Close Window

ENCYCLOPEDIA ARTICLE

Seismographic instrumentation

Various devices or systems of devices for measuring movement in the Earth. Ground motion is generally the result of passing seismic waves, gravitational tides, atmospheric processes, and tectonic processes. Seismographic instrumentation typically consists of a sensing element (seismometer), a signal-conditioning element or elements (galvanometer, mechanical or electronic amplifier, filters, analog-to-digital conversion circuitry, telemetry, and so on), and a recording element (analog visible or direct, frequency modulation, or digital magnetic tape or disk). Seismographs are used for earthquake studies, investigations of the Earth's gravity field, nuclear explosion monitoring, petroleum exploration, and industrial vibration measurement.

Design requirement

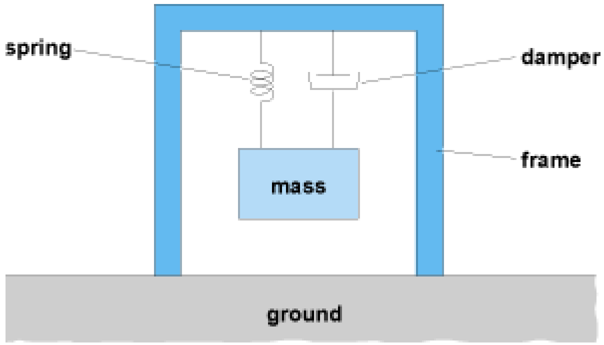
Seismographic instruments may be required to measure ground motions accurately over a range approaching 12 orders of magnitude, from as small as 10^{-11} m (the Earth's background noise level in the 2 mHz to 100 Hz band at very quiet sites) to as large as several meters (strong ground motion in the near-field of a very large earthquake). The instruments may be required to measure frequencies as low as $\sim 10^{-5}$ Hz (the semidiurnal gravitational tides), and even lower frequencies that are involved in tectonic strain monitoring, to as high as $\sim 10^{4}$ Hz (as observed from acoustic emissions from rock failures in mines at distances of a few meters). Seismic waves from earthquakes are observed in the bandwidth of $\sim 3 \times 10^{-4}$ Hz (the gravest free oscillations of the Earth) to ~ 200 Hz (a local earthquake recorded by a seismometer installed in a borehole 100+ meters deep). In exploration seismology the frequency range of interest is typically 10–1000 Hz. No single instrument can operate over such a large dynamic range and frequency bandwidth. Thus a variety of instrumental designs are seen in seismometry.

Seismometers

The seismometer is the basic sensing element in seismographic instruments, and there are two fundamentally different types: inertial and strain. The inertial seismometer generates an output signal that is proportional to the relative motion between its frame (usually attached to the ground or a point of interest) and an internal inertial reference mass. The strain seismometer (or linear extensometer) generates an output that is proportional to the distance between two points.

In the inertial seismometer (**Fig. 1**), the inertial mass is an element of a damped mechanical oscillator, in either a spring-mass or a pendulum configuration. The restoring force may be either an elastic force (including the inertial elasticity of a piezoelectric device), an electrical spring, or gravity. Damping may be achieved by the use of viscous fluids or by electrical feedback to provide a force that resists the relative velocity of the suspended mass.

Principle of the vertical-component inertial seismometer. Motion is measured between the mass and the frame.



Regardless of the design details, the behavior of inertial seismometers is described by the basic second-order differential equation for the harmonic oscillator,

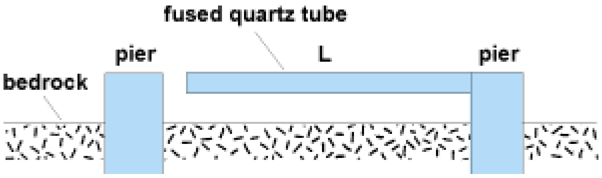
$$\frac{d^2x}{dt^2} + 2\zeta\omega_n\frac{dx}{dt} + \omega_n^2 x = \frac{d^2z}{dt^2}$$

where x is the relative motion between the mass and the frame, ζ is the damping factor ($\zeta = 1$ is critical damping), ω_n is the natural frequency (in radians per second), and z is the frame (ground) motion. The relative displacement, x, or the relative velocity, dx/dt, is sensed by an appropriate transducer. Displacement transducers are typically optical, variable-capacitance, or linear vector differential transformer (LVDT) devices. Velocity transducers invariably used coil-magnet systems until recently. However, a new type of velocity transducer has been developed which uses a molecular electronic transfer cell to detect the motion of an electrolytic fluid. In the case of piezoelectric (lead zirconate titanate, or PZT) seismometers, the voltage generated across the piezoelectric element is proportional to acceleration at frequencies below the resonant frequency (normally very high) of the piezoelectric device. See also: Harmonic oscillator; Piezoelectricity; Transducer

The output of a seismometer is a signal, usually electrical, that is proportional to some function of the ground motion, z. It is possible for this signal, over some frequency range, to be directly proportional to the ground displacement (z), the ground velocity (dz/dt), or the ground acceleration (d^2z/dt^2). Within such frequency ranges, seismographs are commonly referred to as displacement seismographs, velocity seismographs, or accelerographs, respectively. That is, the recorded amplitude represents the appropriate ground-motion quantity multiplied by a frequency-independent constant (the magnification, the velocity sensitivity, or the acceleration sensitivity of the seismograph) for motion in the particular frequency range.

A strain seismometer (or linear extensometer) [**Fig. 2**] is capable of providing a continuous precise measurement of the distance between two points, spaced typically 1 m to 1 km (3.3 ft to 0.6 mi) apart. A wide variety of designs have been implemented, using as reference lengths (L) from one point to the vicinity of the other point such standards as fused silica rods or light beams. Rod-based extensometers normally use a capacitance displacement transducer to sense variations in the position of the reference rod end with respect to the other reference point. Light-beam extensometers invariably incorporate some type of interferometer to detect changes in the length of the optical path between the two reference points. Longer paths require evacuated tubes and laser sources to achieve adequate sensitivity and stability in the length change measurement. The frequency range of interest is from zero to no more than $\sim$1 Hz in most systems. See also: Interferometry

Principle of the linear extensometer in a strain seismograph. Motion is measured between the left pier and the free end of the quartz tube.



The quantity measured in these instruments is the change Δ*L* in the reference length *L*. The ratio Δ*L*/*L* gives the horizontal component (typically) of the strain between the two points. With a displacement resolution of 10^{-9} m (3.3×10^{-9} ft), a 100-m (330-ft) extensometer can measure changes in strain of 1 part in 10^{-11}. However, practical limits in environmental controls (temperature, atmospheric pressure, and mechanical stability) yield long-term stabilities no better than 10^{-7} per year for such instruments.

Secular (long-term) strains are also measured using very long baseline interferometry (VLBI) and geodetic Global Positioning System (GPS) techniques. VLBI uses phase differences in signals from extraterrestrial radio sources (quasars) observed simultaneously at points separated by continental dimensions. Accuracies of a few centimeters in a few thousand kilometers are observed, for a resolution of 10^{-9} in relative distance change between the two remote points. The GPS system is used to observe geodetic strain by absolute position measurement on the Earth's surface. The geodetic deformation is monitored with both continuous (permanent) stations and campaign measurements (temporary deployments at existing benchmarks) over a period of a few years. Accuracies of a few millimeters are attained. See also: Geodesy; Satellite navigation systems

Seismoscopes

A seismoscope is a device that indicates only the occurrence of relatively strong ground shaking and not its time of occurrence or duration. A typical seismoscope inscribes a hodograph of horizontal strong ground motion on a smoked watch glass.

Dilatometers

A dilatometer continuously and precisely measures volumetric strain. The quantity measured is the change Δ*V* in the reference volume *V*, and the ratio Δ*V*/*V* gives the volumetric strain. Dilatometers are typically installed in boreholes in competent rock (preferably granite) at a depth of 100–300 m (330–1000 ft).

Tiltmeters

A tiltmeter monitors the relative change in the elevation between two points, usually with respect to a liquid-level surface. The horizontal distance between the reference points may be as little as a few millimeters or as large as several hundred meters. A displacement transducer is typically employed to sense the vertical separation between the two liquid-level surfaces. Environmental effects limit the long-term stability to about 10^{-6} radian.

Tilt at a point can be measured by an inertial seismometer. Tilt of the horizontal surface is indistinguishable inertially from a horizontal acceleration of magnitude $g \sin \theta$, where θ is the angle and g is the acceleration due to gravity. Any seismometer with DC (direct current or zero frequency) response to acceleration (for example, a horizontal pendulum equipped with a displacement transducer) is therefore a tiltmeter with constant tilt sensitivity throughout the frequency range where its output is proportional to acceleration. See also: Accelerometer

Gravimeters

The gravity meter is just a vertical-component accelerometer, that is, a pendulum sensing ground motion and equipped with a displacement transducer, analogous to the inertial tiltmeter. In its most widely used form, the pendulum is small for portability and ease of thermal stabilization, with a natural frequency of ∼0.1

Hz. Transducer technology and environmental control methods allow the best gravimeters to have a repeatable accuracy of $\sim 10^{-8}$ g. Gravimeters are widely used in geophysical exploration, in the study of earth tides, and in the recording of very low frequency (0.0003–0.01 Hz) seismic waves from earthquakes. See also: Earth tides; Earthquake; Geophysical exploration; Seismic exploration for oil and gas; Seismology

Recording systems

The complete seismograph produces a record of the properly conditioned signal from the seismometer, along with appropriate timing information. The recording system may be a simple as a mechanical stylus scratching a line on a smoke-covered drum in a portable microearthquake seismograph, or as complex as a multichannel computer-controlled system handling 25,000 24-bit digital words per second in a modern seismic reflection survey for petroleum exploration. The range between these extremes includes many special-purpose seismographs, all designed to record ground motion in a particular application.

Deployment

Many methods are used for deploying seismographs, and they depend upon whether the site is temporary or permanent and whether the site is land-based or on the ocean bottom. Seismic station installations are susceptible to several types of noise that contaminate or even mask the desired signals, effectively reducing the operating sensitivity of the instrument. These noise sources are of several types: atmospheric, cultural, ocean current, microseismic, and ambient temperature variation. The atmosphere affects the seismometer through pressure fluctuations directly on the mechanical system and indirectly on the surrounding ground. Cultural and industrial vibrations from human activities can be measured near any population center. In the case of seismographs deployed on the sea floor, ocean currents are a large noise source. Microseisms, the natural background vibrations of the Earth, are generally larger near continental margins than inland—a result of wave action on the coastline. For feedback broadband seismometers, ambient temperature variation is also a significant source of noise.

In the conventional land-based permanent seismographic station, the seismometer is placed upon a stable (usually concrete) pier in an environment as noise-free as possible. Two deployment methods have been devised to mitigate against noise sources. One technique uses seismometers in closely spaced arrays, relying on the coherency of the signal of interest over the array dimensions, and the lack of correlation of the noise components in the seismic wave field. This method is applied successfully in seismic reflection surveying, and in the arrays deployed to monitor from large distance the seismic waves from detonation of underground nuclear explosions. A second noise-reduction method uses borehole or deep mine installations to take advantage of the natural attenuation with depth of much of the noise field due to shallow propagating surface waves, to attenuate the effects of the surface ground motion due to atmospheric pressure fluctuation, and to provide temperature stability.

When deploying a temporary array of portable seismographic stations, as required for aftershock studies or research investigations, the siting criteria also include obtaining permission from the land owners and concerns about vandalism. The portable seismographs are typically housed in small enclosures that are placed on the surface or buried in the ground a few feet. The stations are generally battery- and solar-powered and have sufficient storage capacity to run unattended for weeks to months. Siting the seismometer on hard rock and away from cultural noise sources is preferable but not always possible. Instrument pools of portable seismographs exist for a wide variety of seismic studies. The Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrumentation center, for example, maintains a large stockpile of portable seismographs that are used by researchers.

In the deployment of an ocean bottom seismograph (OBS), the logistics and installation problems are formidable. However, there is considerable incentive to place seismographs on the sea floor since it represents the largest uninstrumented area of the Earth's surface. A number of specialized methods have been devised for deploying, servicing, and retrieving OBS instrumentation. Borehole installations in the sea floor produce the lowest noise levels. Most OBSs use retrievable instrument capsules with on-board recording and sufficient battery capacity for unattended operation from a few weeks to a year or more. Some permanent OBS stations have been installed along cables that link them to shore and provide telemetry and power. Transoceanic telephone cables, decommissioned as a result of increasing reliance on satellite communications, are being considered for the installation of permanent OBS stations on the sea floor. OBS instrument pools exist for a wide variety of seismic studies. For example, both the Ocean Bottom Seismograph Facility of the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution Marine Seismology Group maintain a pool of OBS instrumentation for use by researchers.

Thomas V. McEvilly
Robert A. Uhrhammer

Bibliography

- M. E. Ander, T. Summers, and M. E. Gruchalla, LaCoste & Romberg gravity meter: System analysis and instrumental errors, *Geophysics*, 64:1708–1719, Society of Exploration Geophysicists, 1999
- G. Anderson, H. Staudigel, and F. K. Wyatt, A seafloor long-baseline tiltmeter, *J. Geophys. Res. B*, 102:20269–20285, 1997
- C. R. Bradley, *Very Low Frequency Seismo-acoustic Noise below the Sea Floor*, Ph.D. thesis, MIT/WHOI Joint Program in Oceanography, 1994
- C. Braitenberg, The hydrologic induced strain-tilt signal, a review: Analysis of environmental data for the interpretation of gravity measurements, *Marees Terrestres: Bulletin d'Informations*, 131:10171–10181, Observatoire Royal de Belgique, 1999
- W. K. Cloud, Instruments for earthquake investigation: Earthquake investigations in the western United States, 1931–64, *U.S. Coast Geod. Surv. Publ.*, 41-2:5–20, 1965
- J. Dewey and P. Byerly, The early history of seismometry (to 1900), *Bull. Seismol. Soc. Amer.*, 59:183–227, 1969
- J. Fowler, PASSCAL: A facility for portable seismological instrumentation, *EOS: Trans. Amer. Geophys. Union*, 75:66, 1994
- B. S. Melton, Earthquake seismograph development: A modern history, parts 1 and 2, *EOS: Trans. Amer. Geophys. Union*, 62:505–510, 545–548, 1981
- G. D. Myren and M. J. S. Johnston, Borehole Dilatometer Installation, Operation and Maintenance at Sites along the San Andreas Fault, California, *USGS Open-File Rep.*, no. 89-0349, 1989
- R. A. Stephen et al., The Seafloor Borehole Array Seismic Systems (SEABASS) and VLF ambient noise, *Mar. Geophys. Res.*, 16:243–286, 1996
- R. A. Uhrhammer, B. Romanowicz, and W. Karavas, Broadband seismic station installation guidelines, *Seismol. Res. Lett.*, 69:15–26, 1998
- E. Wielandt, The leaf-spring seismometer: Design and performance, *Bull. Seismol. Soc. Amer.*, 72:2349–2367, 1982

Additional Readings

- U.S. Geological Survey Albuquerque Seismological Laboratory (ASL): Seismic Background Noise Modeling and Reduction
- Incorporated Research Institutions for Seismology (IRIS) Global Seismic Network (GSN)
- Incorporated Research Institutions for Seismology (IRIS) Program for the Array Seismic Studies of the

Continental Lithosphere (PASSCAL)
- Office of Naval Research (ONR) Ocean Bottom Seismograph (OBS) Facility, Scripps Institution of Oceanography (SIO)
- Woods Hole Oceanographic Institution (WHOI), Marine Seismology Group
- Guidelines for Installing Broadband Seismic Instrumentation

How to cite this article

Thomas V. McEvilly, Robert A. Uhrhammer, "Seismographic instrumentation", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.613200