, the presence of wide-spread thick alluvial fill, and/or the presence of cultural activity within the monitored area, which may force the choice of a site with higher background noise levels.

A good borehole should penetrate well into bedrock (70 to 100 meters) (see 7.4.2.2), so the site should have bedrock at or near the surface to minimize the need to drill through excessive overburden. If possible, the bedrock should be a relatively hard rock (see 7.1.2.2) such as granite or quartzite. Harder, more competent rock increases the rate of attenuation of surface noise with depth and also decreases the chances of borehole collapse during drilling. Soft rocks such as shale, mudstone, or low grade limestone should be avoided if possible.

Good bedrock is highly desirable for providing the best results from a borehole installation, but benefits are still there for boreholes in poorer rock. Note that the first data point in Fig.7.59 (only 4 meters down) was obtained in a very shallow borehole that was drilled entirely in loose alluvial fill. Therefore, the lack of shallow bedrock should not preclude the consideration of a borehole installation for a particular site.

As with vault and tunnel installations, a reliable source of electricity will be necessary to power the site, a shelter will be needed to house the recording equipment, and some form of communication capability (telephone line, internet connection, or RF or satellite link) is frequently desirable (see IS 8.2). Accessibility for both the drilling equipment and maintenance personnel (see also 7.1.2.4) should also be considered during site selection activities.

Unfortunately, the need to be able to provide adequate security is also becoming a major factor in selecting station sites in many parts of the modern world. There is little point to investing in a good site if it can not be protected from vandalism. Adequate security has many different meanings depending on the particular situation. It may be as simple as a passive protective fence or as elaborate as alarmed fences and entry ways or even an on-site caretaker depending on the anticipated level of potential damage.

It should be noted that stations on very small islands (such as most coral atolls) do not benefit from borehole installations because the ground motion generated by ocean-wave loading of the beach penetrates rather deeply into the subsurface environment. For this reason, all borehole sites should be at an adequate distance (at least several km) from any coastline.

7.4.5.4 Contracting

Seismic boreholes are usually drilled by a local contractor using specifications supplied by the organization building the station. Hiring a local driller helps reduce mobilization and setup charges, which are frequently a significant portion of the cost of a seismic borehole. Specifications should be rigid and specific enough to ensure that the finished borehole will be suitable for seismology but flexible enough to prevent excessive costs. Most drilling contractors will have little or no experience of seismic boreholes and it is recommended that the contracting agency use an independent expert with extensive drilling and casing experience whose duties include on-site observation and supervision of all drilling and casing operations. This precaution is advisable to ensure that the drilling contractor performs all operations according to the specifications because departures from specifications are hard to detect, document, and prove after the project is finished. The contract should be specific about who is responsible for unexpected difficulties which might arise during the drilling and casing operations; courses of action should be specified if operations are delayed for any reason whatsoever. These include but should not necessarily be restricted to on-site down time which might be due to bad weather, shortage of drilling materials, crew availability, drill rig breakdowns, loss of circulation, injuries on the job, delays in subcontractor availability, holidays and unexpected changes which might be encountered in the quality of the subsurface rock.

7.4.5.5 Suggested borehole specifications

The drilling specifications for a seismic borehole should be written in such a way as to ensure that the completed borehole will be suitable for acquiring high quality seismic data. Parameters such as borehole verticality, depth, diameter, and casing type must be clearly specified. It is also important to specify how these parameters will be measured during construction or in the finished borehole.

Borehole verticality is the specification which drillers have most trouble meeting. Borehole verticality must be specified because all borehole seismometers have only a limited range of tilt over which their mechanical internal leveling mechanisms operate. Therefore, the sensor package must be aligned within a given tolerance from true vertical. This in turn requires that the borehole itself be aligned within a certain tolerance of true vertical. The required verticality specification will depend on which borehole seismometer is to be installed in the completed borehole because each seismometer has a unique mechanical leveling range (typical examples: CMG-3TB has a 3 degrees range, the KS-36000 has 3.5 degrees and the KS-54000 has 10 degrees). In general, the closer the verticality specification requirement is to vertical the higher the cost of the borehole.

The working depth of the borehole is usually specified as the depth of the open cylinder within the borehole confines after construction is complete. The driller is usually left with determining the depth of the hole to be drilled in the rock in order to achieve the desired working depth.

Most boreholes are cased with standard casing used in oil fields because it is readily available throughout the world. This casing is usually specified in terms of its outside diameter (OD) and its weight per unit length; the combination of these two parameters determines the wall thickness and in turn the inside diameter (ID) of the casing. The seismometer manufacturer usually recommends a range of casing in terms of the ID's of the casing in which his sensor will operate satisfactorily. These two methods for specifying borehole diameter must not be confused when writing specifications. As an example of typical hole diameters, a KS-54000 requires a casing with at least a 15.2 cm ID whereas, if equipped with proper hardware, a CMG-3TB (see DS 5.1) will fit into a slightly smaller casing. The specification usually permits the use of a range of OD's and weight specifications in order to facilitate acquiring the casing locally to decrease shipping costs. The individual threaded casing sections should be assembled together with a thread sealing compound and enough torque to ensure that each joint is properly sealed against leakage.

The bottom end of the casing is often equipped with a one way valve (called a float shoe) to seal the lower end against water entry and to facilitate cementing operations. This device allows the cementing mixture to be forced out of the bottom of the casing and prevents water from entering the borehole once the cementing operation is completed.

The casing must be firmly cemented to the surrounding rock walls of the borehole in order to ensure good mechanical coupling. The cementing operation usually consists of pumping a premixed cement mixture down the inside of the casing, out through the float shoe at the bottom, and forcing it back up to the surface between the casing and the bedrock. This operation ensures that all of the annular volume between the steel casing and the rock is filled with cement without voids containing air or liquid. When return cementing mix is observed in the annulus at the surface, a cleaning plunger is forced down the inside of the casing with water under high pressure. This expels the cement mix contained within the casing volume out of the bottom through the float shoe and finally sets (locks) the one way valve within the float shoe to prevent fluids from re-entering.

After the cement has set, it is advisable to require the driller to perform a leak test to ensure that the casing has been adequately sealed. Leak testing usually consists of first pressurizing the water-filled borehole to a specified pressure, sealing it off and leaving the pressurized borehole for a specified time period. The pressure within the borehole should not drop more than a pre-specified amount.

The upper end of the casing is normally terminated with a "packoff" device. This assembly is normally provided and installed by the contracting organization at the time of seismometer installation. The packoff unit seals the top of the borehole and provides a means of passing instrumentation cables into the borehole.

7.4.5.6 Instrument installation techniques

It is a relatively simple operation to install a borehole sensor but certain precautions are required. The sensors are usually fitted with two cables. The first cable is intended to provide sufficient strength to lift the weight of the sensor and any extra pulling force required to removing the sensor from the borehole. This is usually a steel cable or "wire rope". The second cable contains the electrical connections for power, control of the various mechanical operations within the sensor, and to transmit the seismic signals back up the borehole. For holes of significant depth, a small lightweight electrically driven winch and mast assembly can be used to lower the sensor into the hole and to retrieve it if necessary. Lowering and raising the sensor should be done fairly slowly because the sensor package sometimes catches on the casing pipe joints as it moves up or down the borehole. On the way down, this problem is usually temporary but usually results in a short free fall of the sensor and a sudden stop when the load-bearing cable becomes taut. If severe enough, the sudden stop can damage a sensitive instrument. If the sensor catches on a pipe joint on the way up, tension in the load bearing cable rapidly increases to dangerous levels if the winch is not stopped in time. If the sensor disengages from the pipe joint while the lifting cable is under high tension, the sensor will undergo possibly damaging levels of acceleration. If the sensor does not disengage and if the winch is powerful enough, the lifting cable may break and endanger personnel.

It is advisable to carry out a dummy run in the completed borehole using a metal cylinder with similar dimensions and weight to the seismometer package. This will help minimize the risk of damage to or losing the equipment during installation. Such a dummy run could be part of the acceptance procedures for the drilling contract.

Traditionally, borehole seismometers are rigidly clamped to the inside of the cased borehole with manufacturer-supplied mechanical hardware to ensure adequate coupling between the sensor and ground motion. The hardware usually includes a mechanically driven locking mechanism for clamping the sensor to the walls of the borehole. This device sometimes consists of a motor driven or spring loaded pawl that is extended on command from the side of the sensor package to contact the borehole wall opposite the sensor (GS-21, CMG-3TB). Sometimes this function is performed by a separate piece of hardware known as a “holelock” that is clamped into the borehole and on which the sensor package is subsequently placed (KS-36000, KS-54000, and earlier Guralp sensors). In the second case, additional hardware is sometimes required to stabilize the upper end of the sensor package (the centralizer assembly in KS instruments). Mechanical clamping mechanisms have been used successfully for many years and have produced satisfactory data from many installations
.
However, many installations of this type produce more long-period noise in the horizontal components than in the vertical component. In some of these installations, the horizontals were orders of magnitude noisier at long periods than the vertical. The source of the excess noise in the horizontal components has been difficult to isolate and eliminate. For many years, it was suspected that some of this noise was somehow generated by air motion in the vicinity of the sensor package. Conventionally designed horizontal components of long-period seismometers (this includes all sensors with garden-gate type of suspension such as the STS1, CMG-3 series, KS-36000 and KS-54000) are extremely sensitive to tilt because of their inability to separate the influences of pure horizontal acceleration input to the sensor frame

(the desired input) from the signal that arises from the tilting of the sensor package (tilt noise). Therefore, fairly elaborate schemes for reducing the potential for air motion around the sensor within the borehole have been devised and utilized with varying success. Through trial and error, it has become customary to wrap the sensor package (KS-36000's and KS-54000's) with a thin layer of foam insulation in an attempt to somehow modify the flow of heat near the seismometer in the borehole. In addition, it has become common to place long plastic foam borehole plugs immediately above these sensor packages deep in the borehole and near the top of the borehole to block air motion in these sections of the borehole. Additional insulation, which is intended to further reduce air motion within the borehole, is sometimes utilized near the top of the sensor package.

Recently, a highly successful method for significantly reducing the long-period noise levels in borehole installed horizontal components has been developed at the Albuquerque Seismological Laboratory. It consists of simply filling the entire empty air space below and around the sensor package with sand. In this type of installation, none of the auxiliary installation hardware such as the borehole clamping mechanism or holelock, the azimuth ring, the pilot probe, the centralizer, the foam plugs and/or insulation are utilized to install the seismometer. The seismometer package is simply lowered onto a bed of sand at the bottom of the borehole - sometimes, a piece of hardware called a sand foot is installed on the bottom of the sensor. A volume of sand is then poured into the borehole to a depth extending to the top of the seismometer package. The volume required can be easily calculated from the dimensions of the package and the inner diameter of the borehole.

Experimental investigations have demonstrated that it is easy to remove the seismometer from the sand if necessary for maintenance purposes even when the sand is saturated. Normally, the sand left in the hole from a previous installation is not removed from the hole prior to the next installation. Only a fraction of a meter of borehole depth is lost per installation; if necessary, the sand can be removed from the borehole with a downhole vacuum cleaner that has been designed at ASL.

This method of installation is expected to reduce horizontal noise to levels approaching the noise level of the vertical component at any particular site. The horizontals should be expected to always be slightly noisier than the vertical component because remnant real ground tilt will always be present regardless of how deep the sensor is installed. To date, extensive testing at ASL utilizing both KS and CMG (see DS 5.1) instruments and several actual KS sand installations in the field have indicated that sand does indeed produce significantly reduced levels of horizontal noise. The sand installation method has been adopted for future installations by the IRIS GSN program.

One additional advantage of a sand installation is that the seismometer package costs considerably less than for a clamped installation.

One note of caution should be introduced at this point. Conventional hole-lock based installations produce very noisy horizontal data if the sensor package is immersed in water or another liquid such as motor oil. Therefore, every effort is normally made in the field to keep liquids out of the borehole. Although not thoroughly tested to date, sand installations are expected to provide quiet horizontal data even if the sensor is immersed in water as long as the water is not flowing.

Determining the orientation of the horizontal components of a seismometer installed in a deep borehole is not a simple matter because one can not physically get at the instrument once it is installed. One must resort to indirect methods for determining how the instrument is oriented. For the past 25 years, the KS series instrument installations have relied on a gyroscopic procedure to determine the seismometer orientation as follows. First, the hole-lock is installed in the borehole at the intended operating depth; then, a gyroscopic probe is lowered into the hole and mated with an alignment slot in the hole-lock. The gyro system determines the orientation of this alignment slot with respect to a known azimuth (usually north) on the surface. An adjustable azimuth ring located on the base of the KS sensor is then set to compensate for the alignment of the hole-lock slot to north. This ensures that when the seismometer is lowered into the borehole and the key on the alignment ring is mated with the alignment slot in the hole-lock, the sensor is in a north-south, east-west orientation.

This method was considered adequate to determine the azimuth of borehole installations for many years, but it had some serious shortcomings. The method was subject to errors due to mechanical assembly tolerances and was frequently plagued by nonlinear gyro drift. The major problem with the system was the fragile nature of the gyro probes themselves; they proved to be very susceptible to shipping damage and extremely expensive to repair. In addition, the manufacturer was not willing to warrant his expensive repair work in any way. Therefore, a much cheaper alternate method of orienting borehole seismometers has been developed and is currently replacing the gyro probe approach in programs with limited budgets.

The new method involves the installation of a horizontal reference seismometer on the surface near the borehole at a known orientation. The digitally recorded output of this surface sensor is then compared using the coherence and correlation functions with the digitally recorded outputs of the horizontal components of the sensor installed in the borehole to determine the relative azimuthal orientation of the borehole components with respect to the surface horizontal.

With the advent of sand installations, the horizontal components of newly installed seismometers are no longer being oriented in the conventional north-south east-west configuration. Instead, many borehole sensors are being installed at arbitrary azimuths with respect to north; the alignment of the horizontals with respect to north then becomes part of the data set. This approach has become feasible because modern computing power and digital data trivializes the task of rotating the data to any azimuth desired by the data user.

7.4.5.7 Typical borehole parameters

As the result of the SRO and IRIS programs, there are now many broadband borehole installations in use around the world. Most of these boreholes are geometrically quite similar because they were designed to accommodate the same seismic instruments. All of these boreholes are approximately 16.5 cm in diameter and most of them are drilled to a maximum of 3.5 degrees departure from true vertical. They are all cased with standard oil field grade casing and most of them are watertight.

There is some variation in the depths of these boreholes. As mentioned above, the vast majority of seismic boreholes are approximately 100 meters deep. However, some of these boreholes are considerably deeper if they were drilled in areas with thick overburden or poor bedrock. For instance, the borehole sensor at DWPF (Florida) is installed at 162 meters depth because the overburden at DWPF is approximately 46 meters thick and the upper layers of bedrock consist of interleaved units of varying grades of soft limestone. The borehole at

ANTO, which is drilled in competent rock for most of its depth, is the deepest and oldest IRIS borehole at 195 meters. This was the first field borehole that was drilled for the SRO program: as more experience was gained, it became apparent that boreholes that deep were not cost-effective. A few of the boreholes are shallower primarily because severe difficulties were encountered during the drilling operations that necessitated finishing the borehole at a shallower depth than originally desired. For example, the sensor at JOHN (Johnson Island) is at a depth of 39 meters because severe borehole collapses were encountered while attempting to drill deeper. The site is on a coral atoll and the surface layers are very poorly consolidated; true bedrock probably lies at very great depths. Drilling in volcanic regions often proves to be very difficult. The borehole at POHA on the island of Hawaii was terminated at 88 meters because the drillers experienced severe "loss of circulation" conditions throughout the drilling operation. The surface layers at POHA consist of badly fractured weathered basalt layers and basalt rubble separated by scoria rubble, ash flows, sand and other assorted debris produced by an active volcano. Drilling conditions in the volcanic deposits on Macquire Island proved to be so difficult that it was impossible to complete a borehole.

7.4.5.8 Commercial sources of borehole instruments

Currently, there are only two known commercial sources of high sensitivity broadband borehole seismometers. For many years, Teledyne Geotech in Dallas Texas, USA (now Geotech Instruments LLC; www.geoinstr.com) was the only source of high sensitivity instruments (KS-36000, KS-54000, GS-21, and 20171) designed specifically for borehole installation. Both the KS-36000 and the KS-54000 are three-component broadband, closed loop force feedback sensors that are designed for deep (up to 300 meters) borehole installation. The GS-21 is a conventionally designed short-period vertical deep borehole instrument intended for superior high frequency performance. The 20171 is a slightly nosier and slightly cheaper version of the GS-21. The KS-36000 is no longer manufactured but there are many of these instruments still in operation in boreholes around the world. Recently, Geotech has introduced a new sensor, the KS-2000, which is available both as a surface package and a 4-inch borehole package.

For the past few years, Guralp Systems Ltd. (www.guralp.com), Reading, UK, has been producing a borehole version of the CMG-3T (see DS 5.1; referred to by some as a CMG-3TB). This instrument is much smaller and much lighter than is a KS sensor; it is also considerably less expensive. This is a three component, broadband, closed loop, force feedback instrument that is very easy to install. Guralp Systems has recently introduced a new borehole sensor that has both a velocity and an acceleration output and is integrated with its own digitizer. In addition, they are willing to work with the customer to meet any specific requirements.

A borehole version of the STS2 has been under development for several years. Currently, a basic prototype of the instrument exists but the instrument requires further development of the remote control functions and the final packaging design is yet to be determined. Streckeisen has not announced an availability date for the new instrument.

It is somewhat hazardous to quote sensor prices because they are continuously subject to change by the manufacturer and international currency exchange rates change daily, but here are some approximate current relative costs for borehole sensors in 1999 US dollars. These prices should be viewed as being approximate; potential buyers should consult the manufacturer for a current quote.

A basic Geotech KS-54000 was priced at nearly US$ 65,000. Additional costs will be about US$ 40,000 for a conventional installation or about US$ 13,000 if installed in sand and if all the associated installation hardware has been purchased. However, this price may be reduced if the instruments are ordered in sufficient quantities (25 or more). A GS-21was priced at about US$ 8,000 and the 20171 was around US$ 6,000 for the instruments themselves. The associated hardware (soft electrical cable, wire rope, winch etc.) is additional. Estimated delivery time for these instruments is 120 days or more after receipt of order depending on the availability of non-Geotech manufactured parts. The soon to be introduced KS-2000 sensor will be priced at below US$ 10,000 for the surface system and the borehole version will probably be below US$ 20,000.

A Guralp Systems CMG-3TB costs about $28,000 if the instrument is to be installed in sand; and about $39,000 for a hole-lock equipped version. Delivery is currently about 9 months but they are trying to decrease this to about 6 months.

7.4.5.9 Instrument noise

It is important to remember that the purpose of installing seismic instrumentation in boreholes is to obtain quiet seismic data. This will be foiled if the seismic sensor system itself is too noisy to resolve the lower levels of background noise of the Earth which are expected to be found at the bottom of the borehole. As delivered from the factory, sensor self-noise levels sometimes vary over a wide range and some instruments may be far too noisy to operate successfully in a quiet borehole. Therefore, it is recommended that the self-noise of all borehole instruments be measured before installation to ensure that they are quiet enough to be able to resolve the background noise levels anticipated at the bottom of the borehole. Self-noise measurements are usually made by installing two or more sensors physically close enough together to ensure that the ground motion input to all of the sensors is identical. The data produced by the sensors is then analyzed to determine the level of the incoherent power in each sensor’s output; this incoherent power is usually interpreted as the sensor internal noise level (see 5.6). To achieve high fidelity recording of true ground motion, the seismometer system self-noise level should be well below the anticipated background Earth's motion levels across the band of interest at the site.

The low-noise models in Fig. 7.60 can serve as guidelines to the instrument noise levels that may be expected from the CMG-3TB and the KS-54000 sensor systems. In this figure, the CMG-3TB low-noise model (CMGLNM) is the thin solid line and the KS-54000 low noise model (KSLNM) is the thin dashed line. The solid heavy line in the figure is Peterson’s (1993) new low-noise model (NLNM) for the background seismic noise at a quiet site. The reader should recognize that there is no single known site in the world whose background power spectral density levels reach NLNM levels across the entire band. Instead, the NLNM is a composite of the lowest Earth's noise levels obtained from many sites. Similarly, the low-noise models for the instruments should not be regarded as being typical of all instruments because each seismic sensor has a distinct personality of its own. Instead, the low-noise models for the instruments should be regarded as lower limits of instrument noise just as is the case for the NLNM of ambient Earth's noise. In all probability, individual instruments will be noisier than the low-noise model for that instrument over at least portions of the spectrum.

The CMGLNM plot in Fig. 7.60 is based on a composite of experimental test data obtained at the Albuquerque Seismological Laboratory over a period of several years. The central portion (from about 0.6 to about 20 seconds) of the model was not actually measured because of numerical resolution limits of the data processing algorithms and this portion of the model is an estimate. As a general rule, many CMG-3TB instrument noise levels approach the CMGLNM at short periods (less than 0.6 seconds); fewer of these instruments achieve the indicated noise levels at long periods (greater than 20 seconds).

The KSLNM plot in Fig. 7.60 is a factory-derived theoretical instrument noise level. As such, it should be regarded as an optimistic estimate of the lower limits of the self-noise in the KS-54000. Most KS-54000 instruments are probably noisier than the levels indicated by the KSLNM curve.

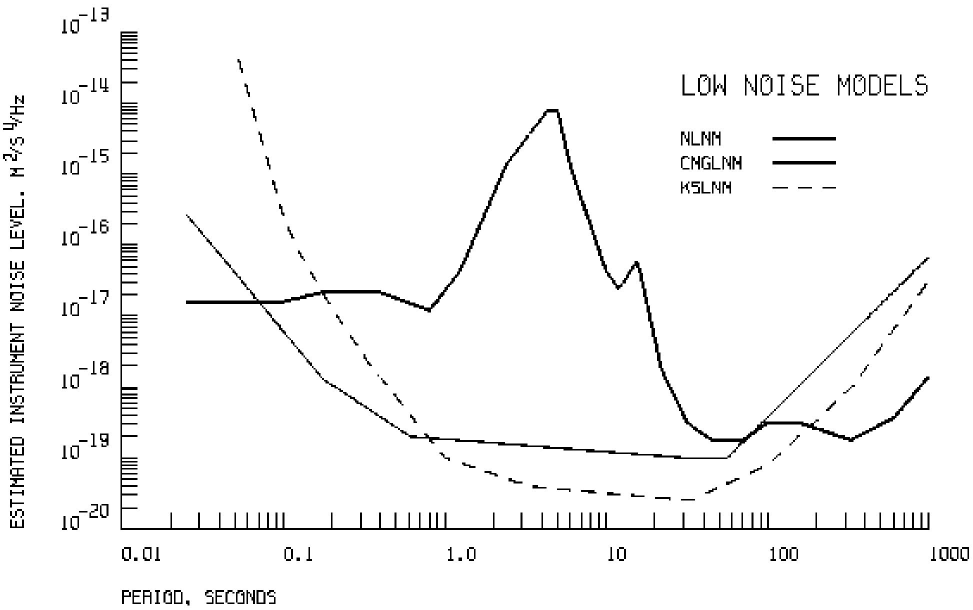


Fig. 7.60 Low-noise models for the KS-54000 (KSLNM) and the CMG-3TB (CMGLNM) sensor system self-noise relative to Peterson's (1993) new low-noise model (NLNM) for background Earth's motion.

7.4.5.10 Organizations with known noteworthy borehole experience

As an organization, Teledyne Geotech (Geotech Instruments – www.geoinstr.com) certainly has the longest history in seismic borehole technology. However, personnel turnover in the past few years has significantly depleted Geotech's direct hands-on experience in boreholes.
Another organization with a long history of borehole experience is the United States Air Force Technical Applications Center (AFTAC – www.aftac.gov). Over the past 25 years they have deployed many KS instruments throughout the world. Most of these installations involve multiple sensor configurations deployed in arrays. Prior to the KS era, AFTAC used the older Geotech Triax instruments in boreholes at some of their arrays. As was the case with Teledyne Geotech, AFTAC does not have personnel with long-term borehole experience; US Air Force personnel tend to rotate in and out of their duty assignments every two years.

The Albuquerque Seismological Laboratory (http://earthquake.usgs.gov/regional/asl/) has been deploying KS sensors in boreholes since 1974 at sites located all over the world and recently has begun installing Guralp CMG-3TB sensors at some sites. The Laboratory has borehole experience on all seven continents ranging from tropical jungle in Brazil to the permafrost of Antarctica. At ASL, the personnel situation has remained relatively stable and there are several personnel with many years of experience working with boreholes – some have been at it for over 25 years.

Southern Methodist University (Dr Eugene T. Herrin, e-mail: herrin@passion.isem.smu.edu) has been active in the borehole field off and on over the years. Recently they have been quite active in developing innovative economical methods for installing broadband borehole arrays. As an organization, Sandia National Laboratories (www.sandia.gov) has considerable experience in borehole technology, most notably with their Remote Seismic Telemetered Network (RSTN) program. However, the lack of continuity in their seismic program has resulted in the loss of many of the personnel with real field experience in borehole technology.

During the past 10 years, the IDA group at the Scripps Institution of Oceanography at the University of California, San Diego (www-ida.ucsd.edu/public/home.nof.html) has become involved in land-based borehole seismology as a part of the IRIS GSN program. They now have experience in drilling boreholes and deploying instruments at several sites around the world.

In conjunction with personnel from the Woods Hole Oceanographic Institute, Scripps is also leading the US effort aimed at developing pioneering borehole seismology techniques for use on the ocean floor. Independent programs in ocean bottom borehole seismology are also currently conducted by groups in France and Japan. Installing seismic sensors in the deep ocean is developing rapidly and we will not attempt to summarize practices in this field.

7.4.6 Borehole strong-motion array installation (R. L. Nigbor, 2002)

7.4.6.1 Introduction

"An important factor in understanding and estimating local soil effects on ground motions and soil-structure interaction effects on structural response is the three dimensional nature of earthquake waves. ...For these purposes it is necessary to have available records of the motion at various points on the ground surface, along two mutually orthogonal directions, as well as at different depths."

These words, published in the proceedings of the 1981 U.S. National Workshop on Strong-Motion Earthquake Instrumentation in Santa Barbara, California, are echoed in every important meeting where policies and priorities have been set regarding strong-motion monitoring. Earthquake engineers and seismologists alike agree: borehole strong-motion data continue to be a priority for better understanding of site response and soil-structure interaction issues.

This section is somewhat of a departure from much of the New Manual of Seismological Observatory Practice, as borehole strong-motion observations are primarily focused on site response and not on the seismic source or wave propagation path. For engineering purposes, borehole data in shallow (< 100 m) soils are of primary importance; these data are used to study amplification of earthquake shaking in the soil layers. However, borehole data in rock, especially weathered rock in the upper 30 m, are also important for the understanding of strong ground shaking in earthquakes. Rock sites often show larger variability in measured ground motions than do soil sites. Examples of well-documented strong-motion borehole arrays are the EuroSeisTest Project (Riepl et al., 1998, and Fig. 7.65) and the Garner Valley Downhole Array (see Fig. 7.61). The user of this Manual should consult these references for further information about the details of borehole arrays and the use of borehole strong-motion data.

As important as borehole data are, many practitioners experience difficulty designing and constructing such arrays. As with the more traditional seismological borehole systems (see 7.4.5), strong-motion borehole arrays present a variety of challenges. Fortunately, much has been learned about borehole strong-motion instrumentation and vertical strong-motion array construction. In the past, borehole systems rarely survived more than two years. However, today there are many successful, long-term three-dimensional strong-motion arrays throughout the world. This accomplishment can be traced to better design, to new instrumentation, to better understanding of the historical failures, and to improved installation procedures.

This section is intended to assist with planning and implementing a successful borehole strong-motion array. Details of the instrumentation are not directly discussed but are available from the manufacturers of borehole strong-motion systems such as Kinemetrics (http://www.kmi.com). The sections that follow discuss borehole array planning, borehole preparation, geotechnical/geophysical measurements, installation procedure, and costs.

Fig. 7.61 shows representative borehole array data from the Garner Valley Downhole Array, Fig. 7.62 is a sketch of a typical, simple borehole strong-motion installation and Fig. 7.63 shows an example of a borehole strong-motion array. These sketches are meant to show the various components and terminology that will be discussed in this section.

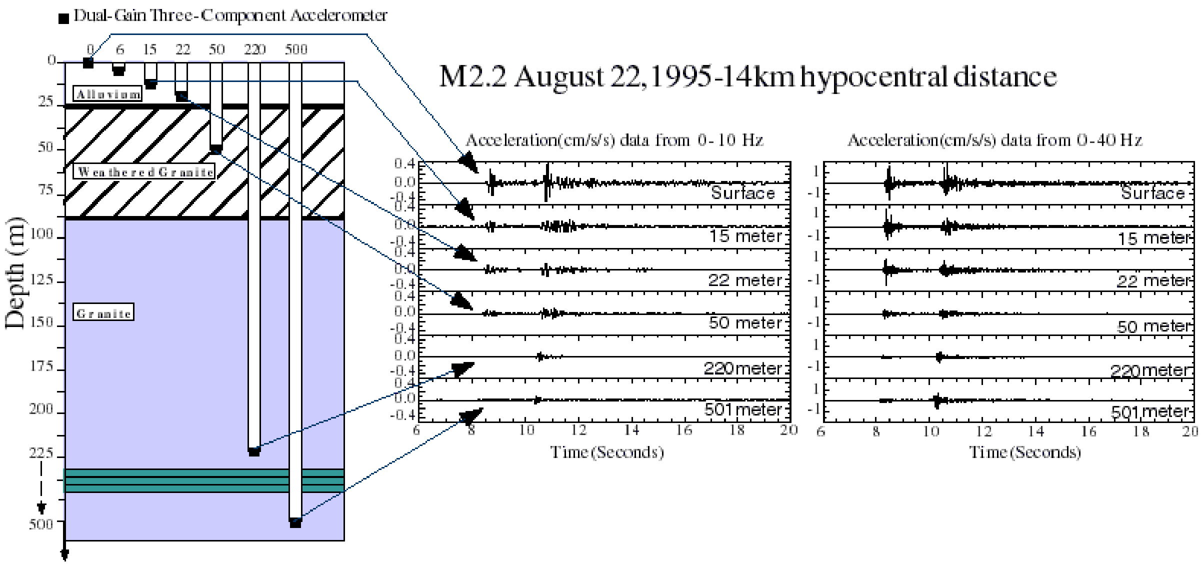


Fig. 7.61 Sample borehole strong-motion array data from Garner Valley downhole array

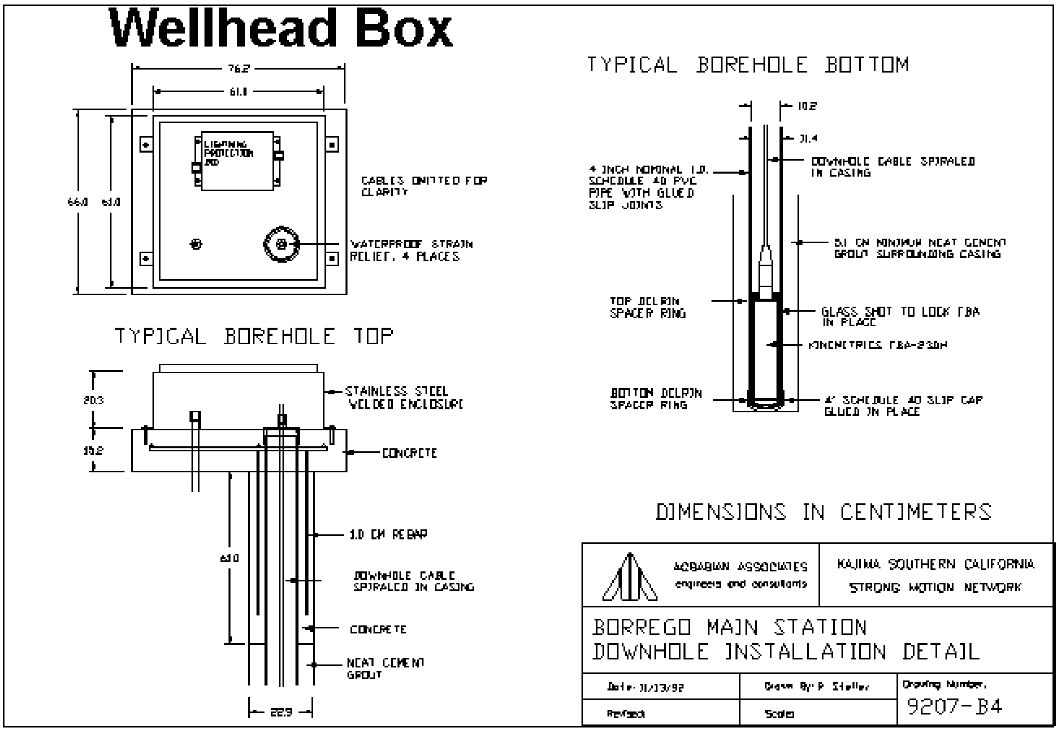


Fig.7.62 Sketch of borehole strong-motion accelerometer installation details.

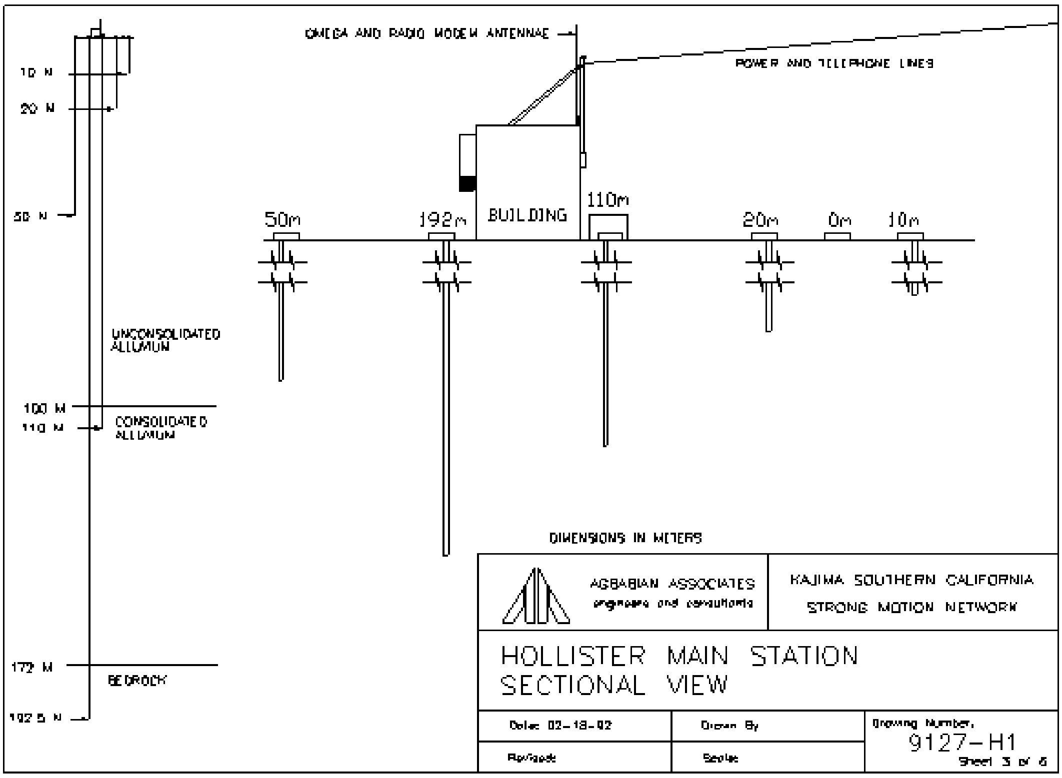


Fig. 7.63 Sketch of a borehole strong-motion array.

7.4.6.2 Borehole array planning

This section focuses on the planning issues related to borehole strong-motion array installation. The most important step in implementing a successful borehole accelerometer system is good planning. Done properly, by the time the borehole accelerometer package is actually lowered into the hole (as in Fig. 7.64 below), 95% of the effort will be complete. The following are important considerations:

- location;
- geologic implications;
- coupling and retrievability issues;
- sensor orientation;
- system issues.

Location

Borehole data are needed for source mechanism and wave propagation arrays, local site effects arrays, and as free field input to structural response arrays. The location of the borehole is principally dictated by the needs of the particular project and thus the required array configuration. Borehole location and depth will also depend on the soils and depth to bedrock. It is recommended that external advice or review be obtained for borehole location selection.

Fig. 7.64 Lowering a borehole accelerometer into the cased borehole.

Ground-borne noise is not the serious issue that it is with high-gain seismic systems, but it is still important to minimize non-earthquake vibrations in a borehole strong-motion installation. Few man-made signals will penetrate tens of meters of soil, so background noise will be reduced in a borehole sensor. However, some boreholes are shallow, and often the borehole accelerometer is collocated with a surface sensor. For this reason, the borehole should be located as far away from cultural (man-made) noise sources as possible. These include large, above ground structures, such as telephone poles, which can be driven by wind, vibration sources such as nearby rock quarries or industrial plants, and roadways bearing large vehicles.

The structure used for housing the recording station itself can be a source of coupled soil-structure vibration and must be designed carefully. The interaction of large structures with the soils can introduce noise into the ground motion. For this reason, the surface accelerometers should be located at least 1.5H distance away from the structure, where H is the height of the structure.

Within an array of borehole and surface sensors, one must optimize the layout with regard to physical concerns such as cabling and environmental protection. The lengths of surface cables should be minimized for several reasons. First, because of cost. Second, the longer the cable the greater the potential for damage or introduction of noise or induced voltage, even if the cable is shielded and in conduit, and even if there is lightning protection both at the wellhead

box and at the recording station (as there should be). The recording station should be located near the wellhead boxes to minimize cable lengths.

Finally, it is best if the wellhead box is dry most of the time although it is assumed that the borehole itself is full of water and the wellhead box is designed to be waterproof. The top of the borehole should be positioned with regard to local water drainage and preferably not in a topographic low.

Geologic implications

Specific knowledge of the geology of a site is extremely useful during planning in order to meet project needs and accurately estimate the costs. The implications of local geology will depend upon the specific purpose of the borehole array. One should at least understand the surface geology, the depth to basement rock, and the local and regional tectonic structure. Fig. 7.65 shows a composite model of the EuroSeisTest site. This is an example of the kind of geologic understanding which should accompany a borehole strong-motion array installation.

The best information will come from both a thorough literature search to find existing information and then pre-installation geophysical studies. Once a site is selected, more detailed geophysical and geotechnical studies will be needed for ground motion and structural response modeling.

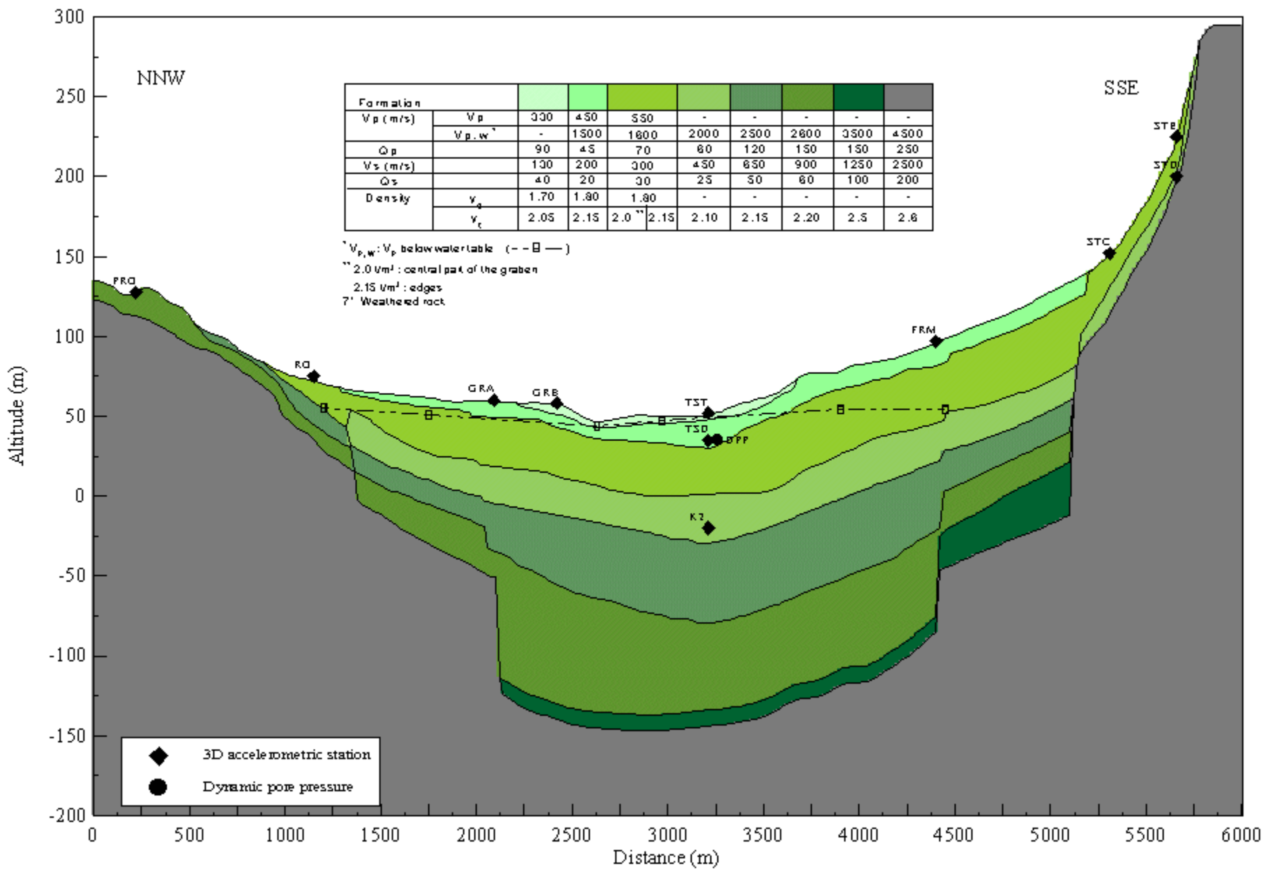


Fig. 7.65 Geologic model of EuroSeisTest showing accelerometer array configuration.

Coupling and retrievability issues

The coupling of the borehole sensor to the surrounding soil is a critical issue for borehole strong-motion systems. The goal of the measurement is to record the particle motion of the native soil or rock at depth. Care must be taken to ensure that the borehole installation minimizes the disturbance of the soil or rock column. The borehole itself, the casing, the grout used to seal the casing and couple it to the surrounding soils, the borehole accelerometer package, and the method used to couple the package to the wall of the casing, all can have some effect on the recorded motions, especially if the motions approach 1g. The issue of coupling is related to instrument retrievability, which is the ability to pull out a borehole sensor if repair is needed. For some borehole sensor installations, a permanent coupling solution (grouting or cementing the sensor in place) may be selected. This is not recommended as experience has shown that borehole sensor failure does occur. Failure of a borehole sensor that can not be retrieved not only entails the replacement of the sensor, but of the borehole as well, and the cost of the borehole often well exceeds that of the instrumentation.

If permanent coupling of the sensor is essential, using some sort of grout, it is advisable to design the borehole system to have a “weak point” above the sensor that will break cleanly when the cable is pulled and leave as little of the cable as is possible in the hole. If the sensor fails, it would be possible to abandon the sensor and cement in a replacement in the same borehole at a slightly shallower depth.

Removable coupling (locking) methods include backfilling the annular space around the package with some specified material, wedge-type locking systems, and pneumatic/hydraulic locking systems. Backfill materials used in the past have included sand, gravel, lead shot, and glass beads. Of these, water saturated sands can be expected to liquefy under vibrating conditions, and lead shot has been found to cold form over time, making retrieval difficult and even impossible. This leaves gravel or glass beads as successful alternatives. Kinemetrics recommends the use of a combination of 3mm and 5mm glass spheres as a coupling method; the company can be contacted for further details.

Several commercial wedge-type locking systems are available from borehole sensor manufacturers. Experience has shown that these will work well in shallower (<50m) installations, but may become unreliable in deeper installations. Some borehole installations, such as the 500m borehole sensor installation at the Garner Valley Downhole Array have used custom hydraulic locking systems. Some temporary borehole strong-motion sensor installations have used pneumatic (air-pressure) locking systems with success, but the air pressure must be maintained.

Sensor orientation

Another important issue in borehole strong-motion studies is the accurate orientation of the horizontal components of the borehole sensors. In the past, practitioners have most often relied on loading poles to manually orient the instrument package. Loading poles are generally square-section tubes which are rigidly attached to the accelerometer package. During installation, the loading poles are joined end-to-end with the painted side facing the same direction as the others, thereby permitting the package to be manually oriented from the top of the hole. This manual method can work well for shallow (< 20 m) borehole installations, but twisting of the poles can introduce large errors for deeper installations.

Fluxgate magnetometer sensors were first used with strong-motion borehole instrumentation in the late 1980's by a firm called Applied Geophysics of Los Angeles. At that time, the compass was used to determine the arbitrary orientation of a slotted end cap installed at the bottom of the PVC casing by the driller. The mating notch on a special borehole package was then rotated and fixed so that, once guided (by gravity) into position in the slot of the cap, the package was oriented as desired. This method was expensive because of the special construction and installation of the cap at the bottom of the hole, and the special packaging required to accommodate the orientation notch.

The current generation of commercial downhole accelerometers (for example, Kinemetrics FBA-23DH) have provisions for an internal fluxgate magnetometer compass to make orientation simpler and much less expensive than either loading poles or borehole bottom devices. With this device, one simply observes the compass orientation via a notebook computer at the surface and rotates the sensor cable until the correct orientation is achieved. Accuracies of 2-3 degrees can be achieved with this method.

It is also possible to simply install a downhole accelerometer with random orientation and then to determine the orientation later by comparing the vector orientation of a surface sensor to that recorded from the borehole sensors. Orientation can be determined after installation by comparing surface and downhole data, either earthquake or microtremor. Note that anisotropy in the near surface soils can produce errors in this type of orientation unless the events are large regional events with significant long-period energy, i.e., with wavelengths much larger than the soil depths. Using a known source location, the orientations can be determined to ± 5° by using linearity of 1st motions on radial and transverse components (see Aster and Shearer, 1991).

System issues

The borehole accelerometer package can not be installed properly without consideration of the overall system, and particularly the recording device. Usually, the recording system will have exceptional dynamic range to take advantage of the low noise qualities of the borehole installation and the accelerometer. Therefore, particular care must be taken avoid system-related noise due to improper grounding and other common problems. Additional issues include system level lightning protection to protect circuitry against large voltage transients. Many of these system issues have been discussed in detail in 7.4.2.1.

7.4.6.3 Borehole preparation

A critical step in a successful borehole accelerometer installation is the preparation of the borehole itself. The borehole should be vertical, carefully drilled, with carefully installed casing grouted to ensure good coupling of ground motions at higher frequencies. Fig. 7.66 shows a typical drilling site. One can see that this can be a major construction effort.

Planning

Site selection for borehole accelerometers is often dictated by factors other than practicality for drilling operations. If there is room for adjustment of borehole location, try to meet or exceed the following minimum clearance requirements:

- 2m from borehole to any obstructions such as fences, walls, or ditches;
- two 10m paths 4m wide on opposite sides of the borehole for drilling equipment;
- no overhead power lines

Access to the site should be able to support repeated trips with heavy trucks without damage. If a site is located in soft soils, consider the use of wood under the wheels of the drill rig and a four-wheel-drive water truck. Some sites may require the use of track-mounted drill rigs for access, or heavy earthmoving equipment to help position the drill rig on site. Fig. 7.67 below demonstrates why these are requirements for a drilling operation. Important steps in borehole preparation are planning, contractor selection, permitting, drilling, sampling, casing, and grouting. These issues are discussed below.

Fig. 7.66 Typical borehole drilling operation in an open area.

Fig. 7.67 Drilling operation in a confined area, showing size of drill rig.

Water availability is critical for drilling operations. A residential-type supply is adequate as long as an on-site water tank or truck is available to provide storage for peak demands. If all water is to be supplied by truck, a water supply capable of filling the truck quickly should be located within a 15 minute drive. Disposal of drill tailings and excess water is usually not a problem in remote sites where the tailings can be spread around the surrounding area to dry. In urban areas, fluids can be channeled sometimes down drains or ditches, but solid tailings must be removed. For shallow holes this can be done in drums and a pickup truck, if a nearby spot can be located to dispose of the tailings. In urban areas, a separation cone can be placed over a waterproof dumpster, and tailings collected in the dumpster, to be removed periodically by a liquid waste hauler with a vacuum-lift truck. In some areas, drill tailings are automatically classified as hazardous waste, which complicates disposal matters tremendously. Be sure to work these issues out before starting the project. In many developed areas, this can be a large cost item, easily as large as the drilling costs.

If multiple boreholes are to be drilled in one location, a separation of 6m between boreholes is generally adequate to prevent damage to a borehole during the drilling of subsequent boreholes. This should preclude the possibility of boreholes drifting laterally into each other during drilling. Shallow holes may be placed closer together by drilling in a line and backing the drill rig over the most-recently completed hole to protect it from damage.

The time of year chosen to begin a drilling project may significantly affect the schedule and cost of a project. Warmer weather is generally desirable, as are long periods of daylight and a lack of rain or snow.

Selection of drilling contractor

The selection of a drilling contractor must be based upon a number of factors; perhaps the least important of these is cost. If geotechnical sampling is to be performed, the contractor must have the equipment and crews familiar with geotechnical drilling practices. The key item in drilling is experience with the tasks to be performed and the equipment to be used. Drilling deeper (>50m) boreholes is not the place to have an inexperienced crew. The driller's reputation for completion of work and quality of work should be reviewed. It is strongly recommended that one obtain references for a drilling contractor.

When obtaining a bid, consider getting separate bids for a fixed price per meter and for actual time and materials used. For deep boreholes, fixed price per meter bids may appear more expensive but can save enormous amounts of money if a site is difficult. In addition, most companies will send out their best crews on fixed price bids, generally giving faster completion and fewer complications. In the long run, fixed price contracts often save money.

Permits

The drilling of boreholes near aquifers is carefully controlled in many countries to ensure that ground water sources are not contaminated. This control is generally exercised by local government, often through environmental health departments. Usually the responsible entity will require the submission of a permit application detailing depth, diameter, location, property lines, adjacent structures, wells and septic systems; well construction method, owner, and licensed driller to perform the work, and a fee of several hundred dollars per well. The application may require the signature of the land owner and the drilling contractor. In addition, some regions require copies of the driller's license and a performance bond before the driller is approved for work. In the US, typical permitting work is as follows:

- submission of permit application and fee;
- after permit application and payment of fee an inspector will usually visit the site before issuing approval of the permit;
- during construction, depending upon location, the inspector may visit the site several times, and may require notification 24 hours before grout is to be placed;
- in some municipalities, an inspector must be present during the grouting process;
- notifying the permitting agency of the completion of wells; usually this is in the form of a drill log which shows lithologic information and details of the well construction.

In other countries, and in rural or remote areas, permitting may not be needed. However, permission by the owner of the land will likely be required in all cases.

Drilling

There are several methods for shallow drilling in soils and rock. The book by Driscoll (1986) on Groundwater and Wells is a good reference for the various methods. Several ASTM (American Society for Testing and Materials) Standards describe drilling methods as well (see http://www.astm.org). A good start is ASTM D420-98 "Guide to Site Characterization for Engineering, Design, and Construction Purposes."

Direct rotary or "rotary mud" drilling is the drilling methodology best suited to most downhole accelerometer installation projects. One major advantage of this method is the support that the borehole wall receives from the drilling fluid that always fills the borehole. This method can be performed in both hard and soft formations, and can be done using fairly compact equipment. The drilling is performed by rotating a bit on the end of a heavy pipe or "drill string", which is driven down by its own weight, or by additional downward forces applied by hydraulic cylinders or chain pull-downs on the drill rig. The bit is lubricated, and drill cuttings are removed by drilling fluid or "mud" that is pumped down to the bit through the drill string. The fluid then returns to the surface through the annulus formed by the outer surface of the drill string and the borehole wall. This is possible because the borehole diameter is generally several inches larger in diameter than the drill string. As the fluid moves to the surface it carries with it the particulate debris produced by the cutting action of the bit. At the surface the fluid is directed into a holding area, either a box or dug pit, to let the cuttings settle out before the fluid is pumped down the drill string again.

Speed of completion is important in drilling due to the potential loss of a borehole by collapse. Some soil formations will remain open for long periods of time even if the fluid level drops significantly; other formations will cave in with the slightest provocation, even when filled with thick drilling fluid. In many instances, the premium paid to work around the clock is justified by the savings of not having to remove the drill string each evening, and the reduced risk of borehole collapse during the night.

Drilling is a messy business due to the large volume of water and mud involved. In a confined urban space such as an alley, a 100 m borehole might be drilled by a truck mounted rig only 8 m long, with an 8m tall tower, with only 1m of clearance on either side of the rig. Water and drill rod would be transported by a single 6m truck. All cuttings could be contained and removed from the site in 200 liter drums or a larger container. This would be possible but is far from an ideal situation. In a rural or remote area, a 250 m borehole might use a rig 15 m long, with a tower of 10-15 m, a separate pumping rig 10 m long, a 12 m drill string trailer, a water storage tank, a mud pit 3 by 6 m, and an area several hundred m^2 to hold cuttings piles and miscellaneous support equipment. Fig. 7.67 shows such a setup.

Installation of a typical 100 mm (4 inch Schedule 40 or 80) PVC casing requires a minimum 200 mm (8 inch) diameter borehole. A larger diameter may be used when needed to maintain a clear hole, but this will increase drilling and grout costs and the potential of damage to the casing from grout cure heat, discussed further in the section on grouting. Most municipalities in the USA require a 50 mm (2 inch) annular seal around the casing, and this diameter meets this requirement. Depending upon the size of the drill rig used, this may be drilled in one pass, or a smaller pilot hole; usually 120 mm (4 7/8 inch) diameter will be drilled first, and all sampling and geophysical testing will be done in the pilot hole before drilling again to the final size.

There is a trade-off between speed of drilling and verticality of the borehole. Since verticality is an important issue for downhole sensor installations, it is important to make the driller aware of this, and stress that slow steady drill rates and perhaps collars attached to the drill string can help keep the borehole vertical. If you can get the driller to agree to a tolerance when doing a contract, this will also help keep the drill rig operator focused on this issue. Deviations of less than 5° from the vertical are acceptable. Larger deviations will affect the dynamic range of most sensors, unless the instrument has some type of auto-leveling device.

Geotechnical sampling

Generally, installation of a downhole accelerometer, or vertical array, is done to understand the effects of local site response on ground motion. Acquisition of soil or rock formation samples during drilling, as well as geophysical information, provide a great deal of information useful in site characterization studies. Not only can these samples provide clear indications of the formations beneath a site, but can also be used in laboratory studies to determine structural characteristics of the formation.

Soil sampling is described by Kenji Ishihara (1996) and by Driscoll (1986). Several ASTM standards also exist for sampling; two important references are ASTM D1586-99 "Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils" and ASTM D1587-94 "Standard Practice for Thin-Walled Tube Geotechnical Sampling of Soils", both from http://www.astm.org.

In general, one will use five major categories of sample types in borehole strong-motion array studies, as discussed below.

- **Bag samples** are simply a collection of drill cuttings carried to the surface by the drilling fluid and caught as they enter the mud box or pit. The accuracy of this sampling method is influenced by a number of factors including depth of the borehole, rate of circulation of drilling fluid, and size of cutting fragments produced by the drilling process. This method has limitations, due to the introduction of clays from the drilling fluid into the sample, as well as older material falling off the borehole wall. However, when used in conjunction with a detailed record of drilling rate, bag samples can provide extensive information about formation.

- **Drive sampling** ("Split-Barrel Sampling" or "SPT" sampling) produces an intact but disturbed sample 2.5-5 cm (1-2 inch) in diameter by driving a sample tube into the formation at the bottom of the borehole. This is done by removing the drill string and lowering the sample tube, mounted on the bottom of a sliding hammer, to the bottom on a cable. The hammer is then actuated by lifting and dropping the cable until the sample tube has been advanced the desired distance. Often the number of blows to advance a given distance is recorded to provide blow count (SPT N-value), a measure of formation hardness. This procedure is time consuming because it requires the removal of the entire drill string from the borehole, but provides samples with excellent depth control. This method is useful only in soils. Fig. 7.68 shows typical drive samples.

Fig. 7.68 Drive samples being collected for later laboratory testing.

- **Pitcher samples** ("thin-walled tube" samples) produce an undisturbed sample 75 mm (3 inches) in diameter and up to 750 mm (30 inches) long. This technique is used when large high quality samples are required for laboratory tests, and where formations are too hard to yield results with a drive sampler. Pitcher sampling is performed by removing the drill string from the borehole and replacing the standard bit with a pitcher sample barrel. The barrel supports a thin wall steel tube on a spring loaded plunger. The plunger allows the tube to retract through the center of an annular carbide bit when it reaches the bottom of the borehole. Drilling then proceeds, cutting an annulus. The 75 mm (3 inch) center core is forced into the thin wall tube. When advancement is complete, the entire assembly is removed and the core shears off at the bottom of the thin wall core tube. The sample may then be stored and transported in the tube, or extruded at the drill site. The original bit is then replaced and lowered to the bottom of the borehole to resume drilling. This is a very time consuming procedure, as it requires removing and inserting the entire drill string twice, but it yields very good undisturbed soil samples. This method is not used in very stiff soils or rock. Fig. 7.69 shows some Pitcher samples in the field.

Fig. 7.69 Pitcher samples.

- **<u>Diamond core samples</u>** are taken in hard formations, usually rock. The procedure for diamond coring is identical to Pitcher sampling, except that a diamond core barrel is used. It also cuts an annulus while retaining the center core inside the core barrel. As with the Pitcher sample, this is a very time consuming procedure, as it requires removing and inserting the entire drill string twice, but is the only way to obtain samples in hard rock. Continuous coring provides a complete undisturbed record of the formations the borehole passes through. There are several ways of performing continuous coring; one method is referred to as “wireline” sampling. This, as well as most continuous methodologies, allow for the mounting of a variety of annular bits at the bottom of the drill string as well as for the exchange of the center portion of the bit from cutter to sample tube via a lightweight wireline cable through the center of the drill string. This permits the retrieval of cores without removing the drill string. This is a superior methodology for deep (>200m) boreholes where the larger drill rigs required to support it are justified.

Casing

A plastic (PVC, poly-vinyl-chloride) cased borehole is recommended for installations to 250 m depth. Medium-walled casing (“Schedule 40” in US standards) is acceptable to about 50 m depth; thick-walled (“Schedule 80”) should be used for installations between 50 and 250 m. Steel casing is recommended for deeper installations. As discussed elsewhere in this Manual, the Kinemetrics FBA-23DH and its associated installation equipment are designed for use with Schedule 40 PVC casing. The bottom of the casing is closed with a slip cap. In the United States, this casing is typically supplied in 20 foot lengths with "bell-end" sockets molded at one end to receive the straight "spigot" end of the next casing section. Other sizes and forms of casing may be used but will require modification of associated installation items. Magnetic casing materials must not be used in conjunction with the flux-gate magnetometer compass option.

Joining of PVC casing sections is done using a solvent glue. A primer is used to clean and etch the surfaces to be joined before the glue is applied. Low temperatures can significantly degrade the quality of a solvent joint, as can the presence of water on the joint surfaces. If temperatures are below 0 degrees C, a low temperature solvent glue should be used. More expensive screw-joint casing can be used as an alternative.

Installation of the casing, except in the shallowest holes, requires filling the casing with water, sometimes drilling fluid, to negate the buoyancy of the casing column thus allowing the casing to be pushed down into the fluid filled borehole, usually by hand. In addition, fluid inside the casing equalizes internal and external pressures, preventing the collapse of the casing due to external fluid pressure in deep boreholes (greater than 100 m).

Attempting to push empty casing into a fluid filled borehole with the weight of the drill rig causes casing to "snake" in the borehole, making accelerometer installation more difficult, as well as increasing the risk of damage to the top of the casing section being forced down or by telescoping an uncured glued joint.

Joining PVC casing by the use of screws in conjunction with gluing is not recommended, due to the potential for protrusion through the interior wall and subsequent damage to the cable during installation, as well as providing a path for leakage of water out of the casing following installation. If screws are used, only stainless steel screws set partially through the casing should be used. Pilot holes should be drilled in the casing after gluing to prevent fracturing of the casing during screw emplacement.

Grouting

Grouting the well casing involves filling the annular space between the casing and the borehole wall with a suitable slurry of cement or clay. For borehole accelerometer installations it is critical that this process is done with care, to ensure that the casing is well-coupled to the native soil or rock.

The grout is pumped into place through a small diameter pipe, usually a 25mm (1 inch) galvanized steel called a “tremie tube”, lowered into the borehole between the casing and the borehole wall. When the end of the pipe reaches the bottom of the borehole, drilling fluid is circulated through the tremie tube to establish a clear path for the grout, and to clean the bottom of the borehole of any settled material. The grout is then pumped down to the bottom of the borehole, where it displaces drilling fluid out of the top of the borehole. The pumping may be done by the pump on the drill rig, or by a separate grout or concrete pump. When the drilling fluid is completely displaced and grout is flowing from the top of the borehole, the pump is stopped and the tremie tube withdrawn, disassembled and cleaned. Many U.S. municipalities require that the volume of grout placed be recorded and that it meet or exceed the volume calculated for the annulus. In some deep boreholes, grout will be placed in several separate loads or "lifts" to reduce the pressure exerted on the pipe by the liquid grout, as discussed later. This is usually scheduled as one lift per day.

Local codes usually require a sanitary seal of cement grout in the top 15m of a well, and seals between all aquifers penetrated by the well. The other areas may be filled with sand or gravel, but it is generally cheaper just to fill the entire annular space with cement grout. This will also make the eventual abandonment of the well (which can require another permit) much simpler.

Common grouting practices primarily center on the use of cement and water (“neat cement”), although the slurry may also contain sand, bentonite clay, or hydrated lime in certain situations. For downhole installations a mix of 400kg (20 U.S. sacks) of Portland cement type A or B per cubic meter of grout works well. Addition of 5kg of bentonite clay per cubic yard will ease the pumping of the grout into deep boreholes.

It is important to recognize that cement grouts exert greater collapse pressure on casing than water or drilling fluid. Installing grout 60m at a time for Schedule 40 PVC pipe provides a safety margin against casing collapse for the added effect of softening of the pipe by the heat of cure of the grout.

Other methods of placing grout, for example through a one-way valve in the bottom of the casing, are sometimes used but are generally considered to be less reliable. Be sure that the drilling contractor is completely comfortable with whatever method is to be used.

7.4.6.4 Geotechnical/Geophysical measurements

The primary motivation for installing downhole accelerometers is to increase understanding of the contribution of site response to the earthquake ground motion. Often the measurements of site response will be accompanied by analytical studies. Detailed understanding of the subsurface geology and soil/rock properties is necessary for such analytical studies. A good example of the kinds of site characterization data needed for strong-motion site response studies can be found in the documentation of the project "Resolution of Site Response Issues in the Northridge Earthquake – ROSRINE" (http://peer.berkeley.edu/news/2001spring/rosrine.html).

The basic site geology provides the primary description of the site. Information obtained during drilling (through observation and soil sample collection) will augment any prior geological knowledge of the general area. Normal laboratory testing of soil samples (disturbed or undisturbed) will confirm soil/rock types. Borehole and surface geophysical measurements can also assist in determination of site geology.

In addition to the site geology, dynamic soil and rock properties are needed for modeling of earthquake site response. The primary modeling properties are density, dynamic modulus, and damping (Q-value). The latter two properties are nonlinear functions of strain. These properties are obtained by laboratory testing of undisturbed samples and by one or more surface or borehole geophysical measurements of shear-wave velocity.

This Chapter gives a brief overview of the most common geological and geophysical measurements used in conjunction with borehole accelerometer installations to determine site geology and dynamic soil/rock properties.

Literature search

In most populated areas there will have been previous geological studies of the region and perhaps even local environmental, ground water, or planning studies. These can contain a wealth of information that will assist in site response studies. Planning for a borehole accelerometer installation should include a thorough literature search for such previous studies.

Potential sources of information on a regional basis are government geological or natural resources agencies. An example is the U.S. Geological Survey. For local studies, sources of information are the local government planning agency, local universities, private water companies, and even local water well drilling companies. A literature search can be a very inexpensive source of information on site geology and even subsurface soil and rock properties.

Pre-installation geophysical studies

Before site selection and borehole drilling, geophysical methods can be used to obtain a more detailed understanding of the site geology and subsurface properties. A good review of methods for site characterization is found in ASTM Standard D420-98 "Guide to Site Characterization for Engineering, Design, and Construction Purposes" and in ASTM Standard D6429-99 "Standard Guide for Selecting Surface Geophysical Methods" (see http://www.astm.org). For borehole strong-motion array applications, common methods are:

- seismic reflection;
- seismic refraction;
- resistivity profiling;
- cone penetrometer.

Seismic reflection and refraction are two techniques for using surface measurements to determine the seismic wave velocity structure of the subsurface geology. Both use a surface source of energy (mechanical or explosive) and instrumentation for measuring travel times of seismic waves at various distances from the source. Inverse analysis of these travel times provides an estimate of the seismic wave velocities of soil and rock layers. These methods can provide a cost-effective determination of general soil/rock layer properties, bedrock depth, and water table depth over a wide area.

Resistivity profiling is another surface technique for measuring the electrical properties of the subsurface geology. The electrical field from a surface AC or DC current source is measured at several locations. Inverse analysis is then used to estimate the resistivity of the subsurface soil or rock. This method can assist in both shallow (< 100 m) or deep (> 100 m) geological studies of a site.

The previous methods have all been noninvasive surface techniques. Initial geological studies of a potential borehole accelerometer site can also include the invasive techniques of cone penetrometer studies. These allow detailed soil/rock type determination at a specific location. A cone penetrometer (a metal probe pushed into the soil) can also obtain information about shallow (< 30 m) soils. Exploratory drilling can also be used in these initial site characterization studies.

Lithology logging

An experienced geologist should be present during drilling to determine the soil and rock classification. This is done by observing the drill cuttings, the samples, and the action of the drill rig. A good procedure for such lithology logging exists in the ASTM Standard D5434-97 "Standard Guide for Field Logging of Subsurface Explorations of Soil and Rock" (see http://www.astm.org).

Laboratory testing of soil samples

Samples obtained during drilling are useful in determining the soil type and soil properties. Basic geotechnical soil properties can be determined by simple laboratory testing, including:

- moisture content;
- dry density;
- LL/PL; and
- void ratio (porosity).

These simple soil measurements can be performed by most commercial or university soil laboratories.

Dynamic laboratory testing, however, requires a much more skilled and specialized laboratory and very high quality undisturbed samples. Dynamic properties of primary interest for earthquake site response analysis are soil shear modulus and material damping ratio (in shear) and their variations with:

- shear strain;
- effective confining pressure;
- loading frequency;
- loading duration; and
- number of load cycles.

Dynamic testing should be performed using triaxial resonant column, simple shear, or torsional shear methods. Appropriate strain ranges for earthquake response studies are 0.0001% to 0.1%. Appropriate frequency ranges are <1Hz to 200Hz. Further details of dynamic testing can be found in the book Soil Behaviour in Earthquake Geotechnics by Ishihara (1996) and other textbooks on soil dynamics.

Borehole geophysical measurements

There are many geophysical measurements available for characterization of the soil and rock properties in a borehole. These can measure chemical, electrical, radiation, and mechanical properties. All require specialized instrumentation and a skilled, experienced field geophysicist.

The chemical, electrical, and radiation properties are generally not of interest in an earthquake site response study, except as they are useful in determining soil and rock types. Sometimes resistivity and natural gamma emission measurements in an uncased borehole (before installing PVC casing) can be useful in determining boundaries of clay, sand, and rock layers

Of particular interest to site response studies are the mechanical properties of the soil and rock, primarily the P-wave and S-wave velocities versus depth (velocity profile). Borehole methods for velocity profile measurement are:

- downhole (vertical seismic profiling);
- crosshole; and
- suspension.

All three methods use a mechanical or electromechanical source to produce seismic waves, and one or more sensors (generally geophones) and a recording system to measure the induced ground motion. Details of these methods can be found in the book by Kenji Ishihara (1996).

For the downhole test, an impulsive energy source at the surface near the borehole top produces seismic waves which propagate radially. These can be either P waves or SH waves, depending upon source configuration. One or more sensors are installed in the borehole at known depths. The source and sensor signals are recorded, and the travel time of the first wave arrival is measured as a function of depth. The instantaneous slope of the travel time vs. depth curve is the reciprocal of the wave velocity at that depth.

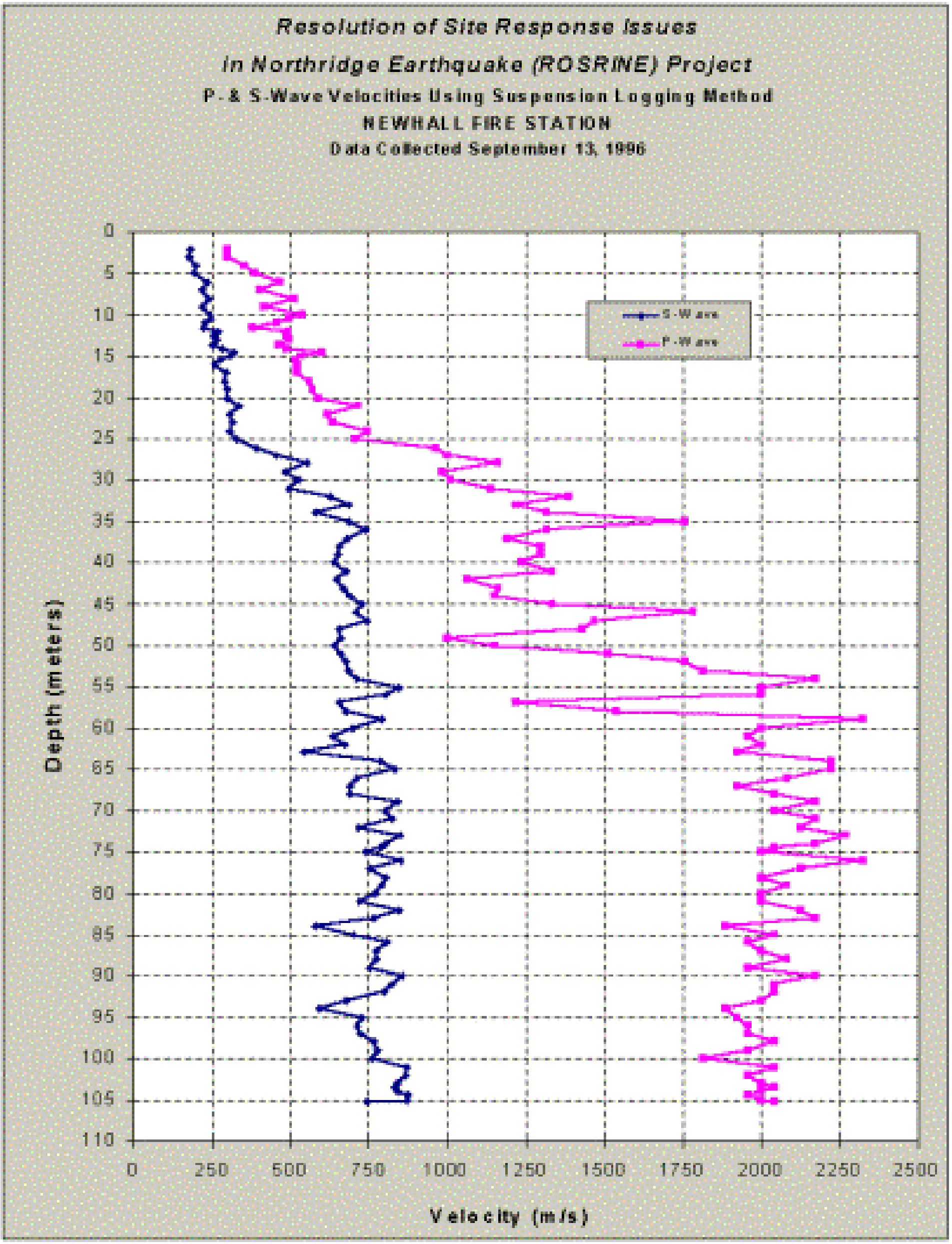


Fig.7.70 Velocity profiles for P waves (red curve) and S waves (blue curve) at a strong-motion site.

The crosshole test requires two or three adjacent boreholes separated by known distances. A source is installed in one borehole and receivers in the others, all at the same depth. The travel time of the generated seismic waves between boreholes is measured, and the velocity calculated by dividing the separation distance (at depth) by the travel time. This method requires careful control over the source and receiver depths, and detailed measurement of borehole separation versus depth. Both the downhole and crosshole methods are normally performed in cased boreholes. The suspension method, however, can be used in either cased or uncased boreholes. It consists of a single probe about 5 meters long, with an impulsive source at the bottom and two sensor sets ("receivers") near the top, separated by 1 meter. The source transmits energy through the borehole fluid to the borehole wall where it is transformed into both P and S waves. These are detected by both receivers, and the difference in arrival times is measured. Dividing the 1 meter separation by the travel time differences gives the P- and S-wave velocities for the 1 meter interval between sensors. Fig. 7.70 is a plot of a velocity profile measured with the suspension method.

7.4.6.5 Installation procedure

Depending on the goals and the operational environment of strong-motion installations there exist different guidelines for site selection, instrumentation and installation, e.g., those published by the Consortium of Organizations for Strong Motion Observations Systems (COSMOS) for urban or advanced national seismic strong-motion reference stations. These guidelines are available via http://www.cosmos-eq.org/publications. This section describes the careful installation of a downhole strong-motion sensor, its orientation, operational checkout, evaluation period, coupling/locking, and documentation/reporting. Accompanying this procedure will be a procedure for the installation of surface sensors, surface cabling, recording station, and other infrastructure, which have been discussed in more detail in earlier sections of 7.4.

Sensor installation

After completing functional tests of the sensor, the wellhead box, the cables and recorders, and calibrating the internal compass, the borehole package can be installed. The following procedure assumes a standard installation of a Kinemetrics FBA-23DH sensor with glass beads or gravel, and the internal compass for orientation. Installation for other downhole strong-motion sensors will be similar.

If not already done, the borehole should be filled with clean water to within 6m of the top. Filling completely will make installation easier since the water gives the cable near- neutral buoyancy, allowing a single person to handle the weight. In any case, consideration must be given as to where the displaced excess water will go when the package and cable are lowered into the hole.

This is the main reason a drain should be provided for the wellhead box, even though it is sealed from weather, and also why sufficient slack surface cable should be provided in the wellhead box to allow the contents of the wellhead box to be temporarily moved out of the way. In a sealed system, it would be best if the drain were sealed off after performing this function, to prevent moisture from entering the wellhead box after installation is complete. If the borehole has already been checked, the package can be lowered smoothly using the cable, being careful not to allow the cable to slip away. Fig. 7.64 shows this procedure in action. It is good practice to have a second person feeding the cable to the person lowering the package.

If the borehole has not been checked previously, care should be taken to "feel" for any constrictions in the casing which could signal trapping of the package. If such is felt, it is wise to move slowly, and then try coming back up every meter or so until the obstruction is passed. Check the total depth of installation by using the depth markers provided on the borehole cable (if available). Continue until the sensor is resting on the bottom of the borehole.

Orientation

This procedure assumes an internal compass in the sensor package. Once the sensor package has reached the bottom of the casing, apply power to the compass and rotate the package using the cable until the desired orientation is reached. Feed slack cable into the casing to help hold the sensor in position. Allow the package to rest on the bottom to get a steady reading, and measure the accelerometer offsets. Record the offsets carefully.

The acceptable DC offset depends on the final gains expected to be used with the system. If possible, it is desirable to keep the offsets to less than 25 millivolts. To accomplish this, compensating offsets will usually need to be applied to counteract the combination of residual factory offsets and vertical misalignment of the casing at the bottom of the borehole. In other words, if an offset of +150 millivolts is recorded for the horizontal sensor oriented east at the bottom of the hole, then when the package is removed to the top, the offset for the same sensor must be mechanically adjusted so that -150 millivolts is added to whatever the offset is before the adjustment. This must be done carefully so that the package orientation doesn't change from the beginning of the adjustment to the end. This is where some sort of test fixture is helpful to hold the package steady. This procedure may need to be repeated in order to get it right. In fact, expect to repeat this procedure once more after 30 or 60 days of operation before installing the backfill material, after the sensor has adjusted completely to the temperature at the bottom of the borehole. This requires opening the sensor package which can be difficult in field situations. Requiring the driller to produce a vertical borehole within a predetermined tolerance can often avoid this.

Operational checkout

Once the package has been installed and oriented with acceptable DC sensor offsets, one should connect the recording system and check for proper sensor operation. This operational checkout should follow manufacturer’s procedures, and results of the system test should be compared with the factory reference test.

Evaluation period

It is recommended that the array be operated for at least 30 days and as much as 60 days prior to installation of the backfill material. This period is needed to eliminate any initial startup problems, and allow the sensors to achieve steady state temperature response. During this period, the sensor package will rest at the bottom of the borehole. While this is inadequate coupling for large earthquakes, it should prove adequate for small events.

Preamplifier gains in the recording system should be set 10 to 100 times higher than normal in order to record as many small events as possible during this initial test period. Data should be reviewed, and the sensor removed and checked if any problems or questions arise.

Coupling/Locking

Once the downhole accelerometer has functioned properly for a period of 30 to 60 days, it is time for installation of the coupling or locking device. If a permanent locking method (i.e., grout or cement) is to be used, one should carefully install the locking material without disturbing the sensor orientation. If a wedge-type, pneumatic, or hydraulic locking system is used, it should be tightened to final specifications. If sand, gravel, or glass bead backfill is used, proceed with backfilling. Resist the temptation to pull on the cable afterwards to confirm the security of the system. It is possible to shift the package enough to disturb the orientation, and not be able to get it right without pulling it out, or you could lose backfill material to the bottom of the borehole. It is better to trust the process, and assume the material is in position. The proof is in the results.

Documentation/Reporting

Excellent documentation is very important to preserve the details of construction and installation for better interpretation of the data. Most important is the proper organization and use of calibration data. It is suggested that a formal Commissioning Report be created to preserve this installation information. Photographic documentation is also important. All documentation should be preserved along with the data for use in future data analyses.

7.4.6.6 Costs

A borehole strong-motion array can be quite expensive when all the needed work is considered. Besides the cost of instrumentation, there are the planning, preparation, site studies and installation costs. One could omit some of the planning and site characterization costs (this is often done), but at a significant cost in understanding of the resulting strong-motion data.

Costs will vary considerably in different parts of the world. With this proviso, below is a commercial cost estimate for a representative borehole strong-motion array with one borehole at 100 m depth and one surface sensor. The year 2000 costs in US$ in the U.S./California are:

- Instrumentation (one borehole accelerometer, one surface accelerometer, one 6-channel seismograph) - $20,000;
- Downhole sensor cable - $4,000;
- Array infrastructure (power, enclosures, communications, etc) - $10,000 ;
- Planning and initial studies (includes one seismic refraction line) - $10,000;
- Borehole preparation - $15,000;
- Geotechnical/Geophysical Studies (includes lab testing of soils) - $15,000;
- Array construction and installation - $10,000;

TOTAL COST = $84,000.

7.4.6.7 Special references and websites related to strong-motion installations, measurements, data analysis and use

Reports, Guidelines and Workshop Summaries of the Consortium of Strong Motion Observation Systems (COSMOS), available under http://www.cosmos-eq.org, e.g.:

Anonymous (2006). Workshop 2: Guidelines for installation, operation, and data archiving

and dissemination.
Anonymous (2005a). Guidelines and recommendations for strong-motion record processing and commentary. COSMOS Publication CP-2005/1, 36 pp.
Anonymous (2005b). Effects of strong-motion processing procedures on time histories, elastic, and inelastic spectra. COSMOS Publication CP-2005/2, 46 pp.
Anonymous (2004). Invited Workshop on record processing guidelines.
Anonymous (2001a). Guidelines for installation of advanced national seismic system strong-motion reference stations, 45 pp.
Anonymous (2001b). Urban strong-motion reference station guidelines – goals, criteria and specifications for urban strong-motion reference stations. 5 pp.

Other sources

Earthquake Engineering Field Investigation Team (EEFIT) (1993). EEFIT field investigations: Objectives and methods, leaflet.
Guide to Site Characterization for Engineering, Design, and Construction Purposes, ASTM D420-98, http://www.astm.org
Guidelines for Determining Design Basis Ground Motions, Report RP3302, March, 1993, Electric Power Research Institute, Palo Alto, CA.

7.5 Marine seismic observation (M. Shinohara, K. Suyehiro, and H. Shiobara, 2011)

7.5.1 Deep ocean environment, required logistics, sensors and data recording

7.5.1.1 Introduction

In this section, we describe the logistical, legal, environmental and technical requirements and conditions to be considered and met by an observer who attempts to acquire seismic data from the sea floor. Currently, most of earthquakes with magnitude (M) > 4.5 can be detected anywhere in the world including the oceans (e. g., http://earthquake.usgs.gov/). Satellite altimetry data show us the large-scale seafloor topography (bathymetry) of tectonic features such as the oceanic ridges, trenches, and transform faults, which can be compared with global seismicity. Based on these general pictures, an observer can design seismic experiments to look into the heterogeneous structures of different tectonic provinces or locate and analyze background microearthquakes or aftershock sequences in the wake of major off-shore earthquakes, and so forth. We are motivated to use marine observations by the inhomogeneous distribution of land-based stations and insufficient azimuthal coverage of seismic sources and structural-tectonic features to be investigated. Such data resolve systematic biases in derived parameters and models better than data from only land-based seismic observations. Because the oceanic plates recycle through the Earth's crust and mantle through time, there are many fundamental problems to be studied. There are often important gains and it is sometimes necessary to make specific observations on the seafloor rather than from land, or in combination with land-based seismic networks. Examples of gains from including seafloor observations include: achievement of more complete azimuthal coverage, higher spatial resolution and accuracy in earthquake locations and in source mechanisms studies, and in tomographic velocity or attenuation models. Seafloor observations avoid contamination or complications from data sampled over too large a distance and across major heterogeneities.

7.5.1.2 Access

For research purposes, most Ocean Bottom Seismograph (OBS) operations are temporary operations spanning from several to a few hundred days across a spatial scale from 10 to 1000-km. To work in the marine environment, one must first be able to bring the OBSs to the desired locations, then install them there, and to recover them after the mission is finished. This is done by ocean going vessels. Dropping OBSs from a helicopter has been done but recovery requires a boat. If the instrument needs to be positioned at a precise location or requires a special installation scheme such as burying the OBS, one needs extra methods such as utilizing an ROV (remotely operated vehicle) to reach the seafloor or a submersible with robotic functions.

The ship

Depending on the size and the weight of each OBS, the maximum number of OBSs that can be put on board will be restricted. Experiments close enough to shore that the transit time is short may use a smaller boat and deploy groups of instruments during several short cruises. The availability of a ship is an important condition. Ships may be obtained either through application to organizations managing research vessel operations, by open competition through a proposal review system or if you have your own funding, by charter of a commercial vessel. Usually a management body will do the scheduling of the ship and one will need to adjust one’s schedule to fit the ship schedule. In the case of a chartered vessel, one may have more control, but the ship’s capabilities must be carefully looked at in the light of requirements and costs.

The ship must have the capacity to store all the OBSs away from severe vibration and temperature changes that could affect the seismograph system performance. Recently, we have sought to keep onboard work to a minimum and to keep the instruments inside their pressure housings. The instruments can be calibrated by using a calibration coil or applying an electronic test pulse (see Chapter 5, sub-chapter 5.6), and the stored data read without opening the cases. However, there could be situations where one needs to refurbish OBSs, so one needs a clean and dry lab with appropriate space and access to the deck. Such a lab could be a container lab that can be brought to ship for the experiment.

Active controlled source OBS experiments using an airgun array and hydrophone streamer to simultaneously monitor the reflected seismic waves require a ship’s crew trained in this type of operation, and a vessel able to run in a straight line at a constant speed across the ground. Such methods are common in the oil industry, but less common in the academic research world. Details will not be given here, but in general, there is the mechanical system to tow the airguns and the streamer, a pneumatic system with an air compressor system sufficiently powerful to shoot the airguns at the desired pressure (100-150 kg/cm^2), and repetition rate (10s of seconds), an electrical system to control the shooting sequence and to log the sequence and to record the data from the streamer. All these have to be precisely controlled in time and location, usually utilizing the Global Positioning System (GPS). In the case to use a large ship, an antenna position of the GPS system must be considered. Handling high air pressure equipment requires extra safety considerations.

Ship capability
Once one knows the OBSs can be put onboard, the other things to consider are the electrical, mechanical, and Internet Technology (IT) specifications on the ship one plans to utilize to service the instruments. Electrical voltage and frequency (and its accuracy) are some elementary factors to know. If the ship is used for both launching and recovering from the sea a free-fall pop-up package, one will need to discuss with the ship operator how to conduct these operations. One may need more than one method depending on the sea and wind conditions and so widen the margin for successful operations. The release into the water and the capture from the water are the times when things may go wrong such as unwanted impact of the instrument into the ship's hull.

GPS is available on every research vessel, but you will want to know how to obtain the data in digital format including timing information. Keeping accurate time on a ship has been a challenge for many centuries, but is now solved to microsecond accuracy by satellite (GPS) technology. The ship must also be equipped with an accurate depth measurement system. Recent swath bathymetry data are desirable for choosing the drop point of the OBS and so avoiding locally steep slopes that may not let the seismic sensor in the OBS be leveled. Existing bathymetric maps of an area can be used to pick locations for OBSs if the map was made with GPS navigation. GPS based bathymetric maps have an accuracy of better than 100 m, whereas maps based on older data may be too poorly navigated to be useful for choosing OBS locations. Even with a map, checking with a deep echo sounder to be certain of the depth before the OBS is deployed should be attempted.

Communication to OBSs is done by sending and receiving acoustic signals from the ship. Sometimes it becomes difficult to maintain this communication link because of ambient noise, particularly from the ship's engine. Testing and understanding the communication link in various situations is an important practical knowledge to have for successful recovery of OBSs.

Applying for and sharing ship time
Applying for and sharing ship time is different in each country. There is an international database of ocean research vessels where one may find websites of interest (http://www.pogo-oceancruises.org). After getting a successful proposal through peer review and the proposal is accepted, one may find one is required to share a cruise with other research groups or that one has been allotted less than the desired number of cruise days. In such cases, one must prioritize to achieve ones goals within the plan. Usually there will be a chief scientist assigned for such coordination well before the cruise. Unlike on land, there may be scientists from different disciplines such as physical and chemical oceanography or marine biology on a cruise. Even within the solid Earth sciences, there could be geomagneticists, geologists, etc. One may need to explain and demonstrate the importance of your science.

Legal matters
It is necessary to know under which jurisdiction lies the area of your interest (see http://www.un.org/Depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm）.
Generally working in the open sea poses no problem for scientific research except that one needs to comply with international rules protecting the environment. If it is within your territorial waters or within your EEZ (Exclusive Economic Zone), you must notify your own country's authorities. If it is within foreign countries' EEZs, permission must be sought through proper channels (which may be your funding agency). It is important to remember that it may require 8 months or more for permission to be either granted or denied. If EEZs are not well defined due to territorial disputes, you may not be able to conduct any

experiments. Clarifications will require consultation with your Foreign Ministry. There could be different conditions to be met in order to conduct seismic observations in these waters on a case-by-case basis. Difficulties may be encountered in conducting active source experiments due to environmental reasons. Relevant information should be available from the managing body of the research vessel. If the vessel enters foreign waters, then one must follow export/import rules for that country, and also the security export rules for your country of origin.

Environment

Keeping marine ecosystems healthy is recognized as being more and more important. One should not pollute the ocean nor significantly influence the ecosystem. OBS observations should not pose much of a problem in this respect. When conducting an experiment, one may be required to negotiate with fishermen through respective authorities. Unlike commercial companies who may pay compensation to the fishermen for obstructing their work, scientific researchers have traditionally negotiated agreements allowing them to conduct experiments subject to certain time and space limitations but without paying compensation. This means one must know the fishing seasons for different groups of fishermen working in the area of interest. There could also be military operations in the area of one's interest, and one should consult with pertinent authorities such as the Coast Guard. Shipping lanes can be noisy for seismic observations. The best weather window should be sought to avoid stormy, windy, or foggy seasons.

7.5.1.3 Sea water and unconsolidated sedimentary layer

Any OBS on the seafloor has a sea water layer above it so that corrections for topography are required when analyzing data. The water layer at the seafloor cannot be considered a free surface and needs to be appropriately treated unless one is only interested in traveltimes (e.g. Shinohara *et al*, 1994; Thorwart and Dahm, 2005). For controlled source experiments, where shots occur at the sea surface, how the seismic ray travels in the water column can be important. The sound velocity in the water column has a depth profile that changes geographical area and season and is mainly controlled by lateral and vertical variations of water temperature and salt content. For example, water temperatures may be very different in the same latitudes, e.g. due to the warm Golf stream in the Atlantic or the cold streams on the west coast of North America, or when going along an E-W profile from the Mediterranean Sea with 4.5% salt content to the Azores with about 3.5%. Including these considerations in modeling ray paths rather than assuming a constant velocity layer in the water column leads to more accurate structural models.

An unconsolidated sedimentary layer is almost ubiquitous at the ocean bottom. This layer, which can be from a few hundred meters to a few km (or more in some cases) in thickness, must be treated appropriately in data analysis. The P velocity is only slightly faster than the velocity in the seawater in this layer because the pore water dominates the sediments, but the layer is capable of shear wave transmission. There can be a rapid velocity increase with depth as the pores are squashed. OBS data cannot distinguish this layer very well since all refracted phases travel nearly vertically in this layer to the OBS. Resolving how the shallow sedimentary layer varies in space may require that reflection seismic data be acquired over the OBSs. Usually the top of the igneous crust does not run parallel to the seafloor bathymetry as sedimentation occurs after formation of the crust.

7.5.1.4 Noise

The quality of data from the seafloor stations is lower than that of data from most land stations because of the seafloor's much higher noise environment. The ocean surface generates microseisms (Longuet-Higgins, 1950) that at some frequencies may be much stronger than magnitude 6 earthquake arrivals at teleseismic distances (Webb, 1998). Understanding the nature of seismic noise at sea floor is important to understanding seismic observations on and below the sea floor. Unfortunately, noise is also generated by the interaction of seawater flow with the seafloor or with the seismometer at the sea floor. The flow at the bottom of the ocean can degrade long-period performance at 10 sec and longer by directly tilting the seismometer or by deforming the surrounding media (Webb, 1988). The noise amplitudes from tilting can be larger than the amplitudes of most long-period teleseismic phases especially on horizontal-component records. For examples, characteristics of long-period noise in the Atlantic and Tyrrhenian Sea have been obtained using hydrophone, pressure gauge and seismometers (PMD) (Dahm *et al*., 2006). Seismometers in boreholes into the sea floor, present the best environment to study the nature of seismic ambient noise at the sea floor by avoiding flow noise (Fig. 7.71). Crawford *et al*. (2006) showed a results that the seismic noise in an unsealed borehole is larger than that on the sea floor by removing tilt noise due to fluid flow from the data from the 1998 Ocean Seismic Network Pilot Experiment off Hawaii. Their result indicates that cementing of seismic sensors in a seafloor borehole is essential to reduce a seismic noise in a seafloor borehole.

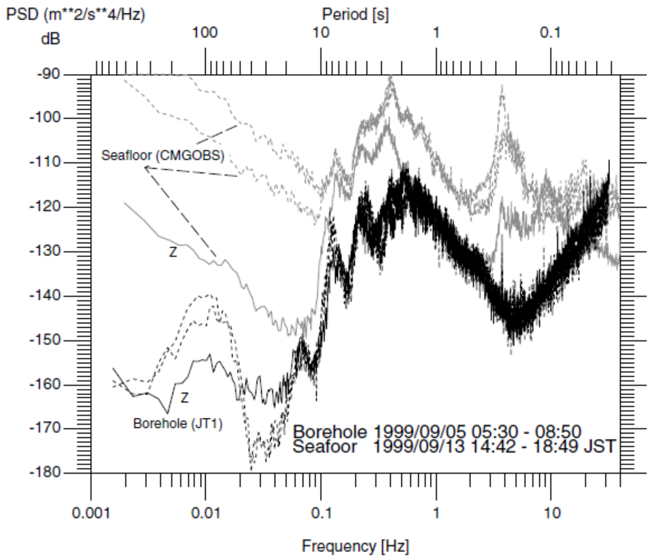


Fig. 7.71 Difference of typical noise power spectra in a borehole installation and a seafloor installation near the borehole of site JT1 (see Fig. 7.80). The seafloor observation is noisier than that in the borehole and the horizontal components are much noisier than the respective vertical (Z) components (after Araki *et al.*, 2004).

In 2000 and 2001, state of the art borehole broadband seismometers were installed in the northwestern Pacific Basin (WP-2) and the Philippine basin (WP-1) (Shinohara *et al.*, 2006). The depths of sensors are 561m and 460 m below the seafloor. The seismic data from the WP-1 and WP-2 seismological observatories enable the study of broadband seismic noise in the frequency range from 3 mHz to 50 Hz in the northwestern Pacific over an observation term covering more than one year of continuous recording. Temporal changes in ambient seismic noise within deep-sea borehole can be analyzed in depth using this data (Fig. 7.72). The noise level as a function of time and period for vertical and horizontal components of the WP-1 and the WP-2 observatories were obtained. The major advantage of borehole observatories is that there are little or no temporal change in noise levels for periods longer than 10s. It is found that the noise levels in the vertical component at the WP-1 reach -180 db (rel $(m/s^2)^2$/Hz) for time-periods between 10 s and 100 s, much lower than noise levels for instruments on the seafloor. In contrast, small temporal variations (maximum fluctuations of 10 dB) in noise levels for periods about a few seconds are seen, which can be correlated with the seasonal variability of ocean microseisms (see Chapter 4).

The WP-1 observatory recorded relatively large noise levels in summer and fall at periods of 4 - 8 s. The vertical component of the WP-2 observatory has minimum noise levels about -145 db, which is relatively high noise level. The high noise level of the vertical component of the WP-2 may be due to damage during installation of the sensor. The noise levels in the horizontal components of WP-2 seismometers are -160 db for periods between 10 s and 100 s and thus lower than that of the vertical component. The records from the WP-2 observatory reveal high noise levels in a period range of a few seconds during winter, which is thought to be the mean stormy season which also generates the largest ocean microseisms observed on land-based seismic stations. For both the vertical and the horizontal components of both the observatories, the noise levels are close to the New Low Noise Model (Peterson, 1993) near 10 s period. In general, the peak in the noise spectrum near a period of 100 s in measurements taken at the seafloor or in a shallow-sea borehole is due to deformation of the seafloor by ocean gravity waves (Webb, 1998). Araki *et al.*, (2004) reported that installation of a seismometer in the basement rocks minimize the effects of the ocean gravity waves. Because all the seismometers of the WP-1 and WP-2 observatories were installed into basaltic basement, there is no peak due to the ocean gravity waves.

The horizontal component records of the WP-1 observatory have larger noise levels than the vertical component records for periods longer than 20 seconds. There is a possibility that the horizontal sensors in the WP-1 seismometer have a coupling problem. In contrast, the noise level of the vertical component for periods longer than 10 seconds in the WP-2 observatory is larger than those of the horizontal component. The vertical sensor of the WP-2 observatory may be damaged. In Fig. 7.72 we have plotted representative noise power spectra measured at the WP-1 and WP-2 borehole sites, together with respective spectra from 3 other borehole sites in the Western Pacific (JT1; for positions, also of WP-1 and WP-2 see Fig. 7.80), the North Atlantic (OFP), and the Central Pacific off-coast Hawaii (OSN1). The spectra of the WP-1 and WP-2 is estimated from one hour record for quite season of each site. Note that all borehole installations have almost the same noise level.

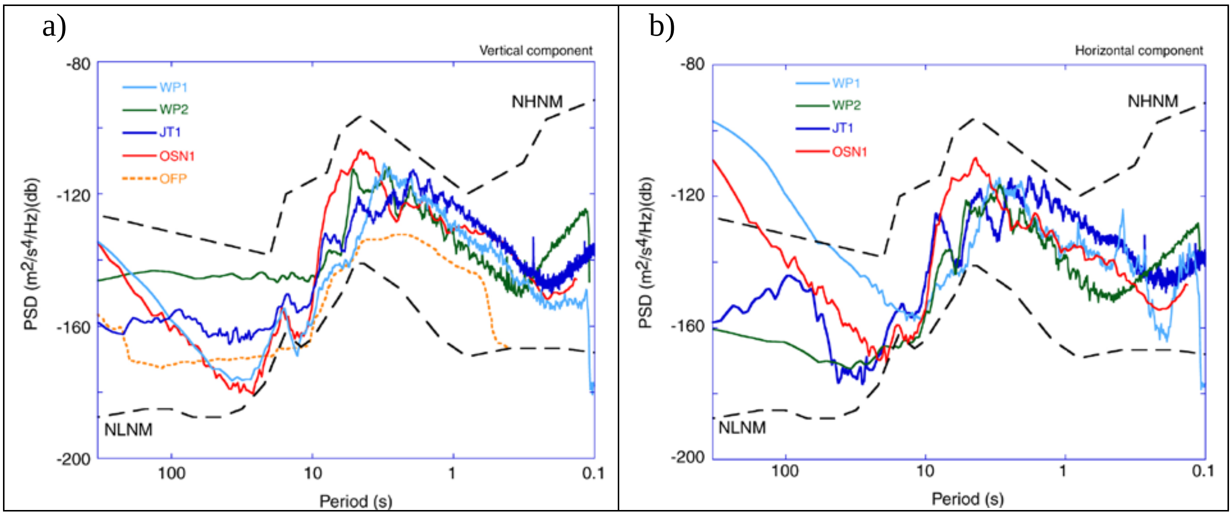


Fig. 7.72 Comparison of ambient seismic noises from seafloor borehole installations: a) for vertical component; b) for horizontal component. WP-1, WP-2 and JT-1 denote borehole

observatories in the western Pacific. OFP and OSN-1 indicate borehole observatories in the North Atlantic Ocean (Montagner *et al.*, 1994) and the Pacific Ocean off Hawaii (Stephen *et al.*, 1999), respectively. NHNM and NLNM indicate the New High Noise Model and the New Low Noise Model by Peterson (1993), respectively.

7.5.1.5 Sensors

Seismic sensors for land stations are selected according to types of observations needed. The possible choices of sensors is not very wide for OBS observations because the requirement for low power consumption and the limited volume available for the sensors within most pressure capsules. For more general information on the theory, principle design and calibration of seismic sensors and their technical specifications the contributions by E. Wieland (Chapter 5 and DS 5.1).

Geophones
The 4.5-Hz exploration-type geophone is mainly used for local and regional earthquake observations. This geophone is also useful for seismic exploration using airguns and explosives. The geophone has the advantage of no power-consumption and small size. The geophone measures signals from approximately 1 to 100 Hz, with a corner frequency at 4.5 Hz. They have a flat response to ground velocity for frequencies greater than this corner frequency. A typical example is the Mark Products L-28. The 2Hz geophone such as the Mark Products L-22 is also used, however, the volume of this sensor unit is larger.

Active type (moving coil)
There are also active seismic sensors (Lennarts) on the market which extend the flat velocity output frequency range of 4.5-Hz geophones electronically (see DS 5.1). This sensor has the advantage of small size for its corner frequency of 1Hz. Because land observations for local earthquakes often use 1-Hz sensors, this sensor is useful for combined analysis of land and OBS data.

Active type (liquid)
The seismometer (PMD) (see DS 5.1) is a three-component seismometer having a fairly broad frequency band response. The velocity amplitude response is essentially flat from 25 to 0.03 Hz with useful output down to 0.01 Hz. The PMD seismometer sensors are robust and require no leveling or clamping. This makes them particularly suitable for sea floor observation. The inertial component is a liquid—water with potassium iodide in solution—in a container which includes permeable grids that serve as cathode and anode. Between the grids a small bias voltage (<0.7 V) is applied, resulting in an ion current. Vibration of the instrument produces changes in the motion of the ionized liquid through the electrodes, resulting in a modulation of the ion current. These modulations are the output signal of the seismometer. From observation, the power spectral density instrument noise level is about -150 dB $[(m/s^2)^2/Hz]$ at frequencies between 30 and 10 mHz. This is ~13 dB higher than for a CMG-1T broadband seismometer. Below 30 mHz, the performance deteriorates (Shiobara and Kanazawa, 2009).

Servo-type accelerometer and MEMS
The up-to-date servo accelerometer or MEMS is also suitable as a seismic sensor for sea floor observation, because they have high resolution and stability. The primary advantage for this type of accelerometer is its compactness, however the power consumption is large and the noise floor of these sensors is slightly higher than the New High Noise Level (Peterson, 1993;

see also Chapter 4). However, because the accelerometers can measure accelerations larger than 1 g, these are useful for studying the source processes of large nearby earthquakes.

Broadband sensors (CMG-1T, CMG-3T)

Broadband (BB) sensors have a flat response to ground velocity from approximately 0.01 to 50 Hz. Typical examples are the Guralp CMG-1T or CMG-3T seismometer (for specifications see DS 5.1) with frequency range from 0.03 to 50 Hz. The BB sensor provides more information compared to conventional short period (SP) seismometers. However, BB seismometers are more expensive, more fragile and more difficult to deploy, operate, and maintain. Data retrieval and analysis can be more complicated than for geophone sensors. BB seismometers use active feedback to the sensor mass and so require a stable, large power supply. In addition, the seismometers may require control of mass centering so that the recorder must continuously monitor the status of the sensor and autonomously control the sensor. Since BB sensors record microseisms over a much wider period range their raw output signal contains much more seismic noise than signals from a short-period geophones. This means that the recorder needs to have a larger dynamic range for A/D conversion.

The vertical sensor in the Guralp sensors is a modified Lacoste type, and the horizontal sensor is an inverted pendulum. The inertial mass is a boom (a solid machined beam) supporting a transducer coil. The vertical sensor mass is supported by a prestressed triangular spring to support its weight and has a natural period of ~0.5 s. The horizontal sensor mass is centered by an unstressed flat triangular spring and has a natural period of ~1 s. The effective mass of each sensor is ~180 g. The springs are connected to the frames with a temperature compensating wire that minimizes the effect of temperature variation. A compact design is achieved chiefly by the short stiff springs and short boom. The adjustments required for operation consist of leveling the boom of the vertical sensor and tilting the bases of the horizontal sensors to center the mass movements in their equilibrium positions. These are made by small (1 cm in diameter and 3 cm long) direct current (DC) motors operating gear mechanisms to tilt the horizontal sensor bases and to apply a small extra force to the vertical sensor's boom. Before and during the installation, the instrument may be subjected to severe motion that can damage the mass support hinges. Therefore, the masses must be locked securely in their frames so that the hinges can be released after installation. This operation is performed by a small motor-driven clamp, which is controlled by a recorder.

The sensors employ feedback to expand their bandwidth and dynamic range. The sensor's response is determined by the characteristics of the feedback loop. The mass position is sensed by the capacitive position sensor. The voltage from the sensor, which is proportional to the displacement of the mass from its equilibrium position, is amplified and fed to a coil on the mass. The current in the coil forces the mass to its equilibrium position. With a high loop gain, motion of the mass is essentially prevented; the feedback voltage is then a measure of the force and, thus, the acceleration applied to the mass. The block diagram of the feedback system is shown in Fig. 7.73. The system velocity response is identical to that of a conventional long-period sensor with a velocity transducer whose natural resonant period is 360 s with a damping factor of 0.707. The velocity output (flat to 100 Hz) is low-pass filtered (<50 Hz) before digitization. The mass position output can be used for periods longer than 360 s.

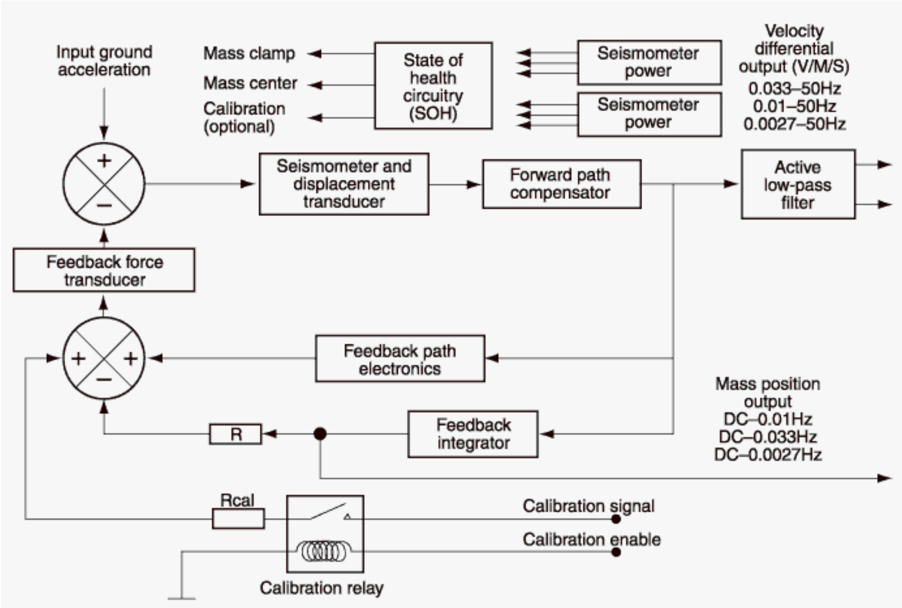


Fig. 7.73 Example of block diagram of broadband sensors. Frequency ranges depend on product model (Guralp model).

Levelling of sensors

It is more difficult to level seismic sensors on the sea floor because humans can not access the sensor in the OBSs directly. Although some sensors do not require leveling, most seismic sensors do. There are two types of leveling systems; passive and active leveling. The passive leveling system uses a gimbal mechanism that levels under the force of gravity and strong damping from placing part of the gimbal mechanism in a high viscosity liquid such as silicone grease. Although this system has a simple mechanism, it is difficult to level sensors with natural periods of more than one second with sufficient accuracy. For broadband sensors, an active leveling system is used. The active system also has a gimbal mechanism, however, the gimbal mechanism is driven by micro-motors and fixed by brakes. The leveling system has two tiltmeters and sometimes also a compass. The Central Processing Unit (CPU) reads the tilt of the sensors and controls the motors to level the sensors. The system levels the sensors before starting the observation and after deployment on the sea floor,. In addition, the system checks the level daily. Both passive and active leveling systems typically work over angles of up 20 degrees.

7.5.1.6 Data recording

The necessity of low-power compact systems

All autonomous OBS systems require a low-power recording unit, because the power-supply will be limited. For example, the power consumption of a recorder developed by Earthquake Research Institute (ERI), the University of Tokyo, is less than 0.3 Watts. The system must be compact due to the limited capacity of most pressure vessels. All system units including the sensors, recording system and battery pack must be accommodated within a sphere type pressure vessel of about 50cm diameter.

A/D conversion

Modern data acquisition systems are based on continuous integration and oversampling in combination with carefully designed digital low-pass filters. In most modern seismic recording systems, a Delta-Sigma-Modulator is used for analog to digital conversion (ADC). The Delta-Sigma ADC needs much electric power, so that it is difficult to use in the conventional way for OBS systems. For some systems the ADC is turned on intermittently to reduce the electric power consumed by the OBS recording system. Some systems still use ordinary successive approximation register A/D converters and sample-and-hold techniques to reduce power-consumption.

Data storage media (Tape, MO, HD, Memory)

In OBS observations with continuously recording instruments, an OBS collects about 30-50 M Bytes of data per day for a 3-component station with 100 Hz sampling rate. Early OBS recorders were based on the Analog Direct Recording method in order to record this huge amount of data. Later quarter inch tape and other cassette tapes and in the early 1990s, Digital Audio Tape (DAT) was often used (Shinohara *et al.*, 1993). At present hard disks (HD) are common as mass storage technologies in OBS systems. HDs are reliable, low-cost and robust and allow for much faster data access than other media for mass data storage like tapes. However, the power consumption is significant when the disk is spinning up. An advantage of hard disks as opposed to other magnetic- and opto-magnetic media is that they are encapsulated and less sensitive to rough and dusty environments. For connecting the hard disk to the recorder, many systems use the Small Computer System Interface (SCSI) others use the Integrated Drive Electronics (IDE) interface. With respect to data transfer, SCSI systems are more reliable than IDE systems, however the latter are less costly. Memory systems such as Compact Flash card (CF) and Secure Digital memory card (SD) now have sufficient capacity for data storage and are rapidly replacing other media in OBSs. For example, the capacity of SD now exceeds 32 GB, which is enough for continuous recording for a few months. These memory systems have no moving parts, and are quite robust.

7.5.2 Ocean Bottom Seismograph (OBS)

7.5.2.1 Introduction

There are two types of equipment for seismic observations in marine environments: pop-up type OBSs and cabled OBSs. The pop-up type OBS is a stand-alone system. These are deployed on the sea floor by free-fall from a research vessel, and are recovered by pop-up after releasing an anchor. The advantages of the pop-up OBS are low-cost for the equipment and observations and that they can be deployed anywhere. However, the data are obtained only after recovery of the OBSs (Fig. 7.74). At the present, pop-up OBSs can be classified by type of sensor, and observation term. Cabled OBS can send data in real-time and power is supplied from land. This means there are fewer limits for power consumption by the OBS. Real time data is required for earthquake monitoring in the context of alarm and disaster mitigation schemes. The disadvantage of cabled OBSs are the high cost. As examples both types of OBSs, as developed and used in Japan, are described in the following in more detail. For technical specifications see section 7.5.4.

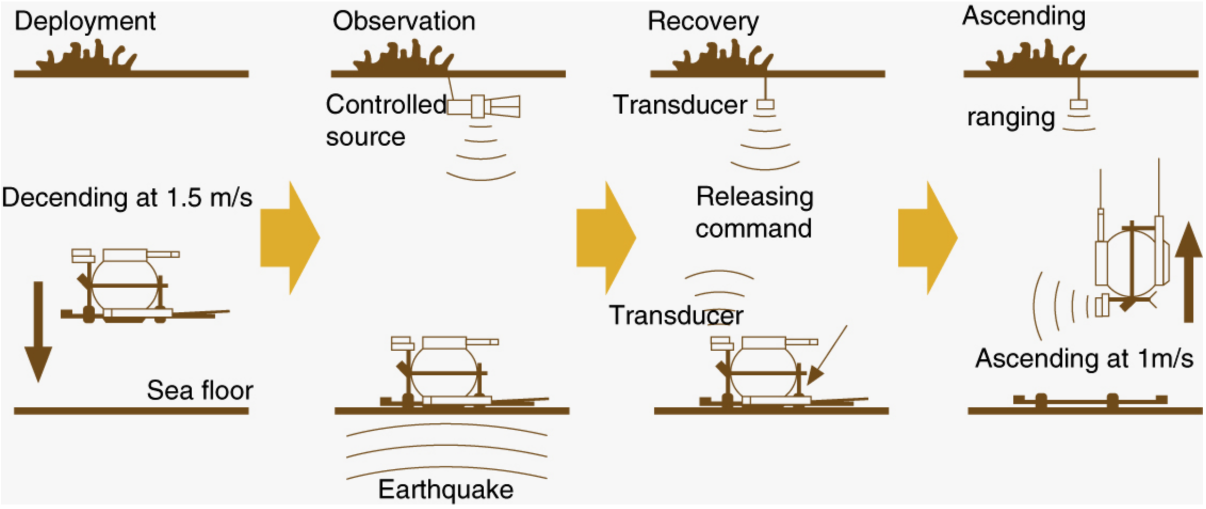


Fig. 7.74 Schema of seafloor observation using pop-up type OBS.

7.5.2.2 Pop-up type OBS

Short-term OBS

In recent years, ocean bottom seismometers (OBSs) have been used to obtain crustal and upper mantle seismic structure and the distribution of earthquakes. Before the 1990's, the OBSs used in these experiments worked with analog recording tape. One of the advantages of analog recording OBSs was that they could record data continuously for more than two weeks. A disadvantage of the analog OBSs was their limited dynamic range per recording channel.

A digital recording short-term OBS (ST-OBS), which has the same recording length of time as the analog OBSs, was developed to obtain higher quality data. The ST-OBS consists of one pressure vessel, an acoustic release system, a radio transmitter, and a strobe light (Fig. 7.75). The pressure vessel (glass sphere) contains sensors, recorder and battery cells. The design of ST-OBS, except for the digital recorder, is the same as the analog recording OBS. First, a commercial portable digital audio tape (DAT) recorder was used to store seismic data to obtain long-term recording at low power and low cost. Next, 2.5 inch SCSI hard disk was used to store data. The use of hard disks has allowed a longer recording period. The latest recorder has memory media such as Compact Flash memory (CF) or SD memory. The first practical digital recorders had 16-bit A/D converters and thus a dynamic range of 96 dB. Nowadays, 24-bit A/D converters are common which allow a dynamic range of up to 144 dB. Recorders usually record 3 or 4 channels of data continuously at 100 or 128 Hz sampling rate. A real-time clock (RTC) with an accuracy of order 10^{-8} controls timing of the recording system including the timing of A/D conversion, the starting of data acquisition at a predetermined time, and so on. The electric setup and monitoring of the recorder inside the sealed vessel, including adjustment of this RTC, can be performed by connecting a computer to the recorder through the pressure vessel. A timing clock pulse is output to outside of a pressure vessel allowing comparison of the RTC of the recorder to a time standard provided by a GPS receiver. The data on the recording media is retrieved after recovery an OBS.

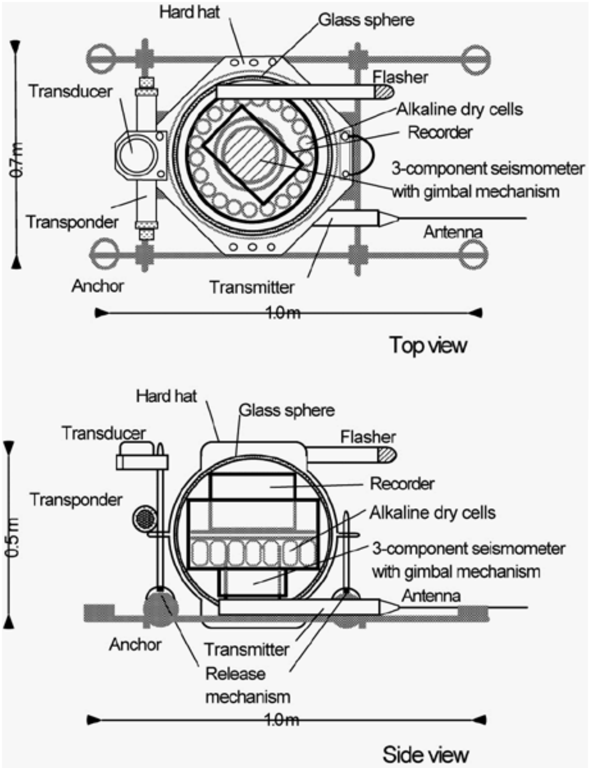


Fig. 7.75 Top view (upper) and side view (lower) of ST-OBS layout. The glass sphere housing instruments has a positive buoyancy and is released by acoustic command. External mechanical configuration has not changed from that of the analog recording OBS (after Shinohara *et al*., 1993)

Long-term OBS

Long-term OBSs (LT-OBS) were developed at ERI to observe earthquakes continuously on the sea floor over more than one-year. For the housing of the LT-OBS, a titanium-alloy sphere made in Russia with 50 cm diameter was selected, so as to avoid problems from corrosion of the pressure vessel (Fig. 7.76). The titanium-alloy vessel was tested for use at 6,000m depth before shipment from the maker. Lennartz's LE-3Dlite is used for the short-period sensors in this OBS operating with a velocity-proportional response in the frequency range between 1 and 80 Hz. Three component sensors are mounted on a leveling system. The leveling unit is equipped with two tiltmeters which have 0.1 degree accuracy. The outputs of the three seismometer components are amplified by a low-noise and low-power analog unit, and are converted to 22-bit digital signals continuously. The sampling frequency is either 200Hz or 128Hz. Data are stored in memory temporarily. When the memory is full, the data on the memory is transferred to Hard Disk (HD). Power to all electric circuits (CPU, sensors, leveling system, and HD) are supplied by lithium battery cells. Each cell has a power capacity of 30Ah. Although the number of battery cells depends on the intended duration of recording, approximately 50 battery cells are needed for one-year of observations. The LT-OBS is equipped with an acoustic release and communication system. The most important function of the acoustic system is to release a weight for recovery. After an acoustic release command is sent from a shipboard unit, the acoustic system on the OBS provides electric power to a weight release unit causing rapid electrical corrosion of the strap holding the weight. Another function of the acoustic system is communication between the sea floor and sea surface. The recording unit on the OBS can be controlled from the on-board unit, for example, starting or stopping recording, leveling the sensor, and checking the status of the recording unit. This type of LT-OBS is widely used for monitoring earthquake activity in Japan. At the present, approximately 200 LT-OBSs are in operation in Japan.

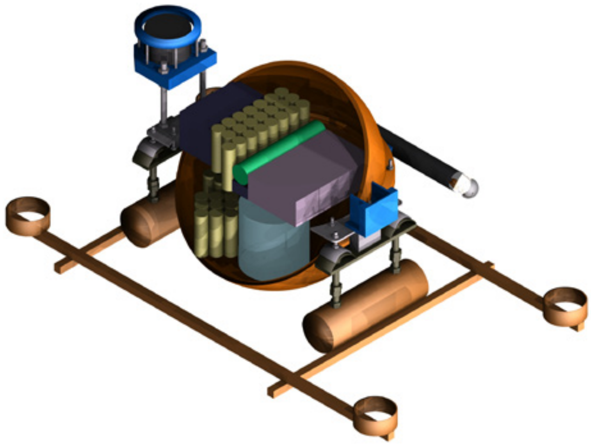


Fig.6 Perspective cutaway of the LT-OBS. The titanium-alloy vessel contains seismic sensor, recorder and batteries. The duration of recording of the LT-OBS reaches one year.

Broadband OBS

Based on long experience with the short-period OBS, a broadband OBS (BBOBS) has been developed at ERI as well. This OBS is equipped with broadband sensors. This system is also mobile, compact, reliable and easy to operate and enables long-term observations. These BBOBSs have been used since 1999, yielding good scientific results and offering more opportunities for observations, especially in the long-period range. The design of the BBOBS (Fig. 7.77) is quite simple, as all units are inside of a housing made of titanium. These BBOBS also use self pop-up for recovery. The key design points were low power consumption of the sensor and recorder including the precise RTC clock, and low weight for the OBS so as to maintain positive buoyancy despite the limited volume of the housing. The titanium-alloy pressure vessel has a diameter of 65 cm, which is slightly larger than the LT-OBS, as required to contain the BB seismic sensor with its larger volume and additional batteries needed to power the BB sensor. The sensor was specially made for our active leveling unit and it is possible to physically separate the mechanical part and the main electronic boards. When the BBOBS is deployed at the deep sea floor, the inside of the housing is an ideal operating environment for the sensor (and also the crystal-oscillator clock) because of small temperature variations experienced and absence of human activity compared to land observatories. The amount of the data stored is about 4 GB for one month if the sampling rate is 200 Hz for three components and when using a completely recoverable compression method. The quality of the data is described in a later section.

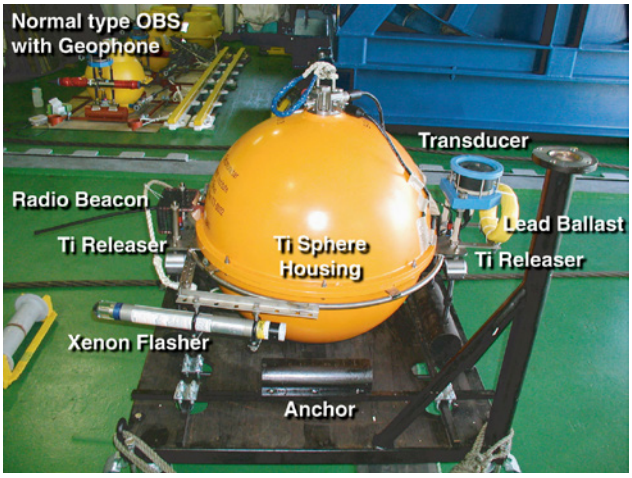


Fig. 7.77 Photograph of the BBOBS before deployment. The shape of the BBOBS is similar to that of the LT-OBS, however, the pressure vessel is larger than that of the LT-OBS due to sensor size.

Ocean bottom accelerometer (OBA)

To understand the characteristics of large earthquakes which occur in a subduction zone, it is necessary to study the asperities, where large earthquakes may occur repeatedly, from a close distance. Since a conventional OBS is designed for high-sensitivity observations, OBS records of large earthquakes which occur nearby are often saturated. A servo-type accelerometer is well-suited for recording large amplitude seismic waves. However it was difficult to use such an accelerometer in OBSs due to the large electric power consumption. Recently, a servo-type accelerometer with a large dynamic range and low-power consumption has been under development. Alternatively, one can use a larger size titanium sphere pressure vessel for the OBS and so contain many more batteries. For long-term sea floor observations of large earthquakes, a small three component accelerometer is installed into conventional long-term OBSs for acquisition of low-sensitivity (strong motion) accelerograms of the sea floor. For example, we use a compact three-component servo-type accelerometer with a weight of 53 grams as the seismic sensor. Measurement range and resolution of the sensor are 3 g and 10^{-5} g. The sensor is directly attached to the inside of the pressure vessel (Fig. 7.78). Signals from the accelerometer are digitally recorded to Compact Flash memory with 16 bit resolution and a sampling frequency of 100 Hz. The OBAs have been deployed several times and accelerograms obtained on the sea floor. One earthquake with magnitude of 7 was recorded by the OBA at an epicentral distance of approximately 20 km. The maximum acceleration reached 5.5 m/s^2. Continuous improvements are being made to the system to obtain better quality data.

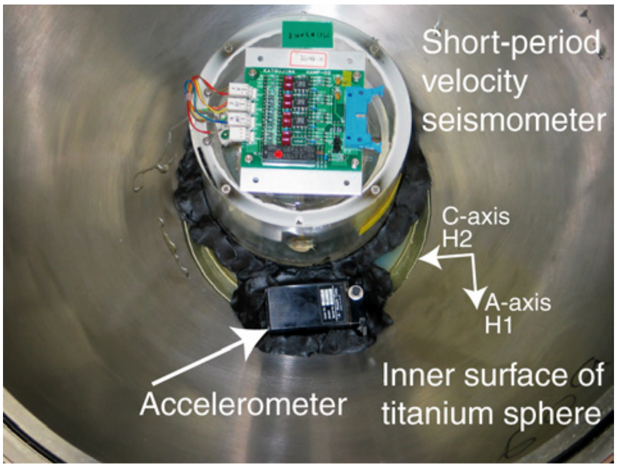


Fig. 7.78 Installation of the acelerometer to the inside of the pressure vessel (Type 1). The accelerometer was fixed beside the conventional three-component seismometer with gimbal mechanism with the same orientation (after Shinohara *et al.*, 2009).

7.5.2.3 Cabled OBS system

In this section some of the existing and planned OBS cabled systems are described. In Japan, a number of optical-cable linked ocean bottom seismic stations and tsunami stations have been deployed since the 1990's (Fig. 7.79). Cabled geophysical observation systems are deployed off Hokkaido, Sanriku, Boso, Izu, and Shikoku. In 1994, the Earthquake Research Institute, University of Tokyo deployed a cabled OBS network system around an earthquake swarm area off Izu. Data from three seismic sensors on sea floor are transmitted on-line by using optical fibers to a land station. In 1996, an ocean bottom geophysical observatory using a sea floor optical fiber cable was installed off Sanriku. The Sanriku system has three seismometers and two tsunami gauges. These data are transmitted to a land station in real-time by individual fibers. The sea floor optical fibers are buried in areas where the water depth is less than 1,000 meters to protect the cable from fishery activities. These systems provide integrated observation from both on land and under the sea. The disadvantages of the existing cabled OBS systems are their high cost and limited adaptability. Once the system is deployed, it is very difficult to add sensors for new observation. The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) is constructing a new cabled OBS system using wet-mate-able connectors. Sensors can then be replaced using a Remotely Operated Vehicle. The system will be deployed off central Japan where a huge earthquake is expected to occur. These existing systems are based on the technology of trans-ocean communication cables which need high reliability. However, since the existing system is so expensive, it is difficult to deploy many observation nodes for experimental use, for example when it is important to observe earthquakes using a spatially high density seismic network. Therefore a new cabled OBS system is being developed using Internet-Technology to lower the cost for spatially high density seismic observations (Kanazawa and Shinohara, 2009). This system is planned to be deployed in the Japan Sea during 2010.

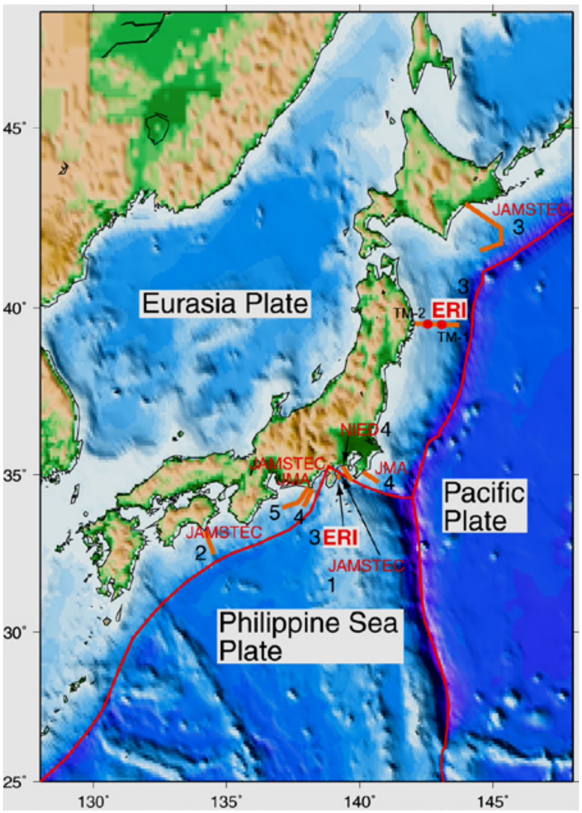


Fig. 7.79 Locations of cable OBS system for local earthquake observation around Japan. Numerals indicate the number of observation nodes for each system. Operating agents are also shown. Note that the existing cable OBS systems have a small number of observation nodes. TM-1 and TM-2 indicate positions of real-time tsunami-meter.

7.5.2.4 Ocean floor borehole system

The Japanese Ocean Hemisphere Network Project installed four borehole geophysical stations at three sites covering a period from 1999 to 2001 (Fig. 7.80). In 1999, two borehole stations (JT-1 and JT-2) were installed during Ocean Drilling Program (ODP) Leg 186 (Sacks *et al.*, 2000) and are located immediately above the inter-plate earthquake generation zone on the landward side of the Japan Trench. The JT-1 and JT-2 stations were installed approximately 50 km apart and have two broadband seismometers, a strainmeter and a tiltmeter for each station. In August 2000, during ODP Leg 191, the borehole seismological observatory WP-2 was successfully installed at ODP Site 1179 in the northwestern Pacific basin (Kanazawa *et al.*, 2001). Borehole seismic observatory WP-1 was installed in the west Philippine basin during ODP Leg 195 in April 2001 (Salisbury *et al.*, 2002). The WP-1 and WP-2 observatories each have two identical broadband seismometers (Guralp CMG-1TD). Together, these observatories can cover a large expanse of the northwestern Pacific in areas that comprise major gaps in the coverage provided by pre-existing global seismological observatories. At present, the data from these four borehole observatories are retrieved by ROV visits at an interval of about 0.5 - 1.5 year (Suyehiro and Mochizuki, 2002). Araki *et al.* (2004) have already reported on the JT-1 and JT-2 observatories and the characteristics of the geophysical data obtained from the JT-1 observatory.

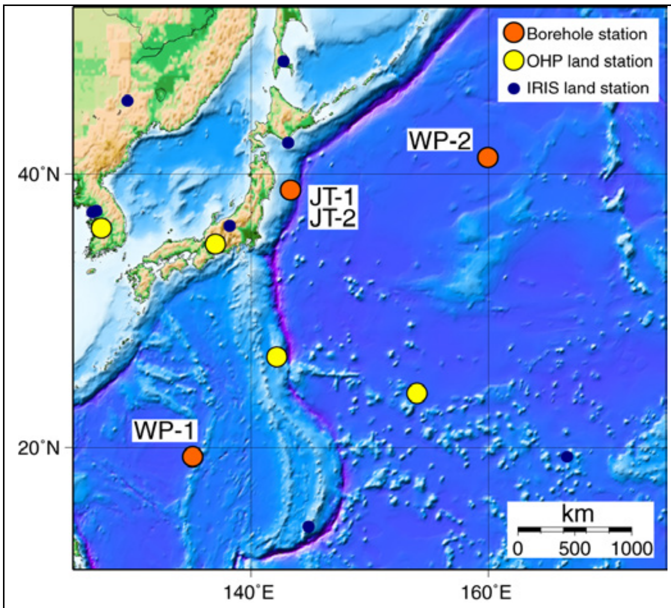


Fig. 7.80 Location map of broadband seismicstation coverage in the north-west Pacific. Small blue and yellow circles indicate land seismic stations, orange circles are seafloor borehole observatories, which were installed by drilling vessel. The JT-1 and JT-2 were deployed in 1999. The WP-1 and WP-2 observatories were installed in August 2000 and April 2001, respect-ively. These sea floor observatories successfully captured broadband seis- mic data for a few years.

7.5.2.5 Dealing with a multiple-OBS long-term dataset

As LT-OBS and BBOBS data became more available, a huge amount of the data is being obtained from these OBSs. One ST-OBS generates less than 100 Mbytes of data during a few months of observations. For one year of observation using LT-OBSs, the amount of the data becomes approximately 20 GB for each LT-OBS. A single array deployment for earthquake observations can use more than 20 LT-OBSs, so that the total amount of the data from the OBS network will be about 0.5 T bytes. The data collected by the OBSs are stored on 2.5 inch HD in a format which depends on the recorder. After the recovery, the data on each 2.5 inch HD must be copied to an ordinary computer using a data reproduction system. The data reproduction system requires a fast speed for data transfer and a huge capacity disk array. Usually, these features are obtained by using an up-to-date CPU and a disk array with a capacity of more than 1 T bytes with a fast interface (e.g. fiber connection).

For OBS observations, each OBS has its own clock. After the transfer of the data, time adjustments for each OBS record are required. The time difference between each OBS clock and a GPS clock is measured just before deployment and just after recovery. Because the temperature of sea water is constant on the deep sea floor, the crystal oscillator should also be at constant temperature on the seafloor. A linear drift in time to the timing offset of the crystal oscillator is assumed, and used to adjust the time stamp of the record to the correct GPS time. After the time adjustment, each OBS record is combined to construct multi-station files for the whole observation period. During this procedure, multi-station files with a time length of one (or a few) minutes are created for easy handling of the data. Time of multi-station files is continuous so that it is easy to make more longer multi-station file for picking up arrivals.

Because a huge number of files are generated as a result, a powerful computer with a large capacity disk array is also needed for this procedure. After that point, the data processing (e.g. event detection) is the same as for land seismic networks.

7.5.2.6 State of OBS activities

In Japan, the development of OBSs was started at the Geophysical Institute, and ERI of the University of Tokyo in 1970's, and now continues at ERI. These groups developed various types of OBSs for surveys of Earth structure and earthquakes observation (e.g. Mochizuki *et al*., 2008). A few universities have ST-OBS for seismic surveys and local earthquake observations. At present a few governmental institutes have ST-OBSs and are operating cabled OBSs. JAMSTEC has a few hundred ST-OBSs and a smaller number of LT-OBSs and BBOBSs. Their ST-OBSs are mainly used for seismic surveys (e.g. Kodaira *et al*., 2004).

The U. S. National Ocean Bottom Seismograph Instrument Pool (OBSIP) has provided instrumentation to support US funded research programs requiring OBSs beginning in 2000. The Lamont-Doherty Earth Observatory at Columbia University, the Scripps Institution of Oceanography at the University of California San Diego and the Woods Hole Oceanographic Institution each have developed and now maintain OBSs for the US OBSIP, including ST-OBSs, LT-OBSs and BBOBSs. The ST-OBSs in the OBSIP can record for about 2 months and use for sensors both geophones and hydrophones. Principal investigators at research universities can request the use of instruments as part of the standard NSF proposal process. Many experiments supported by OBSIPs have been carried out (e.g. Pozgay *et al*., 2009 for the MARIANA experiment).

The Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR) in Germany has both OBSs and Ocean Bottom Hydrophones (OBHs). OBHs were first developed and then OBSs were developed based on the experiences with the OBH. In 2002 a completely revised design was developed for the OBS system to enable the operation of either short period or broadband seismometers. The recording term of BBOBS is up to one year. In Germany, the Institute for Geophysics at Hamburg University and Alfred Wegener Institute in Bremerhaven have also developed and operate OBSs. These institutes are actively carrying out experiments (e.g. Dahm *et al*., 2002). The German Instrument Pool for amphibian seismology (DEPAS), which is operated by the Alfred Wegener Institute für Polar und Meeresforschung, Bremerhaven, uses Guralp CMG 40T (60 sec) sensors in titanium pressure cylinders (http://www.awi.de/en/research/research_divisions/geosciences/geophysics). At present, the DEPAS has a large scale facility of broadband OBS (80 instruments) (Friederich and Meier, 2008). Hamburg University and GEOMAR use SEND Geolon MLS data logger with a power consumption of 0.25 W, 21bit resolution at 50 Hz, and time accuracy of 0.5 ms/day.

The French Research Institute for Exploitation of the Sea (Ifremer) has approximately 20 ST-OBSs for wide angle seismic surveys. The OBS at Ifremer consists of identical recorders based on the GEOMAR data logger and also on their own mechanical design. The Ocean Bottom Instrumentation Consortium (OBIC) in UK comprises three well established academic institutions: the Universities of Durham and Southampton and Imperial College, London. The OBIC has about fifty LT-OBSs, which are mainly used for seismic structure surveys. In 2008, 50 OBSs recorded airgun signals in the source region of the 2004 Sumatra earthquakes, and 10 OBSs were re-deployed to record earthquakes for approximately one year (Barton *et al*., 2008).

7.5.3 Examples of seafloor seismic observations

7.5.3.1 Local earthquakes

One of the best examples of sea floor observations is that of the aftershocks of large earthquakes occurring in marine areas. On 25 September 2003 the great Mw8.3 Tokachi-oki earthquake occurred off Hokkaido, Japan. Four days after the mainshock, a deployment of twenty-nine OBS in the source region was started to study the aftershock activity of this event using a chartered ship with a size of 700 tons. From October 19-21, nine OBSs that had been deployed near the epicenter of the mainshock were recovered by a research vessel and the data used to obtain the distribution of aftershocks. Ten OBSs were redeployed at the same sites as the previous deployment to continue the aftershock observations. On October 18 and 19, eight OBSs were additionally deployed to enlarge the observation area. Consequently, the aftershocks were observed at forty-one sites including three cable OBS sites, and forty-seven pop-up type OBSs were used in total. All the OBSs at the sea floor were recovered by a chartered ship with a size of 700 tons from November 17 to 20. The observation area was 150 km x 100 km that covered the high aftershock activity, as estimated from the land seismic network. The station spacing of the OBSs was approximately 15 km in the trench region. In the landward area, OBS were deployed with a spacing of about 20 km because the aftershocks were estimated to occur in this region at depths deeper than 20 km (Fig. 7.81).

Two types of the digital recording OBS system were used. The 46 OBSs had both vertical and horizontal velocity sensitive electro-magnetic geophones with a natural frequency of 4.5 Hz and one BBOBS (Guralp CMG-3T). Accurate timing, estimated to be within 0.05 s, was provided by a crystal oscillator. All the OBS were a pop-up type with an acoustic release system. The OBS positions at the sea floor were estimated with an accuracy of several meters using acoustic ranging and ship GPS positions. The water depths at the OBSs were determined by the acoustic ranging and hypocenters were determined by using a three-dimensional velocity structure based on a seismic refraction study. According to the obtained epicentral distribution, the aftershocks occurred within the small slip region of the main shock. In addition, the epicentral distribution of aftershocks, except near the large slip region, was similar to that of the earthquakes occurring before the main shock. Although most land-based hypocenters, which included the data from the cabled OBSs, had depths of greater than 20 km, all hypocenters determined by the OBS network had focal depths around 20 km. P and S wave arrivals at seismic stations above a hypocenters are essential in order to obtain precise hypocenter positions. The OBS network satisfies this condition. All hypocenters located by the OBS network were shallower than those determined by the land network (Fig. 7.82) with most of the aftershocks occurring around 20 km depth. The aftershocks form a dipping plane toward the land. It is inferred that this plane shows the upper boundary of the subducting Pacific Plate. The position of the plate boundary estimated by the aftershock distribution is consistent with estimates by the past seismic surveys (Yamada *et al*., 2005).

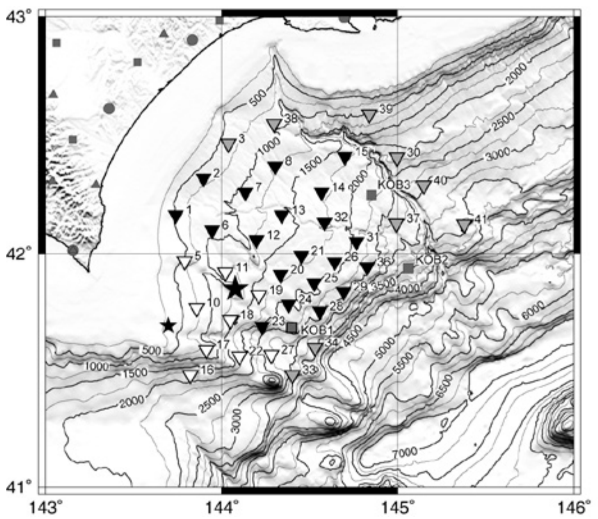


Fig. 7.81 Bathymatric map off-shore of SE Hokkaido with the positions of OBS used for the aftershock observation of the 2003 Mw8.3 Tokachi-oki earthquake. Inverted triangles indicate the positions of pop-up type OBSs, squares the positions of the cabled OBSs, numerals the site numbers, large and small stars the epicenters of the mainshock and the largest aftershock. Gray symbols in the land region show the positions of the permanent seismic stations (after Shinohara *et al.*, 2004).

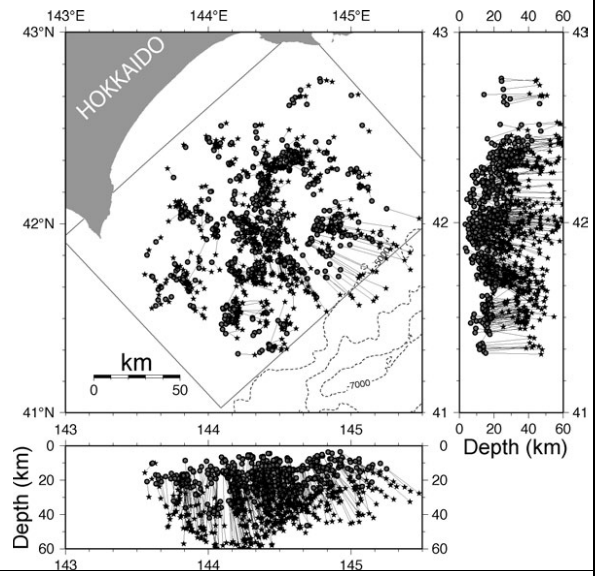


Fig. 7.82 Comparison of the distribution of Tokaichi-oki earthquake aftershock epicenter (upper left) and hypocenter positions in N-S and E-W projection (upper right and lower left) as determined by the OBS network (gray circles) and by the dense land network on the Japanese islands. Arrows relate the land network locations to the OBS locations (after Yamada *et al.*, 2005)

Simultaneous estimation of the hypocenters and 3-D seismic velocity models from the P- and S-wave arrivals of the aftershocks recorded by OBSs was performed (Fig. 7.83). The subducting plate is clearly imaged as a northwest dipping zone in which Vp is higher than 7 km/s. The aftershock distribution reveals that the dip angle of the plate boundary increases around 90 km from the Kuril Trench towards Hokkaido from less than 5 degree to 16 degree. The bending of the subducting plate corresponds to the southeastern edge of the rupture area. The island arc crust on the overriding plate has P-wave velocities of 6–7 km/s and a Vp/Vs of 1.73. A region of Vp/Vs greater than 1.88 was found north of the epicenter of the main shock. The depth of the high Vp/Vs region extends about 10 km upward from the plate interface. The plate boundary just below the high Vp/Vs region has the largest slip at the main rupture. A high Vp anomaly (~7.5 km/s) is found in the island arc crust in the northeast part of the study area. The rupture of the main shock terminated at this high Vp region (Machida *et al.*, 2009).

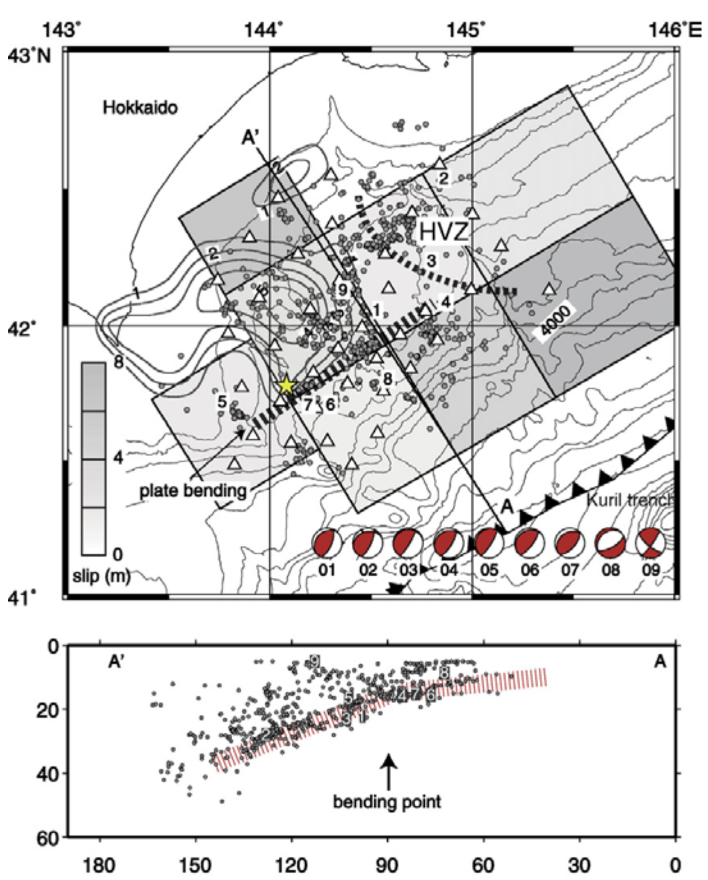


Fig. 7.83 **Top:** Distribution of 589 relocated aftershocks determined beneath the OBS network. The yellow star and the gray circles represent the epicenters of the 2003 Tokaichi-oki mainshock and its relocated aftershock hypocenters, respectively. Triangles denote positions of the OBSs. Focal mechanisms determined by JMA for the numbered aftershocks are shown at the lower left. Lower hemisphere projection is used. HVZ means the high P-wave velocity zone by the tomography with OBS data. The slip distribution of the main shock after Yamanaka and Kikuchi (2003) is shown by thicker contour lines. The tsunamigenic asperity of 1952 Tokachi-oki earthquake (Hirata *et al.*, 2003) is also indicated (gray regions). **Bottom**: Distribution of the relocated hypocenters projected on the vertical cross section along A-A'. (after Machida *et al.*, 2009)

7.5.3.2 Teleseismic events

To investigate the stagnant slab beneath the northern Philippine Sea, we have deployed a large OBS array over the 3 years between 2005 and 2008 (Shiobara *et al*., 2009). This was a key part of the "Stagnant Slab Project" (SSP) started in 2004 and running for 5 years, because these were the first direct and dense observations above this target area aimed at revealing the fine physical structure of the stagnant slab. The transition of the slab morphology along the Izu – Ogasawara (Bonin) – Mariana arc as shown by a global tomography is also a target of interest to be resolved in high resolution by this experiment. The observation area extended about 1000 km (N-S) X 2000 km (E-W), as shown in Fig. 7.84. The first, second and forth year’s cruises were performed by the R/V Kairei (JAMSTEC), and the third year’s cruise was done by a chartered ship. The number of BBOBS deployed was 12, 12, 15 for the first, second and third year observation periods, respectively. All of the BBOBS and OBEMs have been recovered successfully except for one BBOBS that did not come up to the sea surface.

From the noise study of all BBOBS stations, all components showed noise levels at periods around 10 s in the middle between the New Low Noise Model (NLNM) and the New High Noise Model (NHNM) according to (Peterson 1993). The vertical noise data were found to lie in this same middle level at longer periods, but the horizontal noise levels became then higher than the NHNM (see Fig. 7.85 for site T13). The main reason for this high noise level for the horizontal components is assumed to be caused by variations in the BBOBS's tilt due to the sea bottom currents. But, the lower bound of individual noise spectra used for the noise model reaches the NLNM between 10 s and 30 s in the horizontal component that shows the high noise level in the noise model (Fig. 7.85).

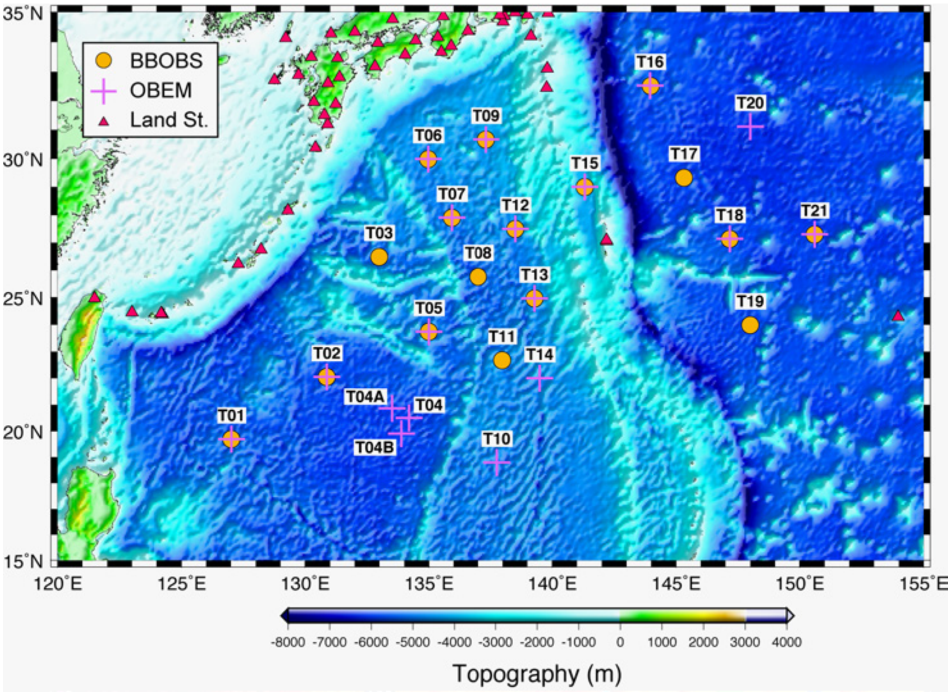


Fig. 7.84 Location map of BBOBS in the SSP. Orange circles and red triangles show BBOBS sites and land BB seismic stations, respectively.

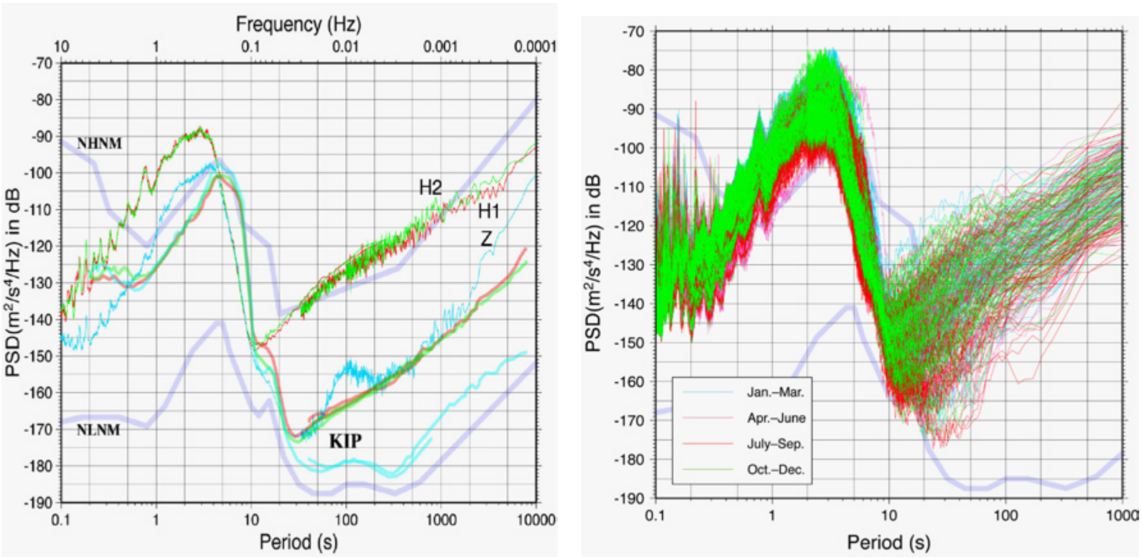


Fig. 7.85 **Left**: One noise model obtained for the BBOBS at the T13 site. Thin curves noted as Z, H1 and H2 correspond to the vertical and two horizontal components. For reference, the noise model of the island station at Hawaii (KIP) is also indicated as thick curves. **Right**: The noise spectra to be used for the H1 curve of the noise model. The lower bound of noise spectra reaches the NLNM that is also seen in two other components.

Results from the dataset from the first and second years of observation include surface wave tomography (Isse *et al*., 2009) and receiver function analysis (Suetsugu *et al*., submitted). The former revealed a better resolved upper mantle model for this area than has been seen before. The later study demonstrates clear differences in the mantle transition zone at the edge of the stagnant slab (Fig. 7.86).

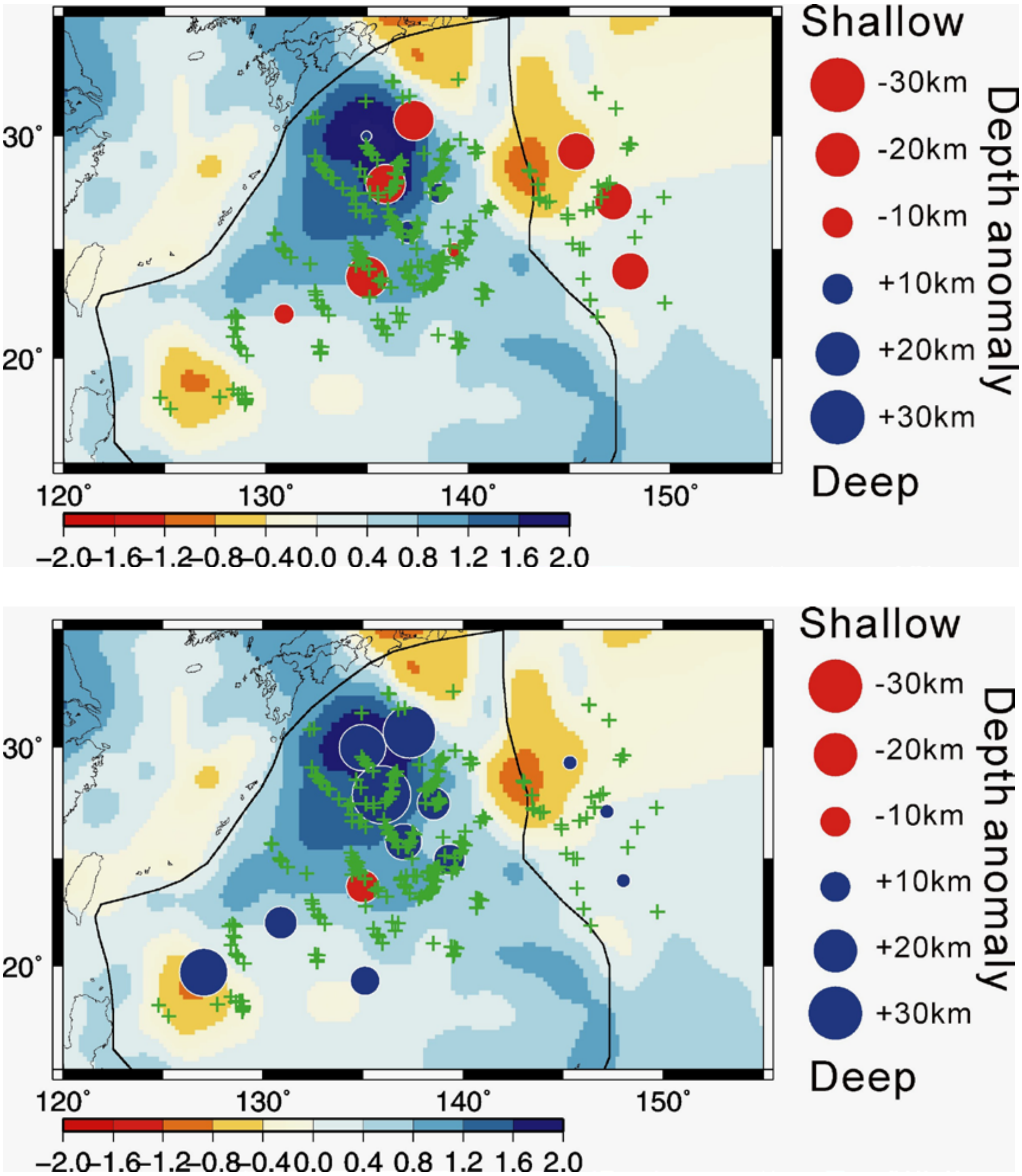


Fig. 7.86 Results of the receiver function analysis for each BBOBS site using two year long data of the SSP as indicated in red and blue circles. Green crosses indicate pierce points of Ps waves at each interface. **Top**: The depth anomaly for the 410 km interface of the mantle transition zone. **Bottom**: Same as the top figure but for the 660 km interface. The background map shows the Vp anomaly from the global tomography (Obayashi *et al.*, 2009) with the scale bar in % at the lower left of each figure. It is clear that the 660 km interface is deeper where the stagnant slab exists expressed as the high Vp anomaly.

7.5.3.3 Tsunami events

Three ocean bottom seismographs (OBSs) and two ocean bottom tsunami-meters (OBTMs) were deployed off Sanriku, northeastern Japan by the Earthquake Research Institute of the University of Tokyo. All data from the OBSs and OBTMs are transmitted to land in real-time. On 30 May 1998, a thrust-type earthquake (Mw 6.1) occurred off the Sanriku region. The two OBTMs, TM-1 and TM-2, which were installed at depths of 990 and 1563 m, respectively, about 80 and 100 km apart from the hypocenter, detected a small tsunami generated by this earthquake. with a peak-to-peak amplitude of only about 1.5 cm and a wavelet period of about 300 s (Fig. 7.87). The OBTMs had quartz-type pressure sensors with pressure resolution and full scale of 0.5 mm and 3,000 m, respectively, and a sampling interval of 100 ms. Hino *et al*. (2001) estimated reliable tsunami source parameters and showed that ocean bottom tsunami-meters are useful for studying plate subduction.

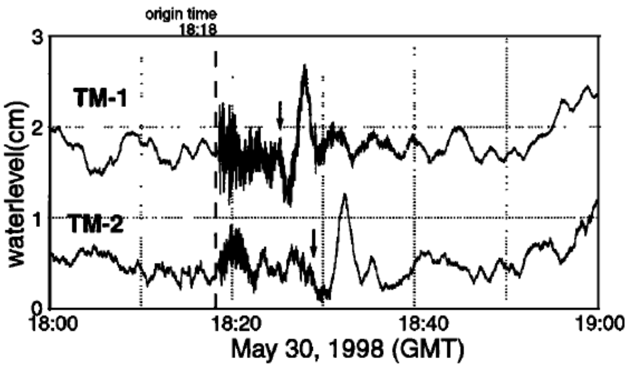


Fig. 7.87 Tsunami records obtained by the OBTM stations, TM-1 and TM-2. See Fig.9 for positions of TM-1 and TM-2. Ocean tide components were removed and moving average of 60 s length were applied (after Hino *et al.*, 2001).

7.5.4 Technical specification examples

Specifications of ST-OBS

Sensor : Tri-axis 4.5Hz~ (-3dB) (Sercel L-28 for ERI)
Recorder : 24bit, 100/200Hz sampling, 0.29W in average (HDDR5)
Data media : Firewire HDD (ex. 40GB, max. 4 drives)
Clock : Within the recorder, MCXO (<±0.1ppm, QEM77-AH)
Power : 6 Li cells (for 90 days obs.), DD size (3.9V, 30AH)
Transponder : Slant ranging, anchor release control
Anchor releasing : Forced electric corrosion of two thin Ti/Stainless plates
Housing : Glass sphere (Ø 432mm), 25kgw of buoyancy
Recovery aids : Radio beacon and xenon flasher (Novatech)
Dimension : 1.0m/1.0m/0.6m (width/depth/height)
Weight in the air : 80/40 kgw (with/without anchor)

Specifications of LT-OBS

Sensor : Tri-axis 1~80Hz (-3dB), 400V/m/s, 0.1W (Lennartz LE-3D for ERI)
Gimbal : Active leveling (≤20°)
Recorder : 24bit, 100/200Hz sampling, 0.29W in average (HDDR5)
Data media : Firewire HDD (ex. 40GB, max. 4 drives)
Clock : Within the recorder, MCXO (<±0.1ppm, QEM77-AH)
Power : 50 Li cells (for 356 days obs.), DD size (3.9V, 30AH)
Transponder : Slant ranging, anchor release/recorder control
Anchor releasing : forced electric corrosion of two thin Ti plates
Housing : Titanium sphere (Ø 500mm), 33kgw of buoyancy
Recovery aids : radio beacon and xenon flasher (Novatech)
Dimension : 1.0m/1.0m/0.7m (width/depth/height)
Weight in the air : 120/80 kgw (with/without anchor)

Specifications of BBOBS

Sensor : Tri-axis 360s~50Hz (-3dB), 1500V/m/s, 0.28W (Guralp CMG-3T for ERI)
Gimbal : Active leveling (≤20°) with fluxgate compass
Recorder : 24bit, 100/200Hz sampling, 0.29W in average (HDDR5)
Data media : Firewire HDD (ex. 40GB, max. 4 drives)
Clock : Within the recorder, MCXO (<±0.1ppm, QEM77-AH)
Power : 78 Li cells (for 400 days obs.), DD size (3.9V, 30AH)
Transponder : Slant ranging, anchor release/recorder control
Anchor releasing : Forced electric corrosion of two thin Ti plates
Housing : Titanium sphere (Ø 650mm), 70kgw of buoyancy
Recovery aids : Radio beacon and xenon flasher (Novatech)
Dimension : 1.0m/1.0m/0.8m (width/depth/height)
Weight in the air : 240/160 kgw (with/without anchor)

Specifications of OBA
Sensor : Tri-axis DC~ (-3dB), 0.2V/m/s^2, 0.72W (JAE JA-28GA for ERI)
Sensor installation : Fixing to pressure vessel
Recorder : 24bit, 100/200Hz sampling, 0.29W in average (HDDR5)
Data media : Firewire HDD (ex. 40GB, max. 4 drives)
Clock : Within the recorder, MCXO (<±0.1ppm, QEM77-AH)
Power : 120 Li cells (for 365 days obs.), DD size (3.9V, 30AH)
Transponder : Slant ranging, anchor release/recorder control
Anchor releasing : Forced electric corrosion of two thin Ti plates
Housing : Titanium sphere (Ø 650mm), 70kgw of buoyancy
Recovery aids : Radio beacon and xenon flasher (Novatech)
Dimension : 1.0m/1.0m/0.8m (width/depth/height)
Weight in the air : 240/160 kgw (with/without anchor)

Acknowledgments

The authors of Chapter 7 are thankful to Ahmed Elgamal, C. R. Hutt, Dieter Mayer-Rosa, Jamison Steidl, Rod Stewart and Peter Zweifel , for their reviews and suggestions which have helped to improve the original text. The non-native English-American contributors to this Chapter owe particular thanks to Rod Stewart for his careful English proof-reading of the sub-chapters 7.1 to 7.4. W. Hanka , author of section 7.4.4, also thanks M. Brunner (†) for many excellent ideas and carrying out the shielding experiments and K.-H. Jaeckel for very fruitful discussions around this topic.

The authors of section 7.5 on OBS wish to express thanks to Toshihiko Kanazawa, retired professor of marine seismology, Earthquake Research Institute of the University of Tokyo. Valuable comments from the editor of the NMSOP, Peter Bormann during two careful reviews and many suggestions made on the first and second draft helped to improve the paper. The authors also thank Torsten Dahm, Azusa Nishizawa and Spahr Webb for their critical reviews and recommendations and are particularly grateful to Spahr Webb for the troubles he has taken in polishing up the English draft.

Recommended overview readings

Havskov and Alguacil (2004 and 2006)

Isihara (1996)

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