EARTHQUAKE RESPONSE SPECTRA FOR SOIL-FOUNDATION-BUILDING SYSTEMS

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SYNOPSIS

The seismic response of buildings which takes into account the interacting effects of the supporting soil medium; the foundation construction including the performance of piles, piers and basements for buildings of 1 to 15 storeys above grade has been investigated using a cyclic truss type model to simulate the soil-foundation-building systems. One horizontal component and the vertical component of the 1940 El Centro and 1952 Taft earthquake accelerations have been selected as input excitations. The seismic response is largest for low, short period buildings on hard soil; least for the filled ground; and intermediate for rock formation and soft type soil. The response amplitudes vary for different soil types, foundation construction and building height and they are considerably reduced with increasing soil damping. The vertical acceleration input produces considerable axial forces in the columns of low buildings supported on hard type soil.

INTRODUCTION

There is lack of general agreement among engineers as to the quantitative effects of different site conditions and foundation construction on the seismic response of buildings ranging from low, medium and high-rise classifications. Solution of this problem is essential for rational improvements in seismic design and for protection of life and property.

With the attainment of this objective in mind, many hundreds of experiments have been performed by computers using the soil-foundation-building (SFB) system model which is cyclic and truss type to simulate actual buildings supported on different soil types and provided with proper foundation construction. It has been found that there exists a singular response spectrum for a certain soil kind and the response amplitude is dependent on the predominant period and the amount of energy dissipative capacity (damping) of the soil. The singular response curves for four soil types have been integrated into a Multiple Spectra (MS) Response Curves for use in seismic design of buildings. The MS response curves provide satisfactory explanation why low buildings of short periods supported on "good" soil often suffer serious damage. A method of estimating the earthquake force on buildings is proposed for consideration by earthquake-structural engineers. Evidence (not speculations) to substantiate, modify or refine the findings described in this paper would be welcomed.

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SIMULATION MODEL

The model to simulate the soil-foundation-building system is shown in Fig. 1. The surface soil formation above the firm base stratum consists of three layers, each of 5m thickness. Four soil types according to Japanese classification, namely, Type 1, rock; Type 2, diluvium or hard soil; Type 3, alluvium or soft soil; and Type 4, filled soil are considered and the vibrational characteristics are represented by predominant vibration periods, assumed to be 0.1 sec for Type 1; 0.25 sec for Type 2; 0.5 sec for Type 3 and 1.0 for Type 4 soils. The damping ratios assumed are 3% and 5% for rock, 5%, 10% and 20% for hard and soft soil types and 10% and 20% for filled ground, respectively. Unit weight of 1.8 t/m^3 and Poisson's ratio of 0.49 have been assumed for all soil types.

The foundation construction (FC) refers to piles (p), piers (P) and basements (B) for low, medium and high buildings of 1 to 15 storeys. Buildings up to five storeys (N5) are supported by piles while those of eight storeys (N8) or more are supported by piers. Buildings up to 10 storeys are of reinforced concrete (RC) or steel encased in reinforced concrete (SRC). They are modelled to have natural periods (T) based on the relation expressed by $T=0.085N$ sec while buildings taller than ten storeys are of steel (S) construction having periods computed by $T=0.10N$ for the condition of being fixed at the ground level (GL) to a rigid supporting medium. The damping ratio of 3% has been assigned to buildings of different construction and heights. Storey height above ground of 3.5m and basement storey height of 5m have been adopted.

The diagonal members provide the stiffnesses required to simulate the soil, the foundation, and the building components of the system. The columns, girders and diagonal bracing members have the necessary sectional areas for vertical and horizontal loads. Lengthening and shortening of columns from over-all bending are taken into account and the diagonal members resist the lateral forces. The weight of the building is concentrated at the intersection of girders with the columns and similarly at the intersection of horizontal and vertical elements for the basement and the soil mass. The area of diagonal elements for the foundation and soil is proportioned for the required stiffness.

The surface soil formation is continuous in the horizontal direction and a cyclic model of unit length of 50meters is used with buildings standing at 50 meters on centers. The fact that interaction effects of buildings at this separation distance are negligible has been ascertained from previous investigation[1)]. The use of a cyclic type model avoids the need of assuming boundary conditions at the left and right sides of the cyclic model which are sometimes troublesome to deal with.

METHOD OF ANALYSIS

Assigning of varied damping ratios to the building and different soil types necessitates the solution for complex eigenvalues. The solution has been obtained by the QR method and these values are used in the modal analysis by superposing the first 15 modes. The seismic response amplitudes have been determined by the modified linear acceleration method in the usual manner. The case of uniform damping ratio of 5% assigned to the soil-building system has also been solved by the Givens-Householder method for the purpose of comparison with the other cases having different damping values.

The 1940 El Centro and 1952 Taft earthquakes have been used as input excitations, both normalized to 100 gal maximum horizontal acceleration and 60 gal maximum vertical acceleration. These wave forms are fed to the model simultaneously at the bed rock level, -15 meters from the ground surface.

RESULTS OF STUDY

The relation between periods of vibration for SFB system and the base shear coefficients C_B is shown in Fig. 2. Maximum response occurs near the predominent period for each soil type and the response is largest for the uniform damping of 5% for the building and the soil, designated by (5-5) in the figure. For each soil type, the response values decrease as the soil damping is increased from 5%, 10% to 20%, indicated by the response curves marked (3-5), (3-10) and (3-20).

The base overturning moment coefficient, C_M, defined as the total overturning moment at the base divided by the product of the building weight and the distance to its centroid from the GL varies in a manner closely resembling the base shear coefficient variation pattern.

The vertical component input of 60 gal produces axial force variation of plus-minus 20% of the building weight at the base expressed by the base axial force coefficient, C_A, defined as the ratio of the axial force in the columns at the base divided by the building weight above that level. Maximum values occur for low buildings supported on hard soil. The values decrease with increasing height and corresponding increase in the natural period of the buildings.[2)][3)]

SEISMIC DESIGN USING MS RESPONSE CURVES

Based on response curves for soil types and damping ratios obtained through many case studies, a Multiple Spectra (MS) Response Curves have been plotted for: Rock with 3% building and 3% soil damping ratios, Hard with 3% and 5% damping; Soft with 3% and 10% damping, and Fill with 3% and 15% damping as shown in Fig. 3. The basic seismic coefficient, C_o, is plotted against SFB system periods. The maximum response amplitude for Type 3, soft soil is proposed as the standard seismic coefficient of 0.3 maximum. On this basis, the maximum basic seismic coefficients for Rock is 0.4, Hard 0.45, Soft 0.3, and Fill 0.1. These peak values may seem rather hight but it should be noted that for periods shorter or longer than the interacting system period where the peak response occurs, C_o values drop sharply. The seismic coefficient of 0.2 is specified in the

Japanese Standard Building Law so that only buildings supported on Rock, Hard and Soft soil types above the line drawn horizontally at $C_o=0.2$ require careful design consideration and buildings on various soil types below the horizontal line may be considered safe according to Japanese practice.

The following method of seismic design using the MS response curves is proposed. The total earthquake force, F, at the base storey above grade be determined from the following equation,

$$F = C_{dB}W \qquad \ldots\ldots\ldots (1)$$

$$C_{dB} = ZIKC_o \qquad \ldots\ldots\ldots (2)$$

wherein W= building weight for seismic design, Z = seismicity coefficient, I = importance of building or facility, K = structural system coefficient and C_o = basic base shear coefficient to be read from MS response curves depending on the site characteristics.

Accurate evaluation of natural periods of SFB systems is essential in estimating the magnitude of earthquake forces on buildings. Foundation construction consisting of basement, piles and piers reinforces the coupling of the building with the supporting medium and results in imparting greater rigidity to the SFB system and thereby reducing the natural period of the interacting system. The correction in the natural period due to basement and for piles and piers is necessary. These relationships are shown in Figs. 4 and 5.

ACKNOWLEDGMENT

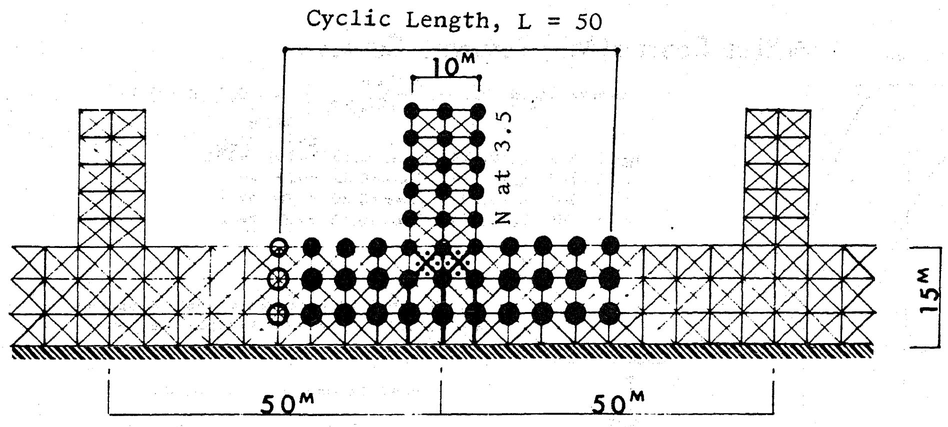
Over 40 students in the Dept. of Architecture of Waseda University have contributed efforts on this important problem in earthquake engineering during the past ten years. The authors express deep appreciation for their cooperation.

REFERENCES

1. Sakurai, J. and J.K. Minami: Some Effects of Nearby Structures on the Seismic Response of Buildings, Proc. 5WCEE, Rome, 1973

2. Minami, J.K. and Joji Sakurai: Some Seismic Response Solutions for Soil-Foundation-Building Systems, International Symposium on Earthquake Structural Engineering, Univ. of Missouri-Rolla, August 1976

3. Minami, J.K. and Joji Sakurai: Effects of Varied Damping Values and Vertical Earthquake Motions on the Seismic Response of Soil-Foundation Building Systems, 4th Japan Earthquake Engineering Symposium, November 1975, Tokyo (in Japanese with one page English abstract)



Shear Moduli of Soil Types (kg/cm^2)			
Soil Layer	Hard	Soft	Filled
Top	443	102	27
Middle	1034	236	64
Bottom	1330	305	82
Computed from shear wave velocities	1058	265	66

Fig. 1 Typical Cyclic Truss Type Model of SFB Systems

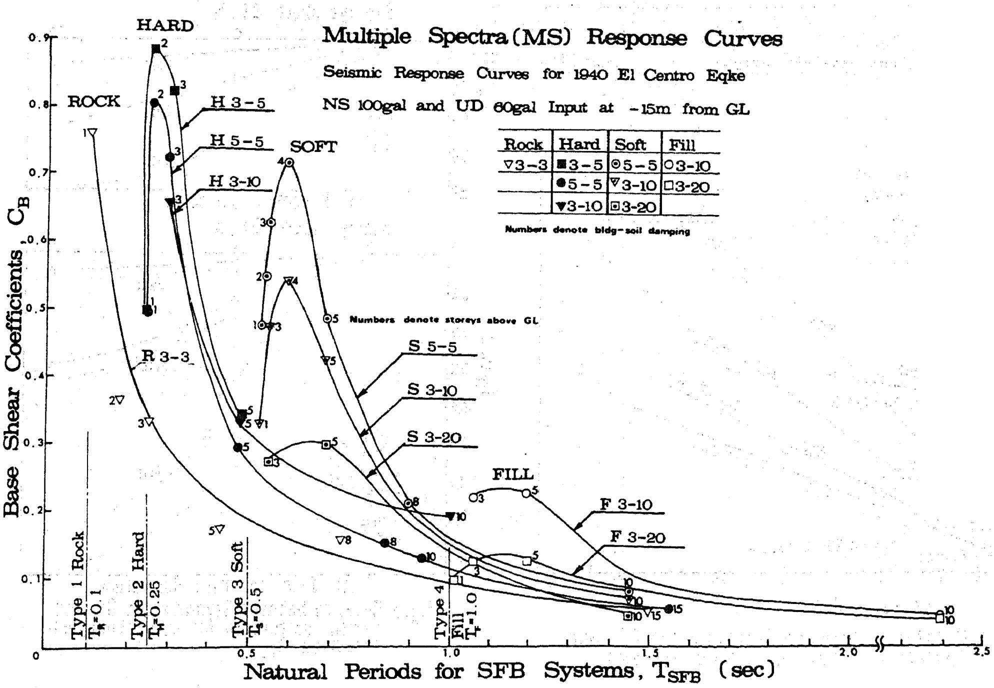


Fig.2 Earthquake Response Solutions for Soil-Foundation-Building(SFB) Systems

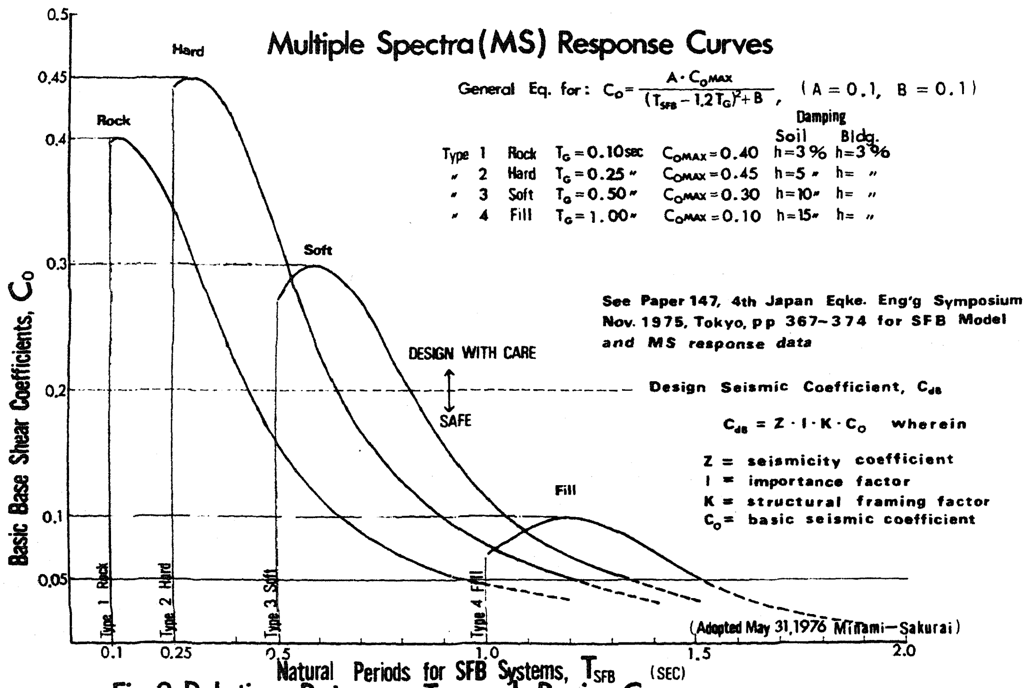


Fig.3 Relation Between T_{SFB} and Basic C_0

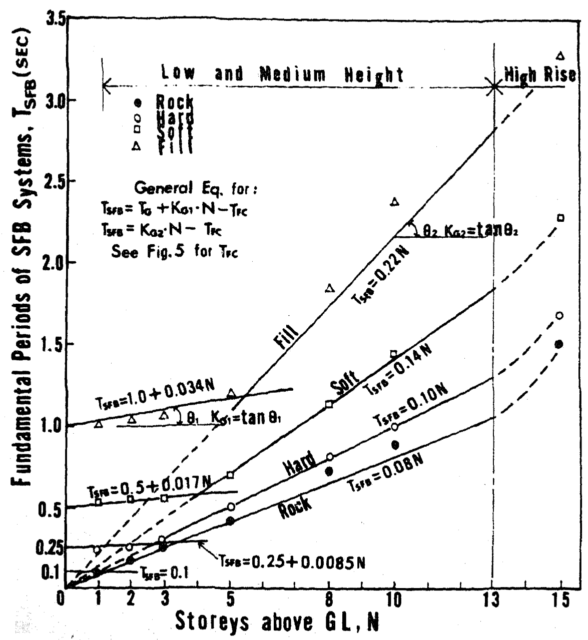
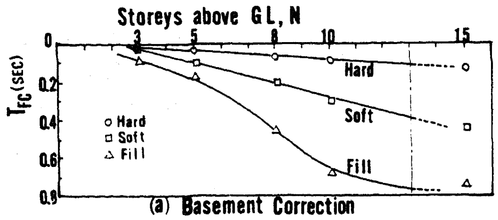
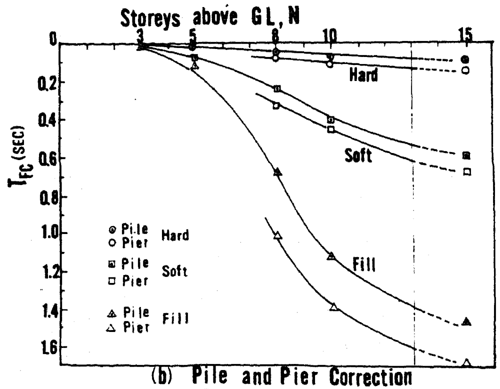


Fig.4 Relation Between Storeys above GL and Fundamental Periods of SFB Systems



(a) Basement Correction



(b) Pile and Pier Correction

Fig.5 Relation Between Storeys above GL and Period Correction for Foundation Construction, T_{FC}

DISCUSSION

T.P. Tassios (Greece)

This is one of the most fundamental papers of this Congress. By virtue of its clarity and its scientific completeness, it will be extensively used and commented during the next years. And, to start with, here are some questions the discussor would like to raise:

1. To which extent the characteristics of other possible earthquakes (other than 1940 El Centro and 1952 Taft used), might influence the results of this investigation, increasing (possibly) the response of softer soils.

2. Same question in case some ground - foundation slip occurs.

3. On the basis of microtremors' measurements, of semi-emperical microzoning computations and/or by means of some simple shear-propagation analysis, soft soils are frequently fined with an amplification factor (on accelerations) of the order of magnitude of 3, even in case of higher intensity earthquakes (non-linear behaviour of soils). Although the discusser tends to disagree with such conclusions, he would greatly appreciate the comments of the authors.

4. An older opinion, according to which soft soils produce an apparent increase of two units of MM intensity, seems today exagerate. Nevertheless, if particle velocity is a sound index of potential damage, the ratio of spectral velocities between soft soil and rock formations, within the same area, expresses somehow the importance of the additional measures we must take against earthquakes in soft soils and, possibly, the importance of fictitions base shear to be imposed by codes. To this respect, it is worth to remind that values of this ratio equal to 1, 3 to 1, 6 have been found is some cases. If, in addition, low fatigue is also to be implicitely considered in the codes, soft soils are evidently more dangerous, due to the longer durations of ground motions they maintain.

   In view of these comments, should the C_o-values be affected, if they were to be incorporated in a code ? This is, for instance the case also in the new USA recommendations:

5. In an example of 8-storey building on soft soil, according to the authors proposal, C_o equals 0,08, for direct foundation, and 0,28 for pile foundations. Is this, rather unexpected increase of 300%, compatible with actual accounts of real earthquakes ?

6. The authors are kindly requested to offer their comments on the conclusions of the following papers (being somehow contradictory to the conclusions of the present paper):

Petrovski et al.,	4-163
Yarar et al.,	7-19

Author's Closure

With regard to the questions of Mr. Tassios, we wish to state the following comments:

1. 1940 El Centro and 1952 Taft earthquake wave forms have been chosen as earthquake inputs to the SFB simulation models in our study of the interaction effects. Rock, hard, soft and filled ground types have been assumed and the vibrational characteristics are represented by the predominant period of vibration for each type rather than other parameters such as wave propagation velocities for the different soil types. Random nature of the El Centro earthquake motion through different soil types will be demonstrated by means of Power Spectrum curves. Fig. 6 shows the power spectrum for rock, hard, soft and filled ground soil types at the ground level in the free field. It is evident that peak values occur near the predominant vibration periods for the different soil types selected in our study. Similar distribution is also exhibited by the Taft earthquake. These two earthquake forms are well known world-wide and were therefore chosen in our study. Other earthquakes may show somewhat different power distributions but earthquakes in general are expected to have characteristics similar one to the other. Development of suitable simulated earthquake wave forms is under consideration by our group.

Past earthquake damage experience points to collapse and serious damage to low rigid buildings on hard soil sites. The settlement, tilting and even overturning of buildings supported on softer soil sites, as on the occasion of the 1964 Niigata earthquake, are due to soil failure such as by boiling or quick-sand liquifaction of sandy soils and landslides of clay layers. The damage to the buildings, in many cases is slight. Providing proper foundation construction counter-measures is of course necessary.

Henry D. Dewell states (1) that "Lest inference by drawn ... that damage is always greater when the structures are founded in alluvial soils than in harder or diluvial soils, it may be mentioned that in the 1923 Tokyo earthquake, the damage to brick and concrete buildings was greater to those buildings situated on the up-town diluvial soil than to similar buildings situated in downtown soft alluvial soil, according to Kyoji Suehiro. R.R. Martel (then at the California Institute of Technology) states that " ..... somewhat similar results were obtained from a study of effects of the Long Beach, California earthquake of 1933. There are damage to brick buildings located on the softer, more recently deposited alluvium with ground water from 2 to 10 feet from the surface, was less than to similar buildings on the order, more firmly consolidated marine terrace deposits with ground water not so close to the surface ....".

We can benefit greatly by heeding the observations of eminent elders such as Martel, Suehiro and others. We are of the opinion that rock and hard soils, because of their stiffness and low damping have large earthquake force input capacity. On the other hand, softer soils because of their greater deformability and consequently higher damping due to large strains have less earthquake force input capability.

2. Soil and building foundation sliding has not been considered. If such sliding occurs, the earthquake force input to the building would be less and the earthquake response would also be less in the light of results obtained by us to date.

3. It is true that soft soils are frequently penalized with an amplification factor on accelerations of the order of magnitude of 3, even in the case of higher intensity earthquakes producing non-linear behavior of soils. Comments made in connection with item 1 apply in part if not wholly. Our multiple spectra response curves for soft and filled ground types have been assigned damping ratio values of 10% for soft and 15% for filled ground, thus taking into consideration indirectly the factors mentioned, as well as by the reduced basic seismic coefficients for softer soils. We consider building damage and soil failure to be fundamentally different in their mechanism.

4. According to an older opinion that soft soils produce an apparent increase of two units on the MM intensity scale does not take into consideration the soil-structure interaction effects. The older opinion is true for free fields without buildings. As pointed out previously under item 1, softer soils deform and lose bearing capacity due to earthquake motions and carry the buildings into distorted positions but the buildings themselves are often in good condition from the damage point of view, indicating little earthquake force input into them. This situation requires reviewing past earthquake damage experience by researching damage literature and most of all our re-thinking on the subject.

Results of our studies to date suggest that values of the "soil profile factor" contained in the proposed Applied Technology Council code for USA (preprints 5-245) may be 1.5 for stiff soils, 1.0 for soft soil sites and perhaps 0.5 for deep aluvium deposits.

5. In the example of the 8-storey building on soft soil, C_o for the case without basement and piers is 0.08 and 0.28 with pier foundation. Even with relatively moderate seismic force acting on the building, it may sink, tilt and even overturn if adequate foundation construction consisting of basement and piers is not provided. With adequate foundation construction to support the building by transfering the weight and the

loads to the satisfactory underground stratum, the coupling of the building with the supporting medium is strengthened, thereby shortening the period of vibration of the integrated system, resulting in larger earthquake force acting on the building. The effectiveness of piles and piers is quite evident. In Japan, the allowable unit stresses for earthquake resistant design are values approaching the yield point for steel so that a seismic coefficient of the order of 0.28 offers no serious problem.

6. The modelization of the soil and foundation components of the system by Dr. Petrovski et al (Preprints 4-163) differs from ours in the number of degrees of freedom for the soil component so that different results may naturally be expected.

The research reported on by Dr. Yarar et al deals with the behaviour of soft soil free field without soil-building interaction. However, there are similarities in the characteristics between his and our power spectrum curves presented in Fig. 6.

Reference

1. Discussion by Henry D. Dewell on "Earthquakes and Structures" by L.M. Hoskins and J.D. Galloway, Transactions ASCE Vol. 105, 1940, pp. 315 -

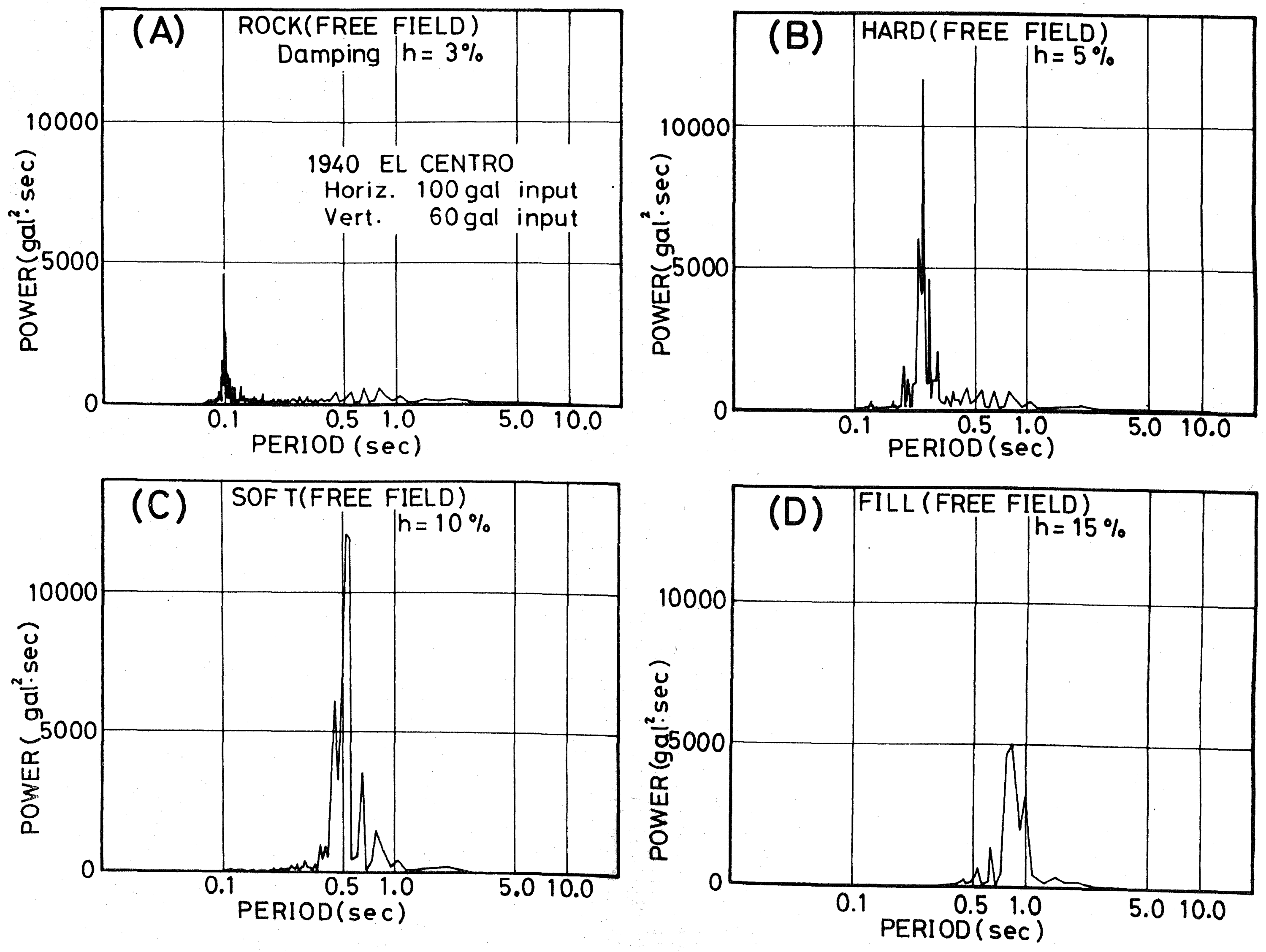


Fig. 6 Power Spectra at Ground Level