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Long-Term Measurements of Ground Motions Offshore

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SYNOPSIS Long-Term measurements of earthquake ground motions offshore, using the Sandia National Laboratories' SEMS device which records only the strongest motions and transmits them upon command to a boat at the surface, have shown that offshore ground motions may in certain cases be substantially different from empirically predicted ground motions based on onshore data. In particular, the attenuation effects of soft and/or gassy soils, the wedging of offshore deposits as a function of direction to and distance from the source, and sharp velocity-depth profiles, are shown to be possible factors contributing to such differences. For the well constrained recording to date, the offshore ground motions are only 13 to 23 percent of those which would be calculated using empirical predictions based on onshore data. To address this situation, Sandia has installed a net of three long-lived (SEMS), two of them in the vicinity of instrumented platforms, in the Sandia Barbara Channel. The results are intended to evaluate the earthquake hazards of offshore energy developments and to provide firm data on the design parameters required for the harvesting of offshore energy resources.

INTRODUCTION

Estimates of anticipated earthquake ground motion for offshore structures have to date necessarily been made from onshore records, because reliable long-term measurements of offshore ground motions have not been available.

Offshore ground motions may differ from onshore motions in several aspects: 1) attenuation factors may be different in saturated seafloor soils, especially if they are soft and/or gassy; 2) wave reflections within the water column may alter site-specific waveforms; 3) if the upper sediments are soft, with low seismic velocities, the resulting velocity profile (increasing sharply with depth) can lead to reflections which may resemble multiple earthquakes, or multiple hits from the same earthquake, at a given site; and 4) if the sediment profile is wedge-shaped as one departs the shore, the entrapment or expansion of the seismic waves may lead to focusing or defocusing effects at a given site. Finally, the location of offshore hypocenters always has some uncertainty because the seismographic net is onshore of the offshore event.

Sandia National Laboratories developed the Seafloor Earthquake Measurement System to obtain data on the possible unique aspects of offshore soil response to earthquakes.

OVERVIEW OF THE SYSTEM

The Seafloor Earthquake Measurement System (SEMS) development was sponsored by the Department of Energy, the U. S. Geological Survey, and five major oil companies (ARCO, Chevron, Gulf, Mobil, and Shell).

The principal design considerations for the SEMS were:

1. Low quiescent power consumption,
2. Broad dynamic range sensing capability,
3. Efficient use of a limited data storage,
4. Simple installation,
5. Remote operation, and
6. Flexible data recovery, including changing the decision-making capabilities of the device.

The SEMS is totally self-contained and consequently can be installed in remote frontier locations. The data are retrieved using a high-data-rate acoustic telemetry system which allows data to be collected at any time during the operational lifetime of the system.

The SEMS consists of two main subsystems:

1. The DAta Gathering Subsystem (DAGS)
2. The Command And Recording Subsystem (CARS), a portable receiving/recording station that provides surface command and recording capabilities.

Both subsystems are controlled by similar microcomputers, consisting of a microprocessor, programmable read-only memory (PROM), read/write random access memory (RAM), a real-time clock, a universal asynchronous receiver/transmitter (UART), and additional input/output devices as required.

The DAGS consists of a pressure vessel containing the batteries, electronics, and acoustic telemetry, and a probe containing the accelerometers and magnetometers (Figure 1). A ballast weight of 5500 to 7500 pounds is used to force the probe into the seafloor sediments. During installation, the SEMS and ballast weight are

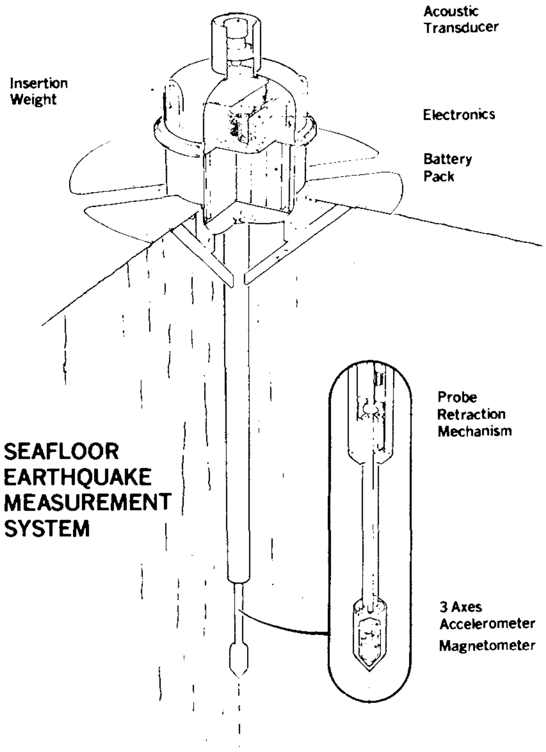

Fig. 1. Seafloor Earthquake Measurement System

lowered to the bottom using a 7/8-in electromechanical cable. The outputs of two orthogonal tiltmeters and a bottom-sensing foot, which are attached to the ballast weight, are continuously transmitted up the cable and monitored. These data, together with the condition of the electronics package being monitored via the acoustic telemetry, are used to determine when a successful installation has been accomplished. If the probe penetration is complete and the tilt is within 15 degrees of vertical, the installation is deemed successful, and the ballast weight is released from the pressure vessel and returned to the ship. When the ballast weight is lifted off the pressure vessel, a 20-in section of 1.5-in diameter pipe between the accelerometer sensor package and the probe is retracted into the probe, leaving the sensor package isolated from the probe.

A Sonotech Model 310 acoustic pinger/release is attached to the SEMS for location during routine data collection. The acoustic release also releases, upon command, a bouyant reel with an appropriate length of 9/16-in Kevlar line which is used to recover the system at the end of its operational life.

Ground motions are measured by a 3-axis, force-balanced, quartz-suspension accelerometer package capable of measuring acceleration levels from 10^{-4}g to 1 g and from dc to 20 Hz. In addition, there is a 2-axis magnetometer mounted with the accelerometers for determination of the azimuth orientation of the accelerometers.

The mass memory consists of 1.08 million bits of magnetic bubble memory. This is equivalent to 218.4 seconds of seismic data. The mass memory is partitioned into eight 27.3-second blocks. Data from a single event can occupy from one to eight blocks, depending on the length and size of the event. The system can store eight short events, one long event, or any combination in between. In order to make the most efficient use of the limited data storage capacity, a sophisticated algorithm is programmed into the microcomputer to control the data acquisition and storage functions of the system. The algorithm consists of two parts. One part of the algorithm determines when an event of interest has occurred. The second part of the algorithm determines whether the data from the event will be stored in the mass memory. The next few paragraphs will describe the details of the memory organization and the microcomputer-controlled data acquisition and storage functions.

The SEMS memory is organized into three separate sections. A 1.7-second pre-event ring buffer continuously accepts the output of all three accelerometers before an event is declared. A 25.6-second event buffer accepts the output of all three accelerometers when an event has been declared by the microcomputer. The mass bubble memory accepts the data from the pre-event and event buffers upon command from the microcomputer. The mass memory is divided into eight 27.3-second blocks (i.e., each block will hold the data from a pre-event and event buffer). The microcomputer monitors the status of mass-memory block, recording whether a block is vacant or occupied; and, if a block is occupied, the microcomputer records the size of the event stored in that block.

As previously noted, all three accelerometer axes are sampled every ten milliseconds, and the data are continuously run through a 1.7-second pre-event buffer. The event occurrence/data-storage algorithm uses only the vertical axis data to control the data acquisition and storage functions of the system. The first part of the algorithm, which determines when an event is occurring, is based on the short-term average/long-term average trigger commonly used in USGS and other systems (Eterno, 1974). The absolute value of the vertical accelerometer output is fed into two averagers. The first, the long-term (LTA), is an average of the 2048 samples, and is a measure of the seismic background level. The second, the short-term average (STA), is an average of the 128 samples, and is a measure of the present seismic level. The ratio of the STA to the LTA is normally one, but exceeds one when a seismic event is occurring. When this ratio exceeds a preset level, nominally 1.5, a seismic event is declared. When an event is declared, the LTA calculation is stopped and the LTA is held constant so that the subsequent event data will not give a false indication of the seismic background level. In addition, the data in the 1.7-second pre-event buffer are held fixed and the incoming data from all three axes for the 25.6 seconds are put in the event buffer.

The second part of the algorithm is entered when an event is declared. This part of the algorithm determines whether the data in the event buffer will be stored in the mass memory. A 25.6-second average of the STA is calculated.

This average is called the block size. The largest block size for an event is called the event size. At the end of 25.6 seconds, when a block of data is contained in the event buffer, and the event-size calculation is complete, the status of the eight blocks of mass memory is examined by the microcomputer. If a vacant block is found, the data in the event and pre-event buffers are stored in the vacant block. If no vacant blocks are found, the microcomputer compares the event size of the present event with the event sizes of the events already occupying the mass memory. If the event size of the present event is greater than the event size of the smallest event already stored in the mass memory, the mass memory blocks of that smallest event are declared vacant and the new block of data is recorded in the vacated mass memory block. If the present event is not larger than the smallest event in mass memory, the present event is delcared over and the system begins looking for another event. Thus one is assured of recording the strongest 218.4 seconds of motions which have occurred. If small events occur, or if spurious signals are recorded (e.g., geophysical surveys, disturbances from ships or adjacent platforms), they will be written over by larger events. This is considered to be a very valuable feature of the system: the events of the past do not preclude the recording of more interesting events of the future.

Data are retrieved using a high data rate acoustic telemetry system (Ryerson, 1980). Data are transmitted upon command from the seafloor package to a shipboard receiver where permanent digital tape records are made. If necessary, the acoustic link can also be used to change the operating and decision-making characteristics of the seafloor package. The data transmission rate of the acoustic link is 2400 bits per second.

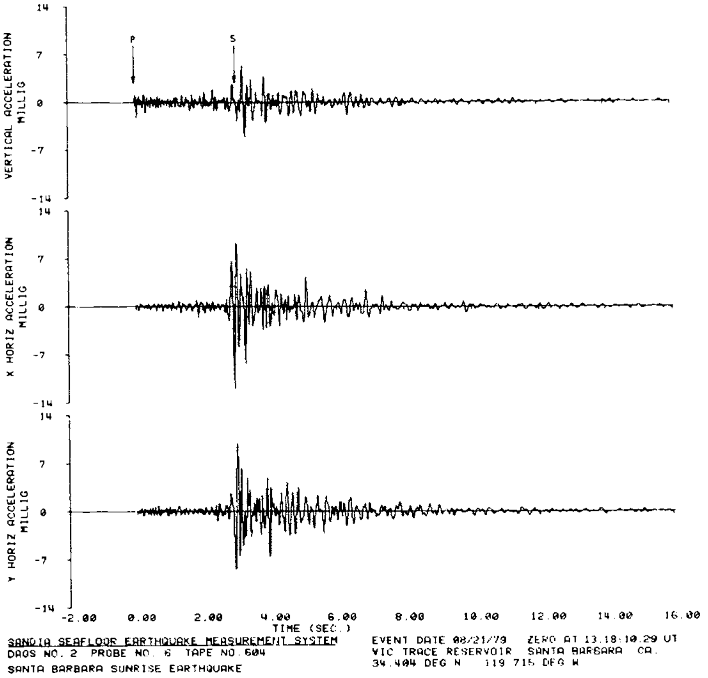

Fig. 2. Earthquake Recorded at Land Site

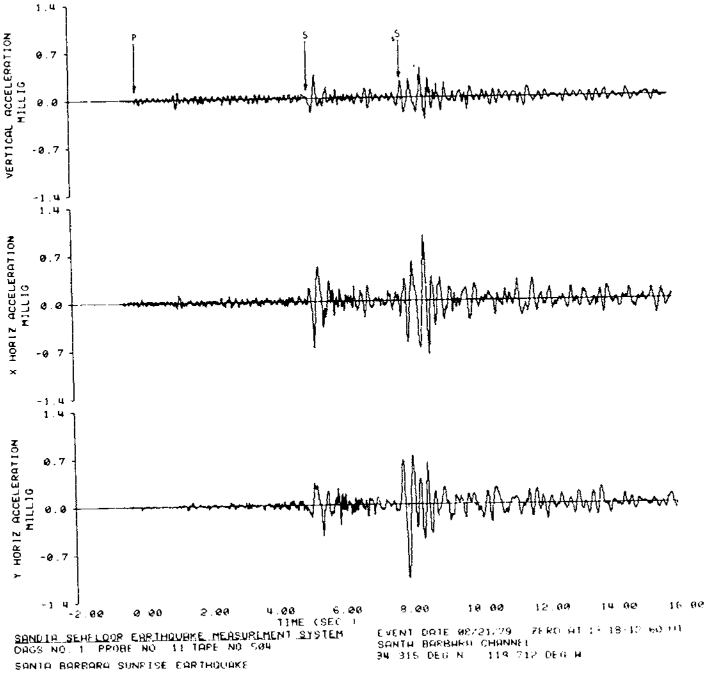

Fig. 3. Earthquake Recorded at Sea Site

FIELD TESTS

In order to evaluate the operational characteristics of the SEMS while maintaining access to the system, the SEMS was installed onshore in Santa Barbara, California in October 1978. Once the system operation was evaluated and modified as necessary, the initial prototype was installed in the Santa Barbara Channel in August 1979 approximately six miles south of the harbor in 400 feet of water. The initial unit operated satisfactorily through February 1980, when it was apparently dragged away by fishermen. During its seven-month operational life, the unit triggered 940 times and recorded seven earthquakes.

An example of an earthquake recorded by this system at the two sites is given in Figures 2 and 3, which show the components (vertical, two horizontal) from the land station, Figure 2, and from the sea station, Figure 3. The event is the Santa Barbara Sunrise Earthquake of 13:18:07.44 UMT August 21, 1979, local magnitude $M_L = 3.2$. The hypocenter was at a depth of about 2.8 miles, and the epicenter was 7.5 miles almost due north of the land site. The sea site, in turn, was 6.3 miles almost due south of the land site. Thus, the epicenter, land site, and sea site form a straight line, allowing a study of the attenuation of motions with distance, fairly close to the source, for this small earthquake. There are a number of empirical attenuation relationships which might be used for such a study. For brevity, only two are considered here:

	Predicted Maximum Acceleration, 10^{-3}g		
Reference	Land Site	Sea Site	Ratio Sea/Land
Donovan (1974)	50.7	35.7	0.70
Wight (1980)	8.0	3.0	0.38
Data, Figs 2 & 3	12	1.1	0.09

The results of both Donovan (1974) and Wight (1980) are for rock sites, and predict that the maximum accelerations recorded at the sea site should be in the range of about 40 to 70 percent of those recorded at the land site, if the sea site were rock. It is known that the upper few tens of feet at the sea site are soft clay, and that soft clay or other soft soils could persist to depths of many tens of feet. The work of Seed, et al (1975) shows that, for very small acceleration levels such as those of Figures 2 and 3, the accelerations at soil sites should be somewhat larger than those recorded at rock sites at the same distance from the earthquake source. Thus, one would expect, based on those empirical studies of onshore data, that the sea site would experience maximum accelerations in the range of, and perhaps somewhat greater than, about 40 to 70 percent of the land-site maximum accelerations. In fact, the sea-site maximum accelerations are only about 9 percent of the land-site maximum accelerations, indicating that, for this site, the attenuation of maximum acceleration is much greater than would be predicted by empirical studies of onshore data.

It appears in Figure 3 that the sea site was hit by two earthquakes, or hit twice by the same earthquake. For example, the weakest motions are from the P-wave, the next strongest by what appears to be the first S or surface wave, and the strongest motions are from the second S or surface wave. To study this situation, Helmberger and McNally (1980) performed a source-model study of this earthquake, with respect to the recorded motions at the land site and the sea site. They assumed a velocity profile similar to that for the Imperial Valley, California. Those calculations showed that both the land site and the sea site should be hit by an S-wave, sS, reflecting up from the deeper, higher-velocity, layers; that the acceleration magnitude of the sS at the land site should be small; that the arrivals of the primary S wave and the reflected sS wave at the sea site should be about 2.8 seconds apart; and that the S and sS accelerations should be essentially comparable, with the sS being perhaps a little larger. Reference to Figure 3 shows that the S and sS arrivals are about 2.8 seconds apart, and the sS accelerations are the larger. Helmberger and McNally (1980) also found that, in order to make the sea-site accelerations match what would be predicted from the source-modeling calculations based on the recorded land-site accelerations, it was necessary to adopt an extremely high value of attenuation for the shear waves. This agrees with the comparisons with onshore empirical results reported above.

It seems clear from these preliminary data and analyses that there may, in certain cases, be fundamental differences between onshore and offshore ground motions due to earthquakes. In particular: if the offshore soils are gassy, or if they wedge diminishingly toward the source, the motions could perhaps be less than at a similar onshore site; but if the soils are not gassy and if the velocity profile is sharp, or if the soils wedge expandingly toward the source, the motions could perhaps be more severe and more sustained than at a similar onshore site.

In order to provide some data to answer this question, Sandia National Laboratories has installed (October, 1980) three more SEMS in the Santa Barbara Channel. These systems were installed in the vicinity of platforms Hondo, Henry, and Grace in 500, 165, and 225 feet of water respectively. These systems incorporated an internal case to protect against fishing nets. The systems will be monitored for one year and will be recovered during September 1981.

CONCLUDING REMARKS

A unique Seafloor Earthquake Measurement System capable of measuring the response of marine soils to earthquakes has been designed, fabricated, and demonstrated. The system is totally self-contained and can operate unattended for up to one year in remote locations. The system uses sensitive force-balance accelerometers to sense the ground motions, and sophisticated microprocessor-controlled electronics to make event detections and data storage decisions. The system uses a high data rate acoustic telemetry system to transfer the data, on command, from the seafloor to a shipboard receiving station.

Preliminary analyses of the data from the first installation indicate that there may be conditions under which seafloor ground motions may be different from onshore motions. The SEMS net should provide long-term data on this situation.

ACKNOWLEDGEMENTS

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