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SYNOPSIS: This paper discusses the use of microseism measurement as a tool to predict local site amplification. Systems analysis techniques can be applied to the microseism data to validate site properties used in wave propagation analysis. Spectral ratio was found to be inversely related to peak rock velocity for soft sites. Microseisms can be used on a normalized basis to extend spatial response information.

INTRODUCTION

This paper discusses the Navy's research program to reduce the vulnerability to damaging earthquakes by developing better procedures to compute ground motion amplification. The Navy has numerous bases located in seismically active regions throughout the world. Safe design of waterfront structures requires calculation of the expected site specific earthquake ground motion for effective design of complex waterfront structures. The Navy's problem is further complicated by the presence of soft saturated marginal soils that can significantly amplify the levels of seismic shaking as evidenced in the 1989 Loma Prieta earthquake and again in the 1993 Guam earthquake. The Navy began its seismic program in response to the 1977 Earthquake Hazards Reduction Act. Executive Order 12699 reinforces that mandate for earthquake safety.

The prediction of seismic ground motion amplification at sites with marginal soil properties is of great importance to the Navy since those sites are so prevalent at the waterfront. Most of the naval facilities were constructed on such type soils before their earthquake damage potential was recognized. Current procedure for estimating ground motion at a Navy site involve performing a site seismicity study in which historical and geological data are used to estimate seismic ground motion levels for use in design of structures. Site specific spectra are then generated to account for local soil conditions using historical earthquake records. The data base of response records do not account for the response of soft marginal sites. An option for a more detailed analysis of local site response of marginal soils involves wave propagation analysis. This approach requires an insitu shear wave velocity profile to determine the site's shear properties. As a minimum, one dimensional wave propagation analysis is performed to determine ground motion amplification. This approach is complex, requires field data measurement and may result in significant underestimation of ground motion amplification for sites with marginal soils. This is not surprising since the approach is characterized by several problems.

Having identified the Navy problems from marginal soil, there is a strong need for a solution such as microzonation, the identification mapping of local site response that considers the specific local soil profile at a Navy base. The use of microseisms will be shown as a tool capable of adding considerable insight on the variation of site conditions, amplification of motion and fundamental period of site response.

MICROSEISMS

Microseisms are generated essentially in three ways (Hasselman, 1963): (1) action of ocean waves on coast, (2) atmospheric pressure variations over the ocean, and (3) nonlinear interactions between ocean waves.Long period microtremors have been observed for quite some time. However, most of the studies have been limited to their origins and wave characteristics (Longuet-Higgins, 1950 and Hasselman, 1963) while only few investigations studied them to explain the ground dynamics of earthquake motion (Ohta, 1978). Until recently, the latter problem has been considered only in the short period range (Tanaka, et al., 1968). Iida and Ohta (1964) investigated relationships between the amplitude of microtremors and soil structures and proposed correlation for the observations on Nagoya, Japan. Kubotera and Otsuka (1970) observed microtremors in the period range of 1 to 3 seconds in Aso Caldera area, Japan. They suggested that the microtremors are mainly Love waves with predominant period, which correlates well with the thickness of the soil deposits.

The Seismic System Model

In the 1960's and 1970's seismologists began to analyze the earthquake process in terms of an assemblage of components. This procedure is still in use today as a tool to better understand the elements that affect the response of a structure at a site. The system model consists of:

- Source model of fault mechanism
- Path model of transmission
- Local site model from bedrock to surface
- Structure model

This process allows for the development of component models that can not only be studied in the time domain but also in the frequency domain. Using linear system theory it is possible to establish a series of transfer functions to represent each of the components.

As early as 1961, Kanai (1961) proposed the idea on which recent work is based, developing the following model:

$$|G| = |E|\ |W|\ |X| = |I|\ |X| \qquad (1)$$

where all factors are complex functions of frequency and

G = surface motion at the site of interest
E = equivalent source motion
W = crustal bedrock path transfer function
X = subsurface site transfer function
I = incident motion at bedrock at the site

and the brackets symbolize the Fourier modulus. Using the above model allows the investigator to analyze sites where earthquake data were recorded. The model can be extended to include microseism excitation by use of two sites equally distant from the source such that it can be assumed they have the same source and path functions. In this case only local site conditions can be different. In microseism research, one site is chosen to be a rock outcrop reference site, the other a general soil site of interest. Fourier analysis will form a main analytical tool. The use of the Fourier spectra provides a measure of the system response. The transfer amplification can be represented as:

$$X = \frac{G(\omega)}{I(\omega)} \qquad (2)$$

If it is assumed that rock outcrop motion is the same as at bedrock, then the transfer amplification function is a direct measure of the soil sites spectral amplification and is a direct measure of its local site response.

System Identification

The system identification process is a powerful tool that can enhance the usage of microseism measurements to confirm fundamental site properties. To illustrate the concept we will focus on respresentation of a simple system composed of a single degree of freedom oscillator. The Fourier transform can be used to assist in quantification of system properties. The general equation of motion of the system can be expressed as:

$$m\,\ddot{y}(t) + c\,\dot{y}(t) + k\,y(t) = x(t) \qquad (3)$$

where:

m, c, k = scalar coefficients for mass, damping and stiffness
x(t) = excitation
y(t) = response

The transfer function can be shown to be:

$$|X(f)| = \left(\frac{1 + (2\zeta\, f/f_n)^2}{(1 - (f/f_n)^2)^2 + (2\zeta\, f/f_n)^2} \right)^{1/2} \qquad (4)$$

For low levels of damping, this can be approximated by the following at peak response frequency $f = f_n$:

$$|X(f)| = 1/(2\zeta) \qquad (5)$$

The system parameters can be estimated from the best fit of the response function. The system mass and stiffness control the fundamental period of response and the peak amplitude of response at the fundamental period is controlled by the system damping. In the specifics of the site response problem, the site is usually analyzed in an engineering analysis using wave propagation techniques. This technique requires a site profile to be modeled by a series of horizontal layers, each having density, shear modulus or shear wave velocity, and damping identified. The simplest boring log data usually reports density data, standard penetration blow counts, and soil classification. Often the blow count data are used to estimate shear wave velocity; however, the relationship between blow count and shear wave velocity is imprecise and has a high level of uncertainty. The density of data is usually more easily defined. The relation of modulus and damping with strain is obtained from laboratory tests and is usually approximated by graphs reported in the literature. Depending on the depth of the boring log, the depth to firm ground or bedrock may or may not be well established. So while under ideal circumstances, we can calculate the site response using wave propagation techniques, we are often limited by lack of data. The systems identification process allows us to use the measured microseism data, such as fundamental period of response and amplification to quantify the possible range of parameters. For example, if the computed period differs from the measured, consideration can be given to adjusting either the depth to bedrock or the initial modulus of the soil which affects the stiffness. If for example the depth to bedrock were well established by the boring log, emphasis could be placed on the shear modulus, since density is usually defined. The amount of damping can be adjusted to converge on the appropriate level of amplification. In this way the measured response to microseims can be used to confirm low level site response and associated material properties. This allows us to converge on an acceptable site model especially when site response strong motion data are lacking. The process helps reduce the levels of uncertainty and establishes the bounds of material properties and site response.

MICROSEISM MEASUREMENTS

This section discusses tests conducted to investigate the effects of geology, reference site selection and nonlinearity of response. Understanding the regional geology is fundamental to selection of an appropriate reference site and correct interpretation of the microseism results. The following sections will discuss the region and the series of microseism measurements performed.

• **Geology of the Oxnard Plain.** The Oxnard Plain represents an ancient delta of the Santa Clara River and was formed at the end of the last glacial epoch that resulted in the surface sediments being interlayered sands, silts, and clays. The San Pedro Formation of Lower Pleistocene age is encountered at approximately 400 feet. Igneous and metamorphic rock are believed to be at depths of 6,000 feet or more. The Quaternary sediments underlying the Oxnard Plain are about 3,400 feet thick in the area near the Naval Facility Engineering Service Center (NFESC), Port Hueneme. The youngest of the Quaternary sediments are composed of loosely to poorly consolidated Holocene (recent, less than 10,000 years old) materials deposited during the post-glacial period of rising seal level and include marine, lagoonal, lacustrine, fluvial-flood plain, deltaic, and eoliian environments. These materials consist of sand, gravel silt, clay, mudstone, local regions of cobbles and boulders, and occasional regions of lenses of peat, carbonaceous material, and sea shells.

• **Microseism Measurements.** A number of soil sites were selected in the NFESC compound for array measurements, the results of which will be presented in following sections. Building 582, a one-story, prefabricated metal building was selected as the location for (relatively) long term reference measurements.

To evaluate the fluctuation of microseism activity over a period of time, instruments were installed at Laguna Peak, a rock reference site and at NFESC Building 582. Laguna Peak is a Navy controlled site with accessibility to facilitate long term measurements. The instruments were set to record the East-West component at 20 Hz for 5 minutes every 2 hours for several days. Figure 1 shows the fluctuation of the record with time for Fourier spectra. The results show that there is daily fluctuation in the level of signal as would be expected. It is important to note that the spectral amplitude of both sites

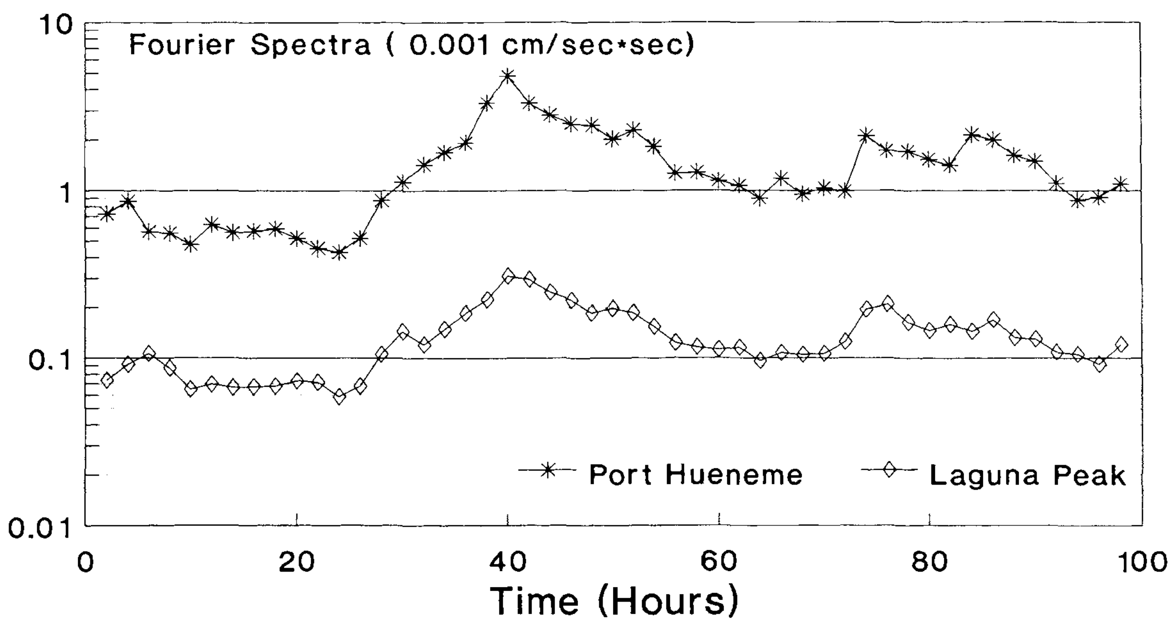

Fig. 1. Fourier spectra for Port Hueneme (soil site) and Laguna Peak (rock reference site).

increases and decreases in unison. This demonstrates the concept of stability of the spectral ratio between both sites. It should be noted that the fluctuation in signal amplitude is gradual. It is reasonable to assume stationarity of the process over a period of minutes to perhaps as much as several hours, but there are significant fluctuations over longer periods.

- **Topography Effects.** The Laguna Peak site was chosen for further study as the main rock reference site. To evaluate the effect of the topography a sea level rock reference site was chosen, Mugu Rock. The Mugu Rock-Laguna Peak transfer function was evaluated. This would allow soil site data to be reference to both Mugu Rock and Laguna Peak. A ratio of about 2 is to be expected for the effect of mountain topography based on the geometry. The horizontal component spectral ratios are on the order of 2 in the period range of 0.5 to 1 second and then approach 1 at higher periods. Both rock sites had relatively narrow bands of signal; computation of spectral ratios outside this band results in division of small numbers by small numbers and hence the spectral ratio in the region of low signal is prone to error. It can be concluded that the topographic effect of the mountain topography is relatively small and is quantified.

- **Array Measurements NFESC Site.** To determine the spatial variation of amplification at the NFESC site, a series of measurements were made using Laguna Peak as the reference site. Twelve stations were used in the measurement. Measurements were made for 5 minutes at each station and all measurements were completed in about 4 hours. Fourier spectra were computed for each station; and for the reference site at Laguna Peak. Spectral ratios were then computed. Figure 2 shows contours of spectral ratio. It must be recognized that contour plots are an attempt to give a spatial representation of the variation of spectral ratio. The spectral ratio is a function of period and must be divided into bands for representation. There is subjectivity involved in the presentation of the data using contour plots. First the division of spectral ratio into bands is judgmental, and second the representation of the data in each band varies in amplitude. One might choose to average the data within the band as shown in Figure 2 or perhaps to plot maxima for each period band. The reader should be aware that the contour plots have limitations and are only expressions of the data. Each spectral ratio is a unique, complete transfer function that shows how one site responds relative to another. The spectral ratio contours are intended to facilitate location of soft spots where amplification is greatest. From the contours, it is noted that the NFESC site does have variation of $\pm$ 15 percent. This is not a major variation and would be expected at a waterfront site.

SITE ANALYSIS

A one-dimensional wave propagation analysis was performed using the data from the boring logs that consisted of soil classification, dry density, and blow count. The blow count data were used to estimate shear wave velocity. Data from the U.S. Army Waterways Experiment Station data base, Sykora (1989), relating blow counts to shear wave velocity for Holocene sands were used. There is considerable uncertainty to estimating shear wave velocity from blow count data. Since laboratory test data are not available, standard relationships correlating modulus attenuation with strain and damping with strain had to be used. The deepest boring logs available for the site and neighboring areas are less than 100 feet. It was estimated that the shear wave velocity reaches 2,500 ft/sec at a depth of 250 feet. With all the assumptions made, the analysis can be only an approximate calculation, but is typical of actual field investigation conditions. The soil profile based on a specific boring log was used as the basis for a one-dimensional wave propagation analysis. The damping was estimated to be about 0.014 of critical based on the A3 station data using the systems identification process applied to the microseism data. Material property-strain level iteration to produce material properties at earthquake effective strains was

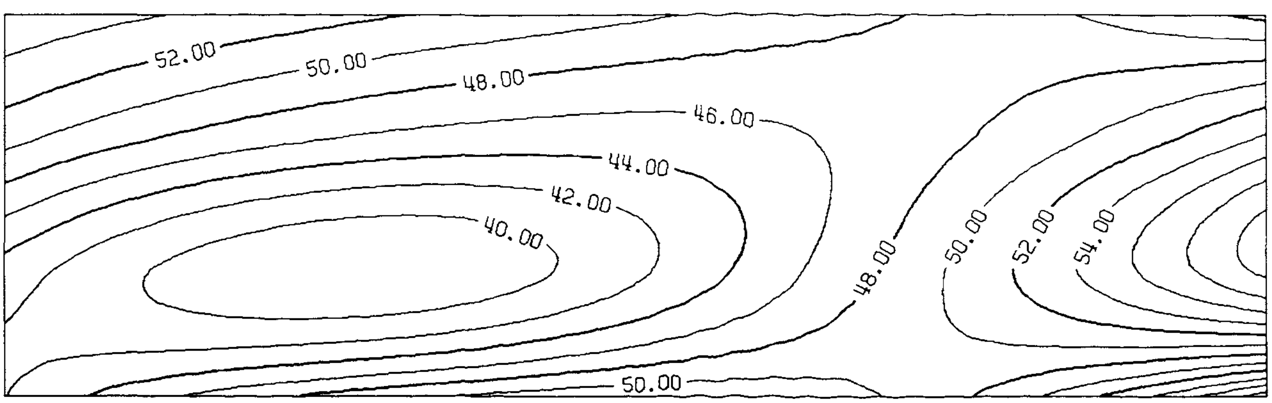

Fig. 2. Contours of East component microseisms Navy Engineering Center area.

omitted since the low level of excitation effectively represented initial values. A microseism acceleration record recorded at site A3 was used as the input motion and assigned at the surface. The results reproduced both the level of amplification and the fundamental period.

The same profile was used for a nominal earthquake at 0.1 g bedrock motion. A nominal 0.1 g acceleration was introduced at a depth of 250 feet. The site is seen to increase surface acceleration significantly. Using lower bound estimates of shear wave velocity reduces the spectral amplification by about 15 percent with only minor reduction in surface acceleration. Variation of the depth of the soil profile results in shifts in the location of the spectral peaks. It was noted that the effect of higher strain levels causes a slight shift of the fundamental period of the site from about 0.5 to about 0.66 and a reduction in amplification from about 48 to about 12. It is again noted that nonlinear scaling effects exist at soft sites between microseism levels of excitation and strong motion levels from earthquakes. The systems identification process applied to microseism measurements is an important step in calibrating and validating site properties for use in analysis.

For an engineering application, the spectral ratio contours can be normalized and used in conjunction with the one-dimensional analysis. This procedure allows the microseism measurements to be used to extend the calculations to augment the lack of spatial data. We are able, by using the systems identification process, to adjust site profile characteristics to agree with measured period of response and then extend the range of that data to cover the measured stations. The computed surface acceleration from the full scale earthquake serves as the basis motion to be used with the normalized contours. The procedure extends data from the single boring log location across the whole site and calibrates the computed response to measured data. A transfer function can be constructed by dividing the spectral ratio of any site by that of site A3 chosen as the reference because it had boring log data and was used for the calculation.

Earthquake Data Treasure Island

Data was compiled in an attempt to develop a trend to amplification at soft sites. Darragh and Shakal (1991) report data for Treasure Island and Figure 3 shows peak spectral ratios for the Treasure Island/Yerba Buena site pairs for the Loma Prieta earthquake and a number of aftershocks. Note that the Yerba Buena site serves as a rock reference site for the soft soil site at Treasure Island and the Y axis reflects the peak rock velocity at the reference site. Also plotted on Figure 3 is microseism data recorded at the same site as part of this project.

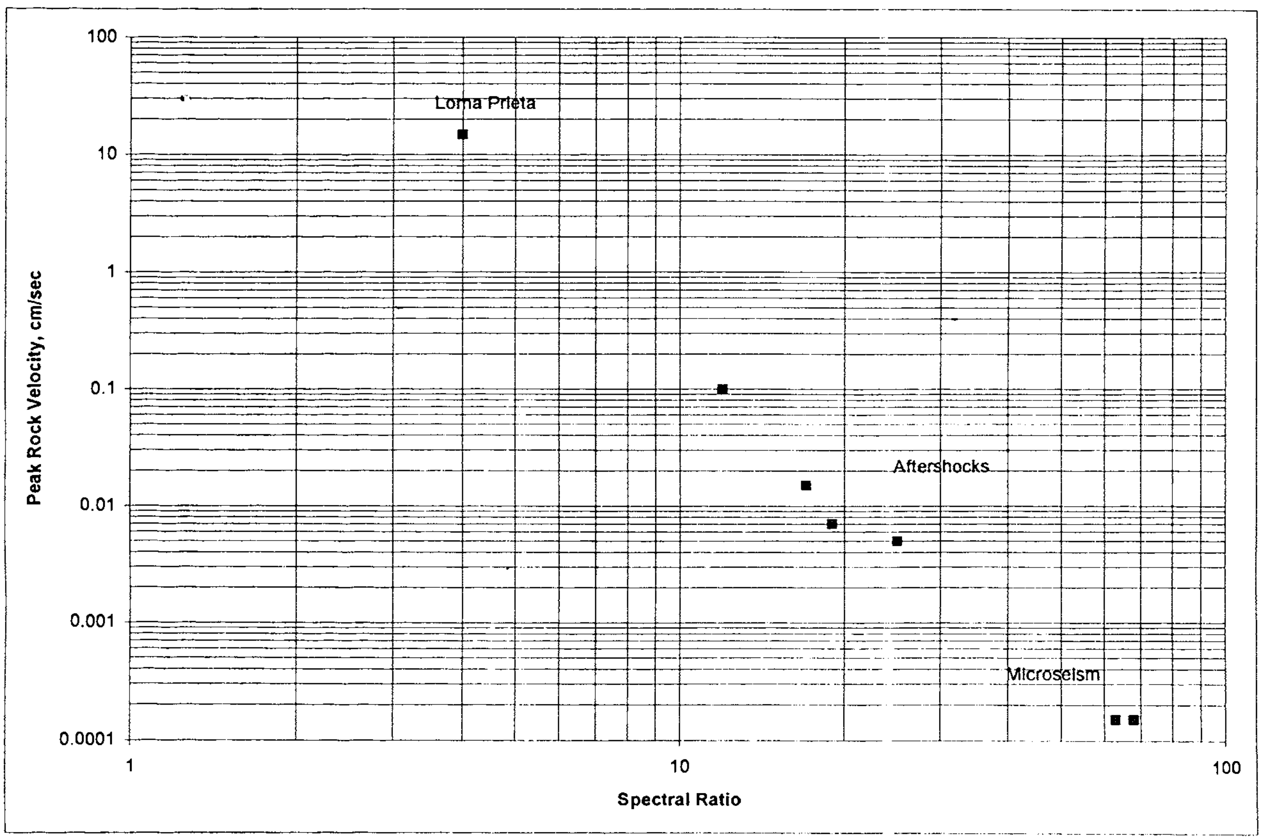

Fig. 3. Relationship between spectral ratio and peak rock velocity for Treasure Island/Yerba Buena Island sites.

Note that the microseism data points are an extension of the strong motion data establishing a clear trend. A relationship can be established for soft sites such that the spectral ratio amplification is inversely proportional to the peak rock velocity. Data for Gilroy and Coalinga also support this conclusion.

SUMMARY

This paper has shown that microseism measurements can be used to gain insight on local site behavior. Measurements can be made between nearby pairs of rock and soil sites and spectral ratio amplification functions constructed. High values of peak spectral ratio were observed on a number of soft sites indicating an inverse relationship between peak rock velocity and amplification. Sytems analysis techniques can be used on the microseism data to establish site soil parameters. Wave propagation techniques can be used to analyze a site and then the site model extended to strong motion response calculation. In summary microseism measurements offer the potential for improving local site microzonation. Space limitations have precluded presenting all of the data, which can be found in Ferritto (1994).

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