Encyclopedia of Earthquake Engineering
DOI 10.1007/978-3-642-36197-5_195-1

Downhole Seismometers

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Synonyms

Borehole seismometers; Direct burial installation; Posthole seismometers

Introduction

This entry reviews the topic of downhole seismometers. The entry is split into three sections. The first section reviews the different types of downhole seismometers. The second section provides an overview of seismic noise sources and their impact on downhole installations. The last section discusses the downhole installation methods.

There are three main motivations for deploying seismometers in a downhole environment. The first is to provide quieter seismic noise environment to improve signal-to-noise ratios. The second motivation is to lower the cost of deployment of a seismic station. The third motivation is to reduce the environmental impact and land use costs by minimizing the physical footprint of a seismic station.

Downhole Seismometer Types

Seismometers can be categorized by the installation environment into three broad classes of instruments, surface (or vault) seismometers, ▶ ocean bottom seismometers (OBS), and downhole seismometers. Downhole seismometers are seismometers that are designed for installation below the surface, ocean bottom seismometers are designed for deployment underwater to depths of 7,000 m or more, and vault seismometers are designed for installation in seismic vaults at or near the surface. The construction of vaults is described in some detail in the "▶ Broadband Seismometers" entry.

Although these three classes of seismometers are markedly different in appearance, the internal sensing transducers and associated electronics are typically similar in design and performance. The difference is in the packaging and topology: in vault seismometers, the three axes are normally side by side, in downhole seismometers the axes are often stacked vertically, and in OBS seismometers either topology can be utilized. Typically, downhole seismometers are packaged in tall cylindrical stainless steel pressure tubes and are watertight to a depth of 50–1,000 m. Vault seismometers are normally not designed for continuous submersion in water. The diameter of a downhole seismometer is minimized to enable the seismometer to fit down narrow boreholes. The diameter of a vault seismometer is not as critical as a downhole seismometer, and vault seismometers are typically shorter and wider for stability (see Fig. 1).

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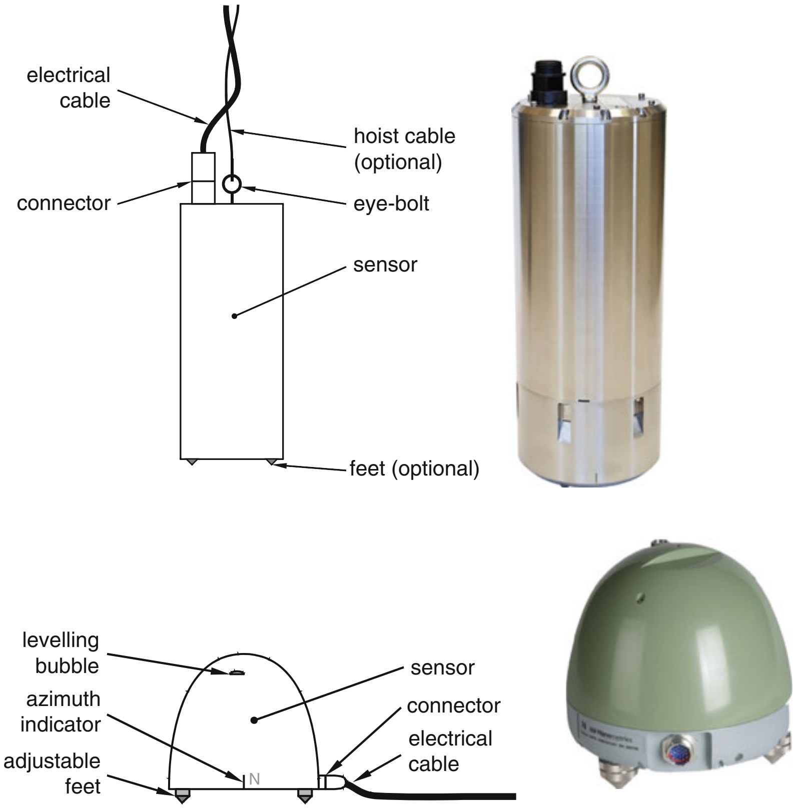

Fig. 1 Posthole and vault seismometers

Vault seismometers are usually leveled by hand using a reference bubble level and adjusting three leveling feet. Downhole seismometers are normally not accessible for manual leveling and have automatic leveling mechanisms where leveling is required.

Downhole seismometers can be further broken down into two different instrument types, namely, borehole seismometers and posthole seismometers.

Borehole seismometers are downhole seismometers that are designed for deployment in steel-cased deep boreholes. These seismometers typically include a holelock assembly as part of the instrument. A holelock is used to mechanically support and connect the seismometer to the borehole casing. It includes an actuator or a passive spring that pushes the entire seismometer against the side of the borehole with a substantial force. This force holds the seismometer rigidly in place and prevents the seismometer sliding down the hole.

A posthole seismometer is a downhole seismometer that does not include a holelock and is designed for direct burial or installation in shallower, uncased holes, known as postholes. A posthole seismometer is designed to be installed in sand at the bottom of a posthole. The sensor will typically also have three fixed feet, which can be useful in side-by-side testing on a pier, or placement at the bottom of a cased hole, as long as that surface is reasonably hard and level. These seismometers are designed for holes up to 50 m deep and may not have the underwater pressure rating of a borehole seismometer. Furthermore, a posthole seismometer's drivers and power supplies may not support the cable lengths required for a borehole seismometer.

A downhole seismometer can be a single-component seismometer, meaning that the seismometer only measures vertical motion or that it can be a three-component seismometer which measures vertical, north–south, and east–west motion. Three-component seismometers are also known as triaxial seismometers.

An important parameter in selecting a downhole seismometer is the self-noise level of the instrument. The self-noise of a seismometer defines the limit of the instrument's ability to resolve ground motion. The self-noise of a seismometer is often graphed with respect to the minimum earth noise as defined by the new low-noise model (NLNM) (Peterson 1993). Although a self-noise graph provides a comprehensive view of seismometer performance over frequency, the long-period performance of an instrument is typically the limiting parameter of the self-noise. This is because all seismometers have self-noise lines that steadily curve upward at long periods.

Seismometers can be further categorized by the lower corner frequency (−3 dB point) of the amplitude frequency response of the instrument. Geophones have lower corner frequencies from 1 to 40 Hz. Short-period seismometers have lower corner frequencies from 1 to 4 Hz, and broadband seismometers have lower corner frequencies from 0,027 to 1 Hz. Broadband seismometers typically have lower noise floors over wider bandwidths than short-period seismometers, and short-period seismometers are typically quieter than geophones. Accelerometers are approaching the performance levels of some geophones and short-period seismometers and can be considered for downhole applications too.

Nevertheless, in most downhole applications today, broadband seismometers are typically used since they can measure all three components of motion, are quieter instruments, and can be realized in packages that fit downhole. Broadband seismometers are more challenging to install downhole than short-period seismometers due to lower tilt tolerances. This entry will focus on broadband downhole seismometers and their installation. However, many of the installation techniques and challenges presented in this entry apply to short-period seismometers, accelerometers, and geophones in varying degrees.

Leveling

In order for a seismometer to measure true vertical and north–south, east–west horizontal motion, the verticality error due to the as-drilled borehole must be compensated for along with the north–south orientation. The methods of north–south orientation will be discussed in a later section (see section "Water Egress"), with this section focusing on leveling. Since a downhole seismometer cannot be leveled manually because it is down a borehole or posthole, downhole seismometers have automatic leveling mechanisms that can adjust the sensing elements or axes to measure true vertical and horizontal motion.

The leveling range of a borehole seismometer is typically 5° to cover the range of verticality error due to the drilling. Some downhole seismometers have wider leveling ranges, but this is only needed in special situations.

Leveling mechanisms in seismometers are challenging to design due to the space constraints inside the seismometer, the need to have high fidelity coupling to ground motion, and the need to maintain a design that is not subject to spontaneous micro-mechanical movements. Different instrument designers have taken different approaches to designing leveling mechanisms for seismometers.

There are four main methods for leveling sensing axes within a seismometer, namely, gimbal leveling, horizontal axis leveling, mainspring adjustment, and electronic centering. Each of these methods has benefits and drawbacks that a user should be aware of in selecting a downhole seismometer. Some of the drawbacks relate to the axis topology within the seismometer. More details will be given below.

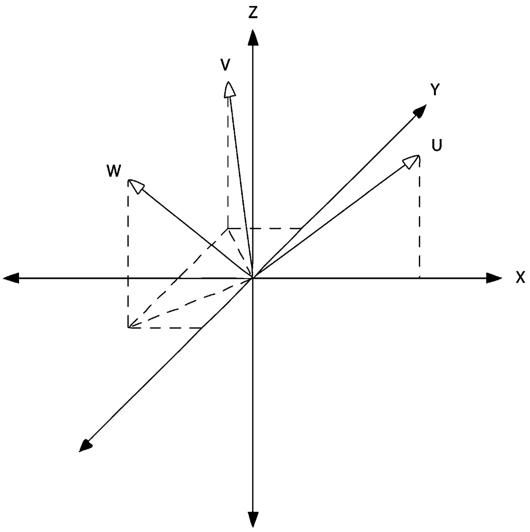

Fig. 2 Axis orientations for XYZ and UVW topologies

Within a triaxial seismometer, there are three sensing components or axes which measure motion in three orthogonal directions. These axes can be configured in a familiar XYZ topology wherein X measures east–west motion, Y measures north–south motion, and Z measures vertical motion. The axes can also be configured in a Galperin or symmetric triaxial topology. In this topology the three axes are tilted at 54.7° from horizontal plane and 120° apart around the vertical axis. These axis directions are known as UVW, wherein U is 52.5° elevation, north 90° west azimuth; V is 54.7° elevation, north 30° east; and W is 54.7° elevation, north 120 east azimuth (Graizer 2009). The symmetric triaxial topology is an orthogonal arrangement where coordinate system rests on its corner (see Fig. 2). The transformation between the UVW coordinate system and the XYZ coordinate system is shown below:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \frac{1}{\sqrt{6}} \cdot \begin{bmatrix} 2 & 0 & \sqrt{2} \\ -1 & \sqrt{3} & \sqrt{2} \\ -1 & -\sqrt{3} & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{\sqrt{6}} \cdot \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ \sqrt{2} & \sqrt{2} & \sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

Mathematically, leveling is the rotation of the seismometer axes about the X-axis and Y-axis only. Rotation about the Z-axis is not handled by the leveling system. Z-axis rotations of a seismometer align the seismometer to true north. This will be discussed separately. A basic rotation of angle θ about the X-axis can be written in 3 × 3 matrix form:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \tag{1}$$

Similarly, a single rotation of angle α about the Y-axis is

$$R_y(\alpha) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \tag{2}$$

The leveling process is the combination of the two rotations and can be written as

$$R_t = R_x(\theta)\cdot R_y(\alpha) \tag{3}$$

$$R_t = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ \sin\theta\sin\alpha & \cos\theta & -\sin\theta\cos\alpha \\ \cos\theta\sin\alpha & \sin\theta & \cos\theta\cos\alpha \end{bmatrix} \tag{4}$$

If the starting orientation of the seismometer axes is the vector, X′Y′Z′, and the leveled position is XYZ, then it can be written:

$$\begin{matrix} x \\ y \\ z \end{matrix} = R_t\cdot \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ \sin\theta\sin\alpha & \cos\theta & -\sin\theta\cos\alpha \\ \cos\theta\sin\alpha & \sin\theta & \cos\theta\cos\alpha \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \tag{6}$$

Expanding these equations results in:

$$x = x'\cos\alpha + z'\sin\alpha \tag{7}$$

$$y = x'\sin\theta\sin\alpha + y'\cos\theta - z'\sin\theta\cos\alpha \tag{8}$$

$$z = x'\cos\theta\sin\alpha + y'\sin\theta + z'\cos\theta\cos\alpha \tag{9}$$

The Y-component is a more complicated expression (Eq. 8), but that is the outcome of the order of the rotations. Changing the order of the rotations, namely,

$$R_t = R_y(\alpha)\cdot R_x(\theta) \tag{10}$$

results in the following expression for the Y-component:

$$y = y'\cos\theta - z'\sin\theta \tag{11}$$

Notice this equation has the same form as the X-component in Eq. 7, so for conceptualizing, this form can be used for both the X-component and Y-component.

Equations 7, 8, and 9 are important because some leveling methods do not actually level the seismometer axes. This results in the seismometer not outputting a true XYZ signal, but rather an XYZ as defined by Eqs. 7, 8, and 9 where an axis output is mixed with signals from the other two axes. These equations will be referred to as each leveling method is discussed in detail.

DOI 10.1007/978-3-642-36197-5_195-1

Gimbal Leveling

With gimbal leveling, there is a leveling platform on which all three seismometer axes are mounted. The seismometer axes are orthogonal to one another in both a symmetric triaxial and a horizontal–vertical topology, and the seismometer axes are fixed to the platform. The platform is leveled around the X and Y axes to eliminate tilt in the X and Y directions. Typically, motorized adjusters are used for leveling in the two directions. There are some passive leveling designs that rely on gravity to shift the gimbal to level using a mass under the gimbal. The seismometer axes can be stacked vertically or placed side by side on the leveling platform. Once the gimbal platform is leveled, the seismometer axes would need to be mass centered to eliminate any residual leveling error and to correct for temperature and spring relaxation. This is a more complex design as compared to the other methods, but it is more accurate in that the seismometer is outputting true vertical and horizontal signals. Referring to Eqs. 7, 8, and 9, the angles θ and α are zero after leveling, and the three equations simplify to:

$$x = x'$$

$$y = y'$$

$$z = z'$$

Horizontal Axis Leveling

The horizontal axis leveling method is a variation of gimbal leveling where the vertical axis is fixed and not leveled, and the two horizontal axes are leveled in one direction only. This method can only be used on XYZ topology seismometers. It cannot be used in symmetric triaxial seismometers because it would affect the mixing ratios when converting from UVW to XYZ. Referring to Eqs. 7, 8, and 9 again, the vertical axis is fixed in position, so Eq. 9 describes the Z-component signal. The east–west axis or X-axis is leveled about the Y-axis, so Eq. 7 with α equal to zero holds. Lastly, the north–south axis or Y-axis is leveled about the X-axis, so Eq. 8 with θ equal to zero describes the Y-axis signal:

$$x = x' \cos\alpha + z' \sin\alpha, \ \ \alpha = 0$$

$$x = x'$$

$$y = x' \sin\theta \sin\alpha + y' \cos\theta - z' \cos\theta \cos\alpha, \ \ \theta = 0$$

$$y = y'$$

$$z = x' \cos\theta \sin\alpha + y' \sin\theta + z' \cos\theta \cos\alpha$$

With this leveling method, the X- and Y-components measure true X and Y motions, respectively, but the Z-component does not measure true Z motion. This is not as bad as it seems as the angles are small. Substituting a typical maximum tilt range of 5° in two directions results in:

$$\alpha = 5^\circ, \ \ \theta = 5^\circ$$

$$z = x' \cos(5) + y' \sin(5) + \cos(5)$$

$$z = 0.087x' + 0.087y' + 0.992z'$$

The vertical sensitivity is reduced by 0.76 % which is not much at all given that it is hard to calibrate a seismometer to better than 1 %. The Z signal also has X- and Y-components mixed in, but at a level ten times smaller than the Z-component. Expressed a different way, there is a loss of orthogonality between the axes. Herein lie the downsides of this method, the loss of orthogonality between axes resulting in the mixing of the Z-axis by X- and Y-components. If the tilt angles were known, then the vertical axis could be corrected after the measurement, but typically the tilt angles are not recorded so it cannot be corrected.

The main problem with this method is that the horizontal and vertical ground motions do not have the same magnitudes at long periods. Long-period horizontal signals are affected by tilt noise, which result in the apparent horizontal ground motion being much larger than the vertical. It is common for horizontal components to have amplitudes 20–50 dB higher at long periods than vertical components. With these levels, the horizontal components mixed into the vertical become significant and can swamp out the vertical signal at long periods. The user needs to be careful about how much tilt noise there is on the horizontals and the degree of tilt of the sensor. This complicates the deployment and places a burden of understanding on the user.

The primary benefit of this method is that it is simpler and less expensive to realize in a seismometer than gimbal leveling. This is because axes in downhole seismometers are typically stacked vertically due to space constraints on the diameter of the borehole. It is challenging to level three axes stacked together, so each axis is leveled individually. If each axis was leveled individually in the X and Y directions, there would need to be six leveling actuators in all: three axes times two directions. The horizontal axis leveling method only requires two leveling actuators, one on the X-axis and one on the Y-axis. There is a saving of four leveling actuators, hence the cost benefit.

Mainspring Adjustment

The mainspring adjustment method can be used in symmetric triaxial seismometers. This method does not actually involve leveling any part of the seismometer. Instead it compensates for the seismometer being off-level by adjusting the tension in the mainspring of the seismometer. All inertial sensors see an apparent horizontal acceleration when they are tilted. For small angles the apparent horizontal acceleration H corresponding to a tilt θ in radians is simply

$$H = g_0\theta$$

where $g_0 = 9.8\ \mathrm{m/s^2}$ is the acceleration due to gravity.

The equilibrium position is maintained by adjusting the tension in the mainsprings of each of the axes to exactly compensate for this apparent acceleration. The tension in the mainspring is adjusted by means of an actuator connected to the mainspring. Many seismometers already have a mainspring actuator to compensate for variations in the elastic modulus with temperature. Expanding the functionality of this actuator to include leveling does not require any more components so there is no impact on cost. However, there are trade-offs in the design which limit the usefulness of this approach.

There is a limit to how far a mainspring can be adjusted due to the geometry and size of a seismometer axis. In addition, with active broadband seismometers, there is a trade-off between mainspring adjustment leveling range and the noise floor of the seismometer due to noise in the

DOI 10.1007/978-3-642-36197-5_195-1

seismometer feedback electronics. A low-noise floor seismometer using mainspring adjustment cannot have the required leveling range. A broadband seismometer with a high noise floor would be able to have the required leveling range, so this method is limited to high-noise floor seismometers.

For this method of leveling, Eqs. 7, 8, and 9 apply:

$$x = x' \cos\alpha + z' \sin\alpha \tag{7}$$

$$y = x' \sin\theta \sin\alpha + y' \cos\theta - z' \cos\theta \cos\alpha \tag{8}$$

$$z = x' \cos\theta \sin\alpha + y' \sin\theta + z' \cos\theta \cos\alpha \tag{9}$$

The seismometer axes are fixed in orthogonal positions within the seismometer, so there is no loss of orthogonality, but the XYZ components do not measure true vertical and horizontal signals.

This method of leveling is less costly to implement, but it is limited to higher-noise seismometers.

Electronic Centering

Electronic centering can only be implemented in force balance seismometers. With this method, the electromagnetic coil circuit known as a forcing coil is used to hold the inertial mass in the equilibrium position and counterbalance change in the gravity vector. Any change in the apparent horizontal acceleration due to gravity is compensated by the forcing coil and electronic feedback. As an axis is tilted, the current in the coil changes which changes the force on the inertial mass. For a horizontal axis, the apparent acceleration H produced is related to the feedback current I, motor constant H, and boom mass M by

$$H = \frac{G}{M} I$$

This method preserves the orthogonality of the axes as the axes are in fixed positions and again, Eqs. 7, 8, and 9 apply, so the XYZ components are not true verticals and horizontals. This is the same as the mainspring adjustment method.

This method has a few disadvantages. The seismometer consumes more power since it is the forcing coil current that is counterbalancing the gravity vector now. In addition, inertial mass must be small to keep the current low and still achieve a wide tilt range, which results in higher levels of Brownian noise (see "▶ Broadband Seismometers").

There are a number of advantages of this method. There are no leveling actuators or mainspring adjustment actuators, making the design more reliable and lower in cost. Depending on the lower corner frequency of the seismometer (see "▶ Broadband Seismometers"), the seismometer can have a wide leveling range of up to 10°.

Downhole Seismometer Selection

There are a number of criteria to consider in selecting a downhole seismometer. These include self-noise floor and axis topology, the cost, the leveling method, the leveling range, the type of seismometer, the physical dimensions of the seismometer, and the reliability and consistency of the seismometer.

The first item to consider in the selection process is the self-noise floor of the seismometer. The choice should depend on the noise environment that the sensor will be deployed in and on nature of

DOI 10.1007/978-3-642-36197-5_195-1

Table 1 Comparison of leveling methods

Leveling method	Maintains orthogonality	True leveling	Cost	Compatibility
Gimbal leveling	Yes	Yes	High	All
Horizontal axis leveling	No	Partial	Medium	XYZ only
Mainspring adjustment	Yes	No	Low	UVW only
Electronic centering	Yes	No	Low	Active only

the application. Ideally, site noise should be the limiting factor in the overall station noise, not seismometer self-noise.

However, the performance needs to be balanced with the cost of the instrument. Instruments with lower self-noise cost more than those with higher levels of self-noise. It is up to the user to trade off performance with cost for their application.

For the axis topology, the symmetric triaxial topology is particularly advantageous in the downhole environment due to the ease of differentiating between installation- and sensor-related noise (see "▶ Symmetric Triaxial Seismometers"). The four leveling methods each have cost and performance trade-offs which are summarized in Table 1.

For high-performance broadband seismometers, the most suitable leveling method is the gimbal leveling as it does not compromise the quality of the data while maintaining orthogonality. The next most suitable method is horizontal axis leveling. Although the data will be neither as accurate nor as orthogonal, there are cost benefits to such an approach. Mainspring adjustment and electronic centering are best reserved for higher-noise, lower-cost seismometers.

For the leveling range, the user needs to ensure that the seismometer has sufficient leveling range to cover their deployment conditions. Insisting on a larger leveling range than needed unnecessarily limits the choice of seismometer. Most downhole applications do not require large leveling ranges.

The type of seismometer, namely, whether it is a borehole or posthole type, will be determined by the type of installation (see section "Types of Installations"). Borehole seismometers tend to cost more than posthole seismometers but can be deployed in deeper holes.

The user needs to ensure that the seismometer will fit into the posthole or borehole that has been drilled. Deeper holes tend to have smaller diameters to reduce the cost per meter of drilling; hence a narrower diameter instrument may be required.

Lastly, a user needs to consider the reliability and consistency of a seismometer. Some seismometers are more reliable than other seismometers due to factors in the design and the quality of the manufacturing. The consistency of the seismometer refers to the spread in the self-noise floor over time and from instrument to instrument. This can best be assessed by huddle testing at least three instruments over a period of time (Sleeman et al. 2006). There are a number of published papers on self-noise floor of seismometers (Ringler and Hutt 2010).

Table 2 documents some commercially available downhole broadband seismometers to be considered in a selection process.

See company websites for further information.

Downhole Seismic Noise Environment

One of the goals of a seismic station installation is to minimize seismic noise and maximize the level of a seismic signal. In other words, the goal is to maximize the signal-to-noise ratio (SNR) that can be achieved at a seismic station. A higher SNR ratio will enable a station to detect smaller-magnitude

Table 2 A sample of downhole broadband seismometers available on the market in 2013

Seismometer name	Manufacturer	Lower corner frequency	Axis topology	Leveling method	Leveling range
Trillium 120 Borehole	Nanometrics	120 s	Symmetric triaxial	Gimbal	±5°
Trillium Posthole	Nanometrics	120 s	Symmetric triaxial	Gimbal	±5° standard ±10° optional
Trillium Compact Posthole	Nanometrics	120 s	Symmetric triaxial	Electronic centering	±2.5° ±10°
KS-54000	Geotech	360 s	XYZ	Unknown	±10°
KS-2000BH	Geotech	120 s (standard)	XYZ	Unknown	±15°
CMG-3TB	Guralp	120 s	XYZ	Horizontal axis leveling	±3° standard ±10° optional
CMG-40T-B	Guralp	60 s (standard)	XYZ	Electronic centering	±8°
CMG-Flute	Guralp	60 s (standard)	XYZ	Mainspring adjustment	±12°
STS-5A	Streckeisen	120 s	Symmetric triaxial	Gimbal	±5°

seismic events. This goal applies equally to surface vaults and downhole seismic installations, but the means to accomplish this goal are different for vaults and downhole installations due to the characteristics of the seismic noise, the seismic signal, and the local geology.

Seismic noise can be broken down into different types or sources of noise. These include wind-induced seismic noise, cultural seismic noise (noise generated by human activities), microseismic noise, moving-water-induced seismic noise, and tilt-induced noise (Fig. 3). Each of these noise sources will be briefly described.

Microseismic Noise

Microseismic noise is caused by wave actions on large bodies of water such oceans, seas, and lakes. As waves enter the continental margins and crash onto shorelines, energy is transferred from the water into the earth, generating Rayleigh waves. Microseismic noise ranges from 1 Hz to 30 s, with a peak at 4–8 s known as the microseismic peak. Microseismic noise is a global phenomenon, but has higher amplitudes closer to coastlines and shorelines.

Tilt Noise

Inertial sensors, such as seismometers, measure accelerations due to the motion of a seismic mass. However, inertial sensors are also sensitive to static accelerations such as gravity. Normally, accelerations due to gravity are counterbalanced by the mainspring in the suspension of a seismometer, but when a seismometer is tilted (rotated around a horizontal axis), gravity appears as an apparent horizontal acceleration. The resulting accelerations due to tilt are indistinguishable from accelerations due to seismic motion (Rodgers 1968; Graizer 2005). This effect is relatively minor on the vertical axis of a seismometer as long as this axis is substantially vertical. On the horizontal axes, the effect is significant and is described as

$$H = g_0 \cdot \sin\theta$$

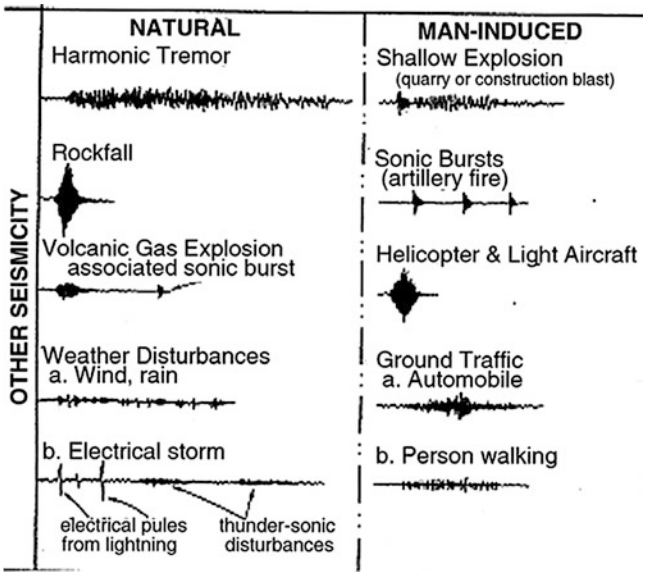

Fig. 3 USGS graphic of seismic noise types

Since the angles are small, the approximation sin $\theta = \theta$ can be used:

$$H = g_0 \cdot \theta$$

where

- $g_0 = 9.8\ \mathrm{m/s^2}$ is the acceleration due to gravity,
- H is the horizontal acceleration in $\mathrm{m/s^2}$, and
- θ is the tilt in radians.

Ground tilts can be caused by human activities, wind, or changes in local barometric pressure, temperature, or soil moisture content. The magnitude of ground tilts is influenced by the stiffness of the ground. Hard-rock sites will be much less susceptible to tilt as compared to a site on clay. Tilt noise causes horizontal components to be typically 20–50 dB noisier than the vertical components at long periods (Bormann 2002).

Tilt noise tends to decrease with depth as many sources of tilt noise are surface effects, namely, wind, air pressure, soil moisture, and human activity. Tilt noise can also be caused by air currents circulating around a seismometer. This effect can be significant in borehole installations if strong vertical convection air currents are allowed to flow. Precautions must be taken to prevent the air moving. This problem can be mitigated with a sand installation, which eliminates air spaces around a seismometer, or with insulation methods, such as foam plugs, to limit the airflow below and above a seismometer.

Wind-Induced Noise

Wind is another major source of seismic noise. Wind transfers energy into the ground as it decelerates from colliding with the terrain, water bodies, buildings, vegetation, and other objects coupled to the ground. The chaotic nature of wind often excites resonances in objects it strikes. Trees and buildings sway in the wind, waves are generated on water, and the ground is compressed. Although the wind blows predominantly in a horizontal direction, interactions with the surface translate the motion into the vertical component. For example, as trees sway back and forth in the wind, alternating pressure is placed on opposite sides of the root bundle imparting vertical motion. Wind-induced seismic noise is short period in nature, meaning that is above 1 Hz. Wind noise is dependent on the wind velocity. Higher velocities generate more noise. For reference, a wind speed below 3 m/s (11 km/h) does not raise the background seismic noise at the surface for grassland sites on sedimentary rock in rolling hills (Withers et al. 1996). Wind induces predominantly surface waves (Love and Rayleigh waves) along with a small component of body waves onto the ground.

Moving-Water-Induced Noise

Seismic noise is generated in watercourses from small streams to large rivers. As water flows downhill, turbulence is created which imparts energy into the ground. Regions with steeper gradients, such as waterfalls and rapids, generate more seismic noise. Moving-water seismic noise is continuous but varies in amplitude depending on water levels. Moving water induces surface waves similar to wind noise.

Cultural Noise

Seismic noise generated by human activities is referred to as cultural noise. The principal sources of cultural noise are related to transportation, construction, military, and mineral extraction activities. However, any human activity can generate cultural noise, even a person walking down a path. Cities have higher levels of cultural noise than rural areas. Cultural noise can be stationary or nonstationary, periodic or random, and generated by sources distributed or localized. Cultural noise does tend to be diurnal, meaning it varies over the day with quietest times in the middle of the night when there is the least human activity. Like wind-induced noise, cultural seismic noise is predominantly composed of high-frequency surface waves but also includes a body wave component.

Seismic Noise Mitigation with Depth

The common factor in wind-induced, cultural, moving-water, and microseismic noise is that the noise is predominately generating surface waves. At short periods, the amplitude of surface waves decays exponentially with depth due to amplitude drop from the surface and due to the upper layers of the earth being highly attenuating or “lossy.” It is well known that high-frequency seismic noise decreases with depth making borehole sites typically quieter than surface vault sites from 1 to 100 Hz (Carter et al. 1991). At long periods, the seismic noise also drops with depth, particularly on the horizontal channels due to a reduction in the tilt noise (Sorrells 1971).

While seismic noise attenuates with depth, seismic signal amplitudes are dependent on a number of factors relating to the geology of the site. As a seismic signal propagates toward the surface, it typically travels through progressively lower Q layers and loses energy. The layers at the surface have the lowest Qs and are responsible for a significant portion of the loss in energy (Aster and Shearer 1991). However, as the velocity of the signal slows, the amplitude increases, and there is also surface amplification effect. In summary, it is difficult to estimate the amplitude of the signal with depth.

Nevertheless, the effect of seismic noise attenuation with depth results in improved signal-to-noise ratios especially when the final layers of earth are highly lossy (Young et al. 1996). Ideally, a downhole seismometer should be placed in hard rock below a highly lossy overburden.

The question that remains is, how deep should the downhole seismometer be placed? The answer is as deep as economically and practically possible as signal-to-noise ratios typically improve with depth in the first few hundred meters. However, the question can be turned around to: how shallow

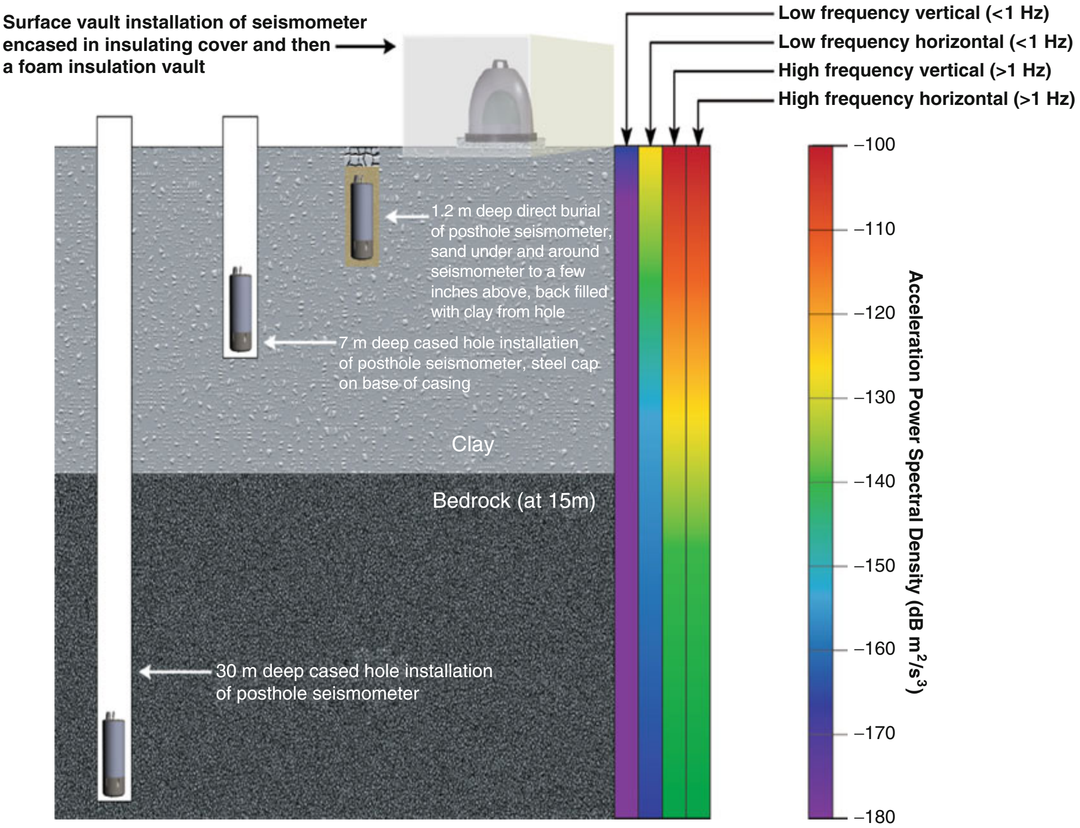

Fig. 4 Vault installation and posthole installations at various depths as measured in Ottawa, On, Canada (Nanometrics Inc 2013)

can a downhole seismometer be placed to result in an improvement in the signal-to-noise ratio? The answer is within 3–10 m of the surface depending on the geology due to the attenuation of temperature, tilt noise, and surface noise.

Consider an extreme example of 15 m clay above quartzite bedrock in an urban environment shown in Fig. 4. This was measured in Ottawa, Ontario, Canada, using Trillium120 Posthole seismometers (Nanometrics Inc 2013). Clay has a very low Q, and the quartzite has a much higher Q. Unsurprisingly, the surface vault has the highest noise at low and high frequencies. The 1.2 m direct burial posthole seismometer installation shows improved low-frequency vertical and horizontal noise and improved high-frequency noise. At 7 m, the posthole seismometer installation shows further improvements in low-frequency horizontal noise and improved high-frequency noise. At 30 m from the surface in bedrock, the horizontal low-frequency noise has dropped 30 dB, the low-frequency vertical noise has improved 10 dB, and the high-frequency noise on the vertical and horizontal channels has dropped 40 dB as compared to the surface vault. This example shows that improvements in noise levels can be achieved in relatively shallow downhole installations. Deeper installations could possibly yield further improvements, but in this example an improvement was achieved in the first 15 m. It should be noted that these results are specific for this site. In general, noise levels will be site specific.

In summary, even shallow posthole installations can provide SNR improvements over surface vaults.

DOI 10.1007/978-3-642-36197-5_195-1

Downhole Seismometer Installations

Types of Installations

Downhole seismometers can be deployed into boreholes or shallow holes.

Boreholes are steel-cased holes that are cemented into competent rock. Typical seismic boreholes are 50–150 m deep, but there are seismic boreholes 2,000 m deep and beyond (Young et al. 1994). Although a cemented steel casing extends to the surface, a borehole poorly propagates surface noise down the borehole. There are two reasons for this. First, the coupling of the casing to the upper softer layers of material is not as good as the coupling to stiffer materials lower down. Second, the borehole is relatively compliant horizontally over the length of the borehole.

These holes can be drilled using water-well or oil-well drilling equipment. The steel casings are cemented into the borehole to stabilize the casing, provide good coupling to the ground, and maintain the integrity of underground aquifers.

Shallow holes are typically holes 0.5–5 m deep that are dug by shovel or lightweight drilling equipment such as augers, small drill rigs, screw-pile equipment, and the like (Fig. 5). These holes are typically larger in diameter as compared to boreholes to enable a wider range of seismometers to be deployed and to improve access to the seismometer. At permanent sites, the hole may be cased in steel or pvc and cemented in. Shallow holes drilled into hard rock do not need to be cased. Seismometers are typically deployed into shallow holes using a sand installation method.

Shallow holes that are used for temporary deployments are typically not cased. This minimizes the cost of the installation. A seismometer deployed in an uncased hole is backfilled with sand or the excavated materials from the hole. This type of deployment is also known as a direct burial installation. A direct burial installation is quicker and easier to install than an installation using a vault seismometer. It is often challenging leveling a vault seismometer in a field deployment since it requires a hard surface, access to the leveling feet, and bubble level. With a posthole seismometer, the procedure is to dig a small hole, place the seismometer in the hole, backfill with earth or sand, and start the autoleveling in the seismometer. There is no further work required to insulate or weatherproof the installation.

Seismometer Emplacement

Once a seismometer is lowered into a borehole, it must be secured rigidly in the hole to ensure good seismic coupling to the borehole casing and the ground. There are two methods for accomplishing this. The first is with a mechanical borehole lock and the second is with a sand installation.

A borehole lock is a device attached to the seismometer which clamps the seismometer to the side of the borehole. Typically, a borehole lock has three fixed pins on one side of the holelock which create a three-point contact with the borehole and one moving pin on the opposite side which clamps the holelock to the side of the borehole. The moving pin pushes the holelock three-point contact pins against the borehole with a force sufficient to hold the seismometer in place. The seismometer is then supported by the four pins. This is a kinematic coupling. The seismometer must not be touching the bottom of the borehole; otherwise the coupling will be over-constrained which can result in undesired motions. With this method of locking, the seismometer takes on the vertical angle of the borehole at that point. The moving pin on the holelock can be actuated with an electric motor or a mechanical system controlled from the surface.

The sand installation method involves lowering the seismometer to the bottom of a borehole or shallow hole and pouring dry sand into the hole sufficient to cover the seismometer in sand. The sand flows around the entire seismometer filling the entire gap between the seismometer and the hole. This method of installation has a few benefits and drawbacks. A sand installation is simpler and less

DOI 10.1007/978-3-642-36197-5_195-1

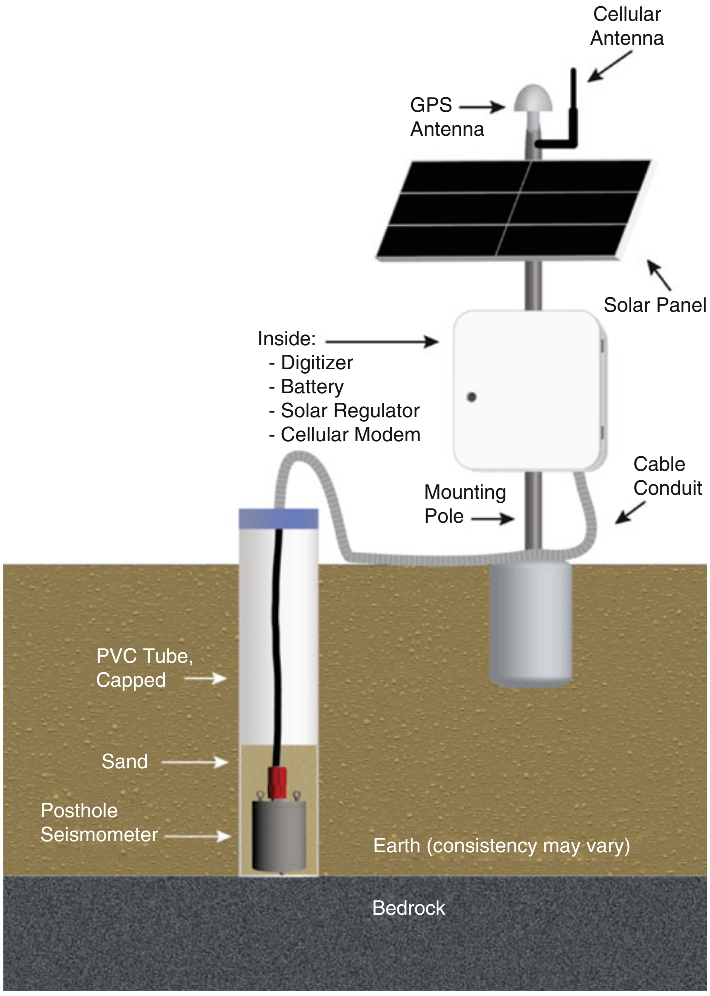

Fig. 5 Components of a typical posthole station with the sensor 1–6 m below the surface

costly than a holelock installation. It eliminates convection air currents around the seismometer and effectively couples the seismometer to the casing. However, sand is a loose material that is prone to spontaneous movements that can be detected by a seismometer during a settling period. Another issue with sand installations is that after a period of time, moisture and dissolved minerals in the sand can solidify the sand making it challenging to remove the seismometer.

Economics of Installations

One of the primary considerations in deploying a downhole seismic station is the cost of the installation, especially in comparison to vault installations. In the past, downhole installations have been substantially more costly than vault installations because downhole installations were predominately 100–200 m-deep borehole installations with high-cost, top-performance borehole seismometers. A typical borehole was drilled using oil-well drilling equipment which costs approximately US$100,000 per borehole. A borehole station of this kind would have had a total installed cost of US$150,000–300,000 depending on the location and ancillary equipment included. This limited borehole installations to those who had budgets large enough to cover cost of a borehole network and had a requirement for excellent signal-to-noise ratios.

Recently, newer instruments and installation methods have dramatically lowered the cost of a downhole installation making downhole stations cost competitive with vault installations.

One of the main innovations is switching away from using oil-well drilling equipment and materials. Oil-well drilling equipment is designed and sized to drill deep wells (up to many kilometers) in complex geologies. This equipment typically includes steerable drill bits to enable horizontal drilling. For a typical vertical seismic borehole of 50–150 m deep, this equipment is expensive to use and in most geologies unnecessary.

Water-well drilling rigs are more suitable and substantially cheaper to operate as compared to oil-well drilling equipment. Water-well drilling equipment is designed for drilling only vertical boreholes 10–300 m deep reducing rig size, complexity, and cost. Water-well drilling services are typically available in most locations reducing deployment costs and are competitively priced due to the demand for water wells. A typical 60 m water well can be drilled in North America for $US 5,000–25,000.

A seismic borehole includes costs for casing, cementing, and pressure testing, in addition to the drilling costs. Casing and cementing costs will vary with depth, casing type, and diameter. Local drilling contractors who are often very familiar with the geology in the region can readily provide up-to-date prices and guidance on drilling.

For posthole installations, cased boreholes, screw piles, and uncased shallow holes can be used. Uncased shallow holes are the least expensive and can be dug with hand or powered augers. Screw-pile installations have costs between boreholes and shallow holes. Screw piles are installed with skid-steers and have the added benefit of being removable at the end of a deployment. Local construction contractors can provide current prices for comparison.

Security of Installations

Boreholes and shallow holes are in general more secure than vault installations for the seismometers. The overall footprint of a downhole installation is much smaller and less visible than a typical permanent vault installation and can be camouflaged more easily. If desired, the entire borehole wellhead can be buried. Buried underground conduits can be routed from the borehole or shallow hole to the communications and power hub. The curious would assume that a visible wellhead is that of a water well which is uninteresting. Often winches and tripods (or masts) are required to extract seismometers from the hole providing a level of physical security that is hard to overwhelm even for the most determined thief.

Nevertheless, a downhole seismometer installation only protects half the equipment at the station. The communications and power equipment is still highly visible and attractive to a thief. Solar panels and backup batteries are popular and useful everywhere in the world and are routinely stolen from less-secure sites (see Fig. 6). A solution to station security must cover all the equipment at a site (Fig. 7).

Typically, there is a trade-off to be made between a rural site which has low cultural seismic noise but is less secure due to its isolation and a secure urban site, such as police or fire station, which has higher cultural seismic noise. Ideally, an operator wants a low cultural noise site that is also secure. With downhole installations, a secure urban site enables the reduction of seismic noise by providing vertical separation from seismic noise which originates at the surface. The degree of attenuation of seismic noise with depth will depend on the local geology and nature of the cultural noise. An urban borehole or posthole may not be as quiet as a good rural site, but it is secure and can be quickly serviced if there is a problem.

A network operator will have to trade security and ease of access for uptime and data quality based on the local geology, cultural seismic noise, economic conditions, cultural norms regarding property, and cost.

Fig. 6 Rural posthole installation with cellular communications in Alberta, Canada

Fig. 7 Rural vault installation with satellite communications in Fiji

Station Footprint

Downhole installations typically have a smaller footprint as compared to vault installations. The land area required for a borehole or shallow hole can be as little as the area of the hole. Typically, a borehole or shallow-hole installation will require a 0.25–1 m^2 of space (Fig. 9). Seismic vaults typically use much more space, particularly if the vault is a walk-in type of vault.

The smaller footprint of a downhole site offers more flexibility in station placement, especially in an urban environment where available land is limited and costly and local building codes restrictive.

Site Environmental Conditions

The site environmental conditions, namely, weather, water, and wildlife, have a large impact on the performance of seismic stations. While great care must be taken with the design of vault installations to mitigate the effects of temperature, wind, air pressure, water egress and flooding, and wildlife, downhole installations are much less susceptible to these effects and require less design effort.

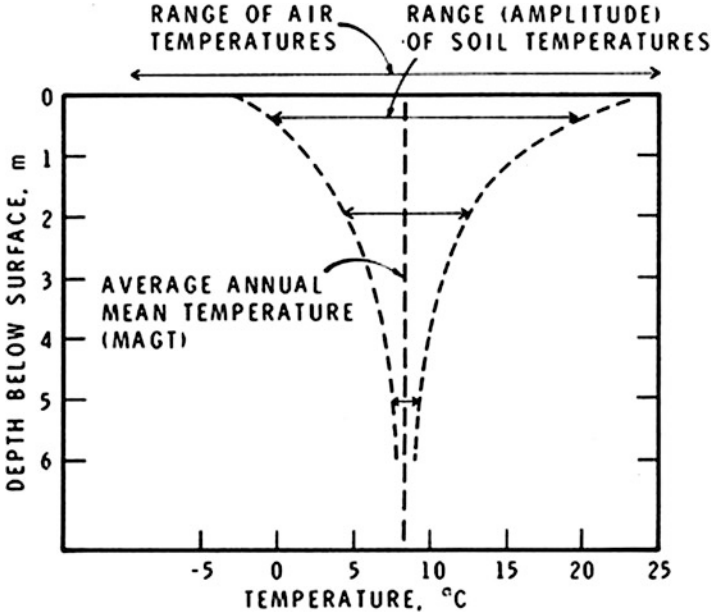

Fig. 8 Ground temperature variations with depth for Ottawa reproduced from Williams and Gold (1976)

Temperature

Seismometers are sensitive to temperature changes, and ideally, a seismometer should be exposed to as little temperature variation as is economic. At the surface, the temperature can range from −20 °C in the winter to +35 °C in the summer in a northern continental climate, with daily fluctuations between 10 °C and 20 °C. Other climates can be more or less extreme. A vault installation uses thermal insulation and structures with high thermal mass to reduce the temperature variation of the seismometer. This requires design work and cost.

A downhole installation relies on the heat capacity and thermal conductivity properties of the ground to reduce the temperature fluctuations to a minimum. The depth where the temperature fluctuation is 1/100 of the surface temperature variation for a given time period is known as the penetration depth and depends on the composition of the soils and the moisture content of the soils. For daily temperature variations, the penetration depth is less than 1.2 m for all soil types. The yearly penetration depths vary from 5 to 20 m depending on the soil conditions. For most downhole seismometer installations, an annual temperature variation of ±3° is acceptable and can be achieved in as little as 3–6 m belowground. See Fig. 8: ground temperature variations with depth for Ottawa, reproduced from Williams and Gold (1976).

Water Egress

Seismic vaults are usually located at or just below the surface on undisturbed soils and are subject to water egress and flooding from time to time. While vaults are often designed to be waterproof, there is usually some weakness in the implementation that enables water to enter the vault over time or during flood situations. Some vaults are equipped with pumps, but over time, pumps fail. This would not be an issue except that vault seismometers and ancillary equipment are not designed for continuous submersion. Flooding causes the temporary shutdown of many vault seismic stations.

Downhole seismometers are designed for continuous submersion and are unaffected by periodic flooding. Generally, boreholes and postholes are designed to be dry, but it is not strictly necessary for the equipment. Shallow hole can be dry or wet, or even below the water table. Water may degrade the seismic performance due to movement of the water, but it will not cause the total loss of data from a station.

Wildlife

Animals from time to time cause problems at seismic stations. This can range from large animals walking in the vicinity of the station or scratching themselves against the station down to mice building nests in the insulation surrounding a seismometer or chewing cables and every critter and its activities in between. Being at the surface, vault installations are simply more accessible and susceptible to these invasions. Downhole Installations are away from the surface and difficult to access even for the smallest animals. Surface noise from animals is attenuated with depth to some degree.

Deployment Considerations

Borehole Verticality

Boreholes are typically not vertical holes but have small tilt angles of up to 10° from vertical. This is due to the accuracy of the driller's equipment and technique and the nature of the material being drilled. Drilling practices that affect the verticality of a borehole include the weight on the drill bit, the speed of drilling, the degree of hole cleaning, drill bit selection, whether a steerable drill bit is used, and the use of verticality monitoring equipment while drilling. Experienced drillers understand the trade-offs in maintaining a vertical borehole. In maintaining a vertical borehole, a driller will want to understand the geology of the area prior to drilling. It is harder for a driller to maintain verticality with complex borehole profiles. For example, it is more challenging to maintain verticality when drilling soft sediments such as clay or sand or in sediments with materials with differing hardness such as glacial till or limestone with cavities. With glacial till, the drill bit can be deflected by rocks and boulders in the sand, and with limestone, the drill bit can drift in the cavities. Other challenging borehole profiles include highly fractured rock and sedimentary rocks with steep dip angles.

In most situations, drillers can maintain the tilt to less than 3° off vertical. Typically, drilling specifications stipulate that the borehole shall be within 3° off vertical or less. USGS suggests a drilling specification of 2° or less (Albuquerque Seismological Laboratory 2001). Even with a vertical error of 3°, the vertical offset or drift at the bottom of the 100 m borehole is just over 5 m. The drift at the bottom of a borehole may be a concern in some installations that have underground features that must be avoided.

Another issue related to borehole verticality is the tilt of the seismometer in the borehole. It is not possible to maintain the verticality of a seismometer as it is lowered; a seismometer will always be resting against the side of the borehole as it goes down and will tend to assume the angle of the borehole when it reaches the bottom. For example, if the seismometer is lowered to 50 m in the borehole, and the borehole at 50 m is 2° off vertical, the seismometer will tend to be 2° off vertical when it comes to rest. See section "Levelling" for how to compensate for the vertical error.

Aligning to North

Seismometers are typically aligned to north. Vault seismometers are aligned to north manually using a compass. A compass bearing is taken, a north–south line is scribed on the vault floor, and the seismometer is manually rotated to align with the north–south line. There are many variations of this method, but overall the process is straightforward.

Aligning downhole seismometers to north is more challenging. The user has only limited access to the instrument downhole, and a compass cannot be used downhole due to the magnetic shielding by the steel borehole casing. Nevertheless, methods have been developed to align downhole seismometers.

The downhole alignment process can be broken down into two steps. The first step is to determine the seismometer orientation relative to north. This can be accomplished using a number of different methods including downhole gyroscopic alignment, surface seismometer referencing, rifle scope alignment, and north-finder alignment. See below:

- With gyroscopic alignment, a gyroscope is activated and aligned to north at the surface. It is then lowered down the borehole and engages with a north-aligned feature on the seismometer or holelock. A reading is taken from the gyroscope to determine the rotational offset from north.
- Surface seismometer alignment involves collecting a seismic data set from the downhole seismometer and a surface seismometer located at the wellhead. The downhole data set is correlated with the surface data set to determine the offset from north.
- Rifle scope alignment involves mounting a rifle scope vertically pointing down the borehole. The rifle scope cross hair is focused on the north–south marking on the seismometer downhole. A reading of the rifle scope rotation relative to north is taken.
- North-finder alignment uses a north-finder instrument which measures earth’s rotation vector to determine north. The north finder can be mounted on the seismometer or lowered down the borehole to engage the seismometer.

The second step is to rotate the seismometer to be north aligned. This can be done digitally, mechanically with a “bishop’s hat” mechanism, or manually with an alignment rod.

- Digital alignment involves mathematically rotating the digital data set to align to north. This can be done with no loss of precision. The user enters a rotation parameter into the seismometer or digitizer configuration, and the instrument subsequently rotates all time-series data.
- Bishop’s hat mechanical alignment is a multistep process. A holelock with a bishop’s hat mechanism is lowered into the borehole and clamped in place. A north-measuring device is lowered onto the bishop’s hat mechanism to determine the orientation of the holelock. The north-measuring device is removed, and the seismometer bishop’s hat mate is rotated and locked at the surface. The seismometer is lowered down onto the bishop’s hat and is now aligned to north. A bishop’s hat mechanism is a device that forces the mating assembly (the seismometer) to a particular orientation. It is called a bishop’s hat because it is shaped like a bishop’s hat.
- Lastly, a seismometer can be aligned with an alignment rod. The alignment rod is attached to the seismometer and the seismometer is lowered into the hole. From the surface, the user rotates the alignment rod and the seismometer together. Once the seismometer is aligned, the alignment rod is removed from the hole. An alignment rod is limited to use in postholes and shallow holes.

Summary

In the past, downhole seismic stations were limited to deep borehole installations which were so expensive that they only justified the deployment of very costly borehole seismometers. These stations demonstrated the reduction of seismic noise and the improvement of signal-to-noise ratios with depth. However, the cost of ownership of these stations limited their widespread adoption.

DOI 10.1007/978-3-642-36197-5_195-1

Fig. 9 Rural borehole seismometer deployment in Alberta, Canada

In the last few years, posthole and direct burial seismometers have been introduced, a better understanding of seismic noise and its dependence with depth has been developed, and more economic installation methods, such as those using water-well drilling equipment, have been established. These instruments and methods have made downhole seismometer installations cost competitive with vault installations, while at the same time improving on the signal-to-noise ratios. In some cases, downhole installations can cost much less than vault installations of similar performance.

Shallow-hole direct burial deployments are an improvement over temporary surface deployments in many aspects. These include improved signal-to-noise ratios, better site security, simpler installation and servicing, smaller footprint, and improved station reliability.

With new borehole and shallow-hole deployment methods feasible, network operators can now balance more finely the cost of a downhole station with the quality of the seismic data enabling operators to collect better data for less money.

Cross-References

- ► Broadband Seismometers
- ► Symmetric Triaxial Seismometers

References

Albuquerque Seismological Laboratory (2001) Specifications for seismic instrumentation boreholes. Retrieved 1 Dec 2013, from U.S. Geological Survey: http://earthquake.usgs.gov/regional/asl/pubs/files/tech_boreholes.pdf

Aster R, Shearer P (1991) High-frequency borehole seismograms recorded in the San Jcinto Fault zone, Southern California Part 2. Attenuation and site effects. Bull Seismol Soc Am 81(4):1081–1100

Bormann P (2002) Seismic signals and noise, Chap 4. In: Bormann P, Bormann P (eds) New manual of seismological observatory practice, vol 1. GeoForschungsZentrum, Potsdam

Carter J, Barstow N, Pomeroy P, Chael E, Leahy P (1991) High-frequency seismic noise as a function of depth. Bull Seismol Soc Am 81(4):1101–1114

Graizer V (2005) Effect of tilt on strong motion data processing. Soil Dyn Earthq Eng 25(3):197–204

Graizer V (2009) The response to complex ground motions of seismometers with Galperin sensor configuration. Bull Seismol Soc Am 99(2B):1366–1377

Nanometrics Inc (2013) Comparison study between vault seismometers and a new posthole seismometer. Retrieved from www.nanometrics.ca: http://www.nanometrics.ca/ckfinder/userfiles/files/VaultvsPostholePaper.pdf

Peterson J (1993) Observations and modeling of seismic background noise. Open-file report 93-322. U. S. Geological Survey, Albuquerque

Ringler AT, Hutt CR (2010) Self-noise models of seismic instruments. Seismol Res Lett 81(6):972–983

Rodgers P (1968) The response of the horizontal pendulum seismometer to Rayleigh and Love waves, tilt, and free oscillations of the Earth. Bull Seismol Soc Am 58(5):1385–1406

Sleeman R, van Wettum A, Trampert J (2006) Three-channel correlation analysis: a new technique to measure instrumental noise of digitizers and seismic sensors. Bull Seismol Soc Am 96(1):258–271

Sorrells GG (1971) A preliminary investigation into the relationship between long-period seismic noise and local fluctuations in the atmospheric pressure field. Geophys J Roy Astron Soc 26:71–82

Williams G, Gold L (1976) Ground temperatures. Can Build Dig, CBD-180

Withers M, Aster R, Young C, Chael E (1996) High-frequency analysis of seismic background noise as a function of wind speed and shallow depth. Bull Seismol Soc Am 86(5):1507–1515

Young C, Chael E, Zagar D, Carter J (1994) Variations in noise and signal levels in a pair of deep boreholes near Amarillo, Texas. Bull Seismol Soc Am 84(5):1593–1607

Young C, Chael E, Withers M, Aster R (1996) A comparison of the high-frequency (>1 Hz) surface and subsurface noise environment at three sites in the United States. Bull Seismol Soc Am 86(5):1516–1528