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CHARACTERISATION OF SITE EFFECTS BY MEANS OF ENERGY SPECTRA

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ABSTRACT

The effects of subsoil conditions on surface ground motion are evaluated in terms of energy spectra. Near-field and far-field strong ground motion recorded during recent destructive earthquakes at nearby rock and soil sites characterized by a comprehensive knowledge of the geotechnical properties are considered. The study suggests that energy spectra at soil sites are amplified with respect to those on rock sites. The maximum spectral amplification is usually well correlated to the natural periods of the sites. The most striking difference between traditional response spectra and energy spectra is the high soil amplification at longer periods, which is not apparent from the consideration of response spectra only.

KEYWORDS

Site effect, input energy, ground motion, soil amplification

INTRODUCTION

The characterisation of seismic motion during an earthquake for engineering purposes requires the identification of suitable parameters for the assessment of earthquake destructiveness potential. The specification of these parameters is necessary both to select significant signals for the design of new structures or to assess the seismic safety of existing structures, or, more generally, to define a design earthquake. A basic assumption in the development of a design earthquake is that strong ground motion at a site is primarily dependent on the magnitude, source-to-site distance and local soil conditions. In particular, subsoil characteristics can significantly affect amplitude, frequency content and duration of ground motion as seismic waves will be modified as they travel through soils from the underlying rock formations.

Traditionally, local soil effects are expressed in terms of the amplification (or deamplification) of a seismic motion parameter at ground surface relative to its value at bedrock. The most commonly used parameters are the peak ground acceleration (PGA), peak ground velocity (PGV) or peak ground displacement (PGD) as well as the shape of the response spectrum. However, these parameters have shown to be insufficient for the description of the damage potential at a site. For instance, it has been observed that PGA might be associated with a high frequency pulse (acceleration spike) which do not produce significant damage to the buildings. In fact, most of the impulse is absorbed by the inertia of the structure with little deformation. On the other hand, a more moderate acceleration may be associated with a long-duration impulse of low-frequency (acceleration pulse) which results in a significant deformation of the structure. Analogously, evidence from different earthquakes indicate that response spectra ordinates are not directly related to structural damage. Unfortunately, response spectra do not reflect the duration of ground motion, which is an extremely important factor in the damage incurred by buildings.

In this context, the damage potential of earthquakes may be more adequately described by means of an energy-based approach and related energy parameters. These parameters incorporate the effects of the duration of acceleration pulses, influenced by differences in source mechanisms, local site conditions, directivity, etc., thus allowing a better characterisation of earthquake ground shaking. Recently, Decanini and Mollaioli (1998) have analysed approximately 300 strong motion records obtained during 37 seismic events in terms of energy parameters. Their findings indicate wide differences in the shape and magnitude of energy spectra depending on subsoil conditions. Further, the energy spectra show to be substantially different from the response spectra.

In this paper, first the basic features of the energy-based approach and the main factors governing site effects are summarised. Next, referring to well known and documented case records from recent earthquakes, the energy spectra of nearby rock and soil sites are illustrated in order to understand how their shapes and peak values are related with local soil conditions.

USE OF ENERGY APPROACH AS A MEASURE OF DAMAGE POTENTIAL

A structure absorbs and dissipates energy when it is subjected to an earthquake ground motion. The energy balance equation in a SDOF system can be written (Uang and Bertero, 1988):

$$E_I = E_k + E_\xi + E_s + E_H \tag{1}$$

where E_I is the absolute input energy, E_k is the absolute kinetic energy, E_ξ is the damping energy, E_s is the recoverable elastic strain energy and E_H is the irrecoverable hysteretic energy that can be directly associated with the damage. The absolute input energy, E_I, is the energy parameter representative of the damage potential in that considers the realistic behavior of a structural system and depends on the features of both the strong motion (amplitude, frequency content, duration) and the structure:

$$\frac{E_I}{m} = \int \ddot{u}_t du_g = \int \ddot{u}_t \dot{u}_g dt \tag{2}$$

In this equation, m is the mass, $\ddot{u}_t = \ddot{u} + \ddot{u}_g$ is the absolute acceleration of the mass, u_g and $\dot{u}_g$ are the earthquake ground displacement and velocity, respectively. In the following the elastic input energy per unit mass, E_I/m, will be taken into consideration. For simplicity, E_I/m will be denoted as E_I.

SOIL AMPLIFICATION OF GROUND MOTION

It is well recognized that soil amplification of ground motion depends upon a number of factors such as the geotechnical site properties, the non-linear soil response and the seismic excitation. A major geotechnical factor is represented by the modal periods of a soil layer. With reference to a soil layer of uniform properties overlying a rigid basement the modal periods of the layer, T_n, can be written:

$$T_n = \frac{1}{(2n-1)} \frac{4H}{V_S} \qquad n = 1,2,\dots\infty; \tag{3}$$

where n is an integer corresponding to each mode of vibration, H is the depth of soil layer and V_s is the shear wave velocity. Of particular interest is the fundamental period of the site, T_1,

$$T_1 = \frac{4H}{V_S} \tag{4}$$

because usually the largest amplification occur at first-mode period. The response of a site depends on the frequency content of the input motion and its relation to the site periods. The period T_n is thus the controlling variable. It must be observed that, for the same velocity profile, the greater depths correspond to longer periods while the shallower depths to shorter periods. Analogously, for the same layer thickness, the softer the soil the longer the period.

Another important factor influencing site response is the impedance ratio, I, between underlying and superficial deposits:

$$I = \frac{\varrho_r V_r}{\varrho_s V_S} \tag{5}$$

where ρ is the mass density and V is the shear wave velocity and the subscripts r and s refer to the surface layer and underelying rock, respectively. For a layer of given thickness, the site response will be the greatest where the impedance ratio is the higher.

OBSERVATIONS OF SITE EFFECTS

The investigation of site effects in terms of energy parameters can be performed by examining the energy spectra of three of the most significant recent earthquakes, i.e., the 1985 Michoacan (Mexico) earthquake, the 1989 Loma Prieta (California) earthquake and the 1994 Northridge (California) earthquake. These well documented earthquakes produced strong motion records at several sites characterized by a number of different subsurface conditions encompassing shallow and deep deposits, consisting of soft as well as stiff soils. According to the conventional methodology, the occurrence of site effects has been detected by comparing, were available, the energy spectra of pairs of rock and soil sites close one each other. For comparison, the response spectra of the same recordings are also presented.

The Michoacan Earthquake

Two well-known strong motions recordings on rock site (UNAM) and on the soft deposits of the Mexico City valley (SCT) are considered. The stations are located approximately 400 km from the epicenter and 20 km from each other. Soil conditions in the valley are characterized by a soft clay layer overlying stiff soils. At SCT site the thickness of the soft clay is about 35 m and the average shear wave velocity is 75 m/s while the underlying stiff soils has a shear wave velocity in the order of 500 m/s or greater. Thus, a large impedance contrast exists between the soft layer and the underlying stiff soils, which is prerequisite for large amplification effects. The fundamental period at the SCT site is about 2 s.

The great distance of the earthquake source from the Mexico

City valley produced horizontal accelerations at the UNAM (rock) site of only 0.03g, while the PGA at the SCT site was about 0.17g, up to five times greater than that at UNAM. Nevertheless, the PGA at the SCT site is not particularly high and corresponds only to a moderate acceleration. The peculiarity of the SCT record is that it consists of a quasiharmonic motion with a period of about two seconds and extremely long duration, with nearly eight cycles of reversals (Bertero, 1989).

It is well established that major damages, which occurred to buildings in the 5- to 20-story range roughly corresponding to the fundamental site period, may have been due in large measure to amplification of earthquake motions by the local soil conditions and the development of a resonance condition resulting form the coincidence of the predominant period of the rock input motion, the natural period of the site and the natural periods of the damaged structures (Seed et al., 1988). This circumstance clearly emerges from the observation of the input energy spectra of UNAM and SCT sites illustrated in the Figs. 1 and 2, respectively. Figure 1 shows a distinct peak with a maximum energy value at the period of 2 s. Figure 2 shows a huge amplification of input energy at T=2 s. The corresponding maximum energy value is one of the largest ever recorded in the long period range.

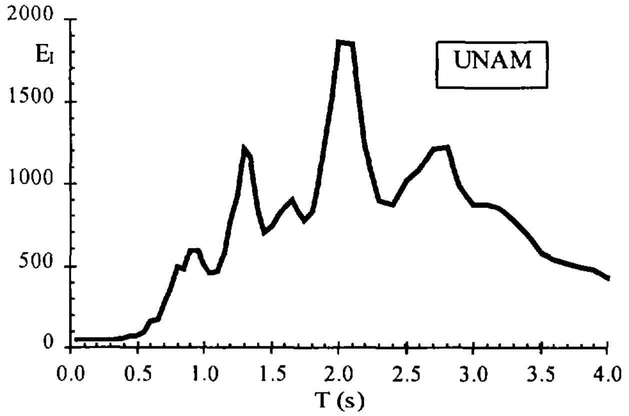

Fig. 1 Michoacan Earthquake, 1985. UNAM station. Input energy, E_I [cm^2/s^2].

It can be said that the response spectrum of the recorded SCT motion also shows a large peak at T=2 s. Notwithstanding, the representation of the SCT motion in terms of response spectrum does not appear, from the standpoint of seismic resistance, as severe as the energy spectrum. Therefore, the consideration of the response spectrum only may be equivocal because it does not take into account the effects of duration, which are otherwise included in the calculation of input energy.

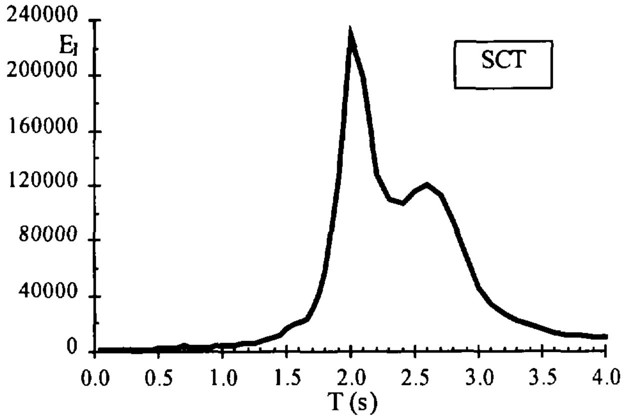

Fig. 2 Michoacan Earthquake, 1985. SCT station. Input energy, E_I [cm^2/s^2].

The Loma Prieta Earthquake

Two rock and soil station pairs were chosen for analysis because of their proximity and the differing subsurface conditions at the soil sites. The first pair of stations is constituted by Yerba Buena Island and Treasure Island, located in the middle of the San Francisco Bay, approximately 100 km from the Loma Prieta epicenter and 2.5 km from each other. Yerba Buena Island is a rocky outcrop. Treasure Island is an artificial island, constituted of loose hydraulic fill over soft to medium stiff clay, in turn underlain by other dense and stiffer clay. Fig. 3 shows the best estimate of the shear wave velocity profile for Treasure Island (EPRI, 1993).

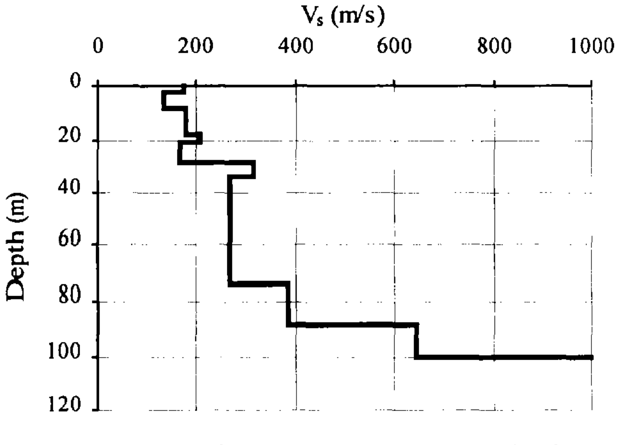

Fig. 3 Shear wave velocity profile at Treasure Island.

From the geotechnical point of view, Treasure Island can be considered as a deep soft soil deposit. The fundamental period at Treasure Island is estimated about 1.4 s while the second and the third mode periods are about 0.5 and 0.3 s, respectively. These estimates are based on the given soil properties of the site (EPRI, 1993).

The response spectra and the input energy spectra of the horizontal components (90 component) of the motion are shown in Figs. 4 and 5, respectively. In both figures it can be seen that the ground motion of the soft-soil site relative to the rock site is greatly amplified at all periods. The response spectrum of the Treasure Island motion (Fig. 4) shows three distinct peaks at T=0.3, 0.65 and 1.4 s, with the maximum spectral amplitude at T=0.65 s. These periods approximately correspond to the three mode periods of the soil deposit.

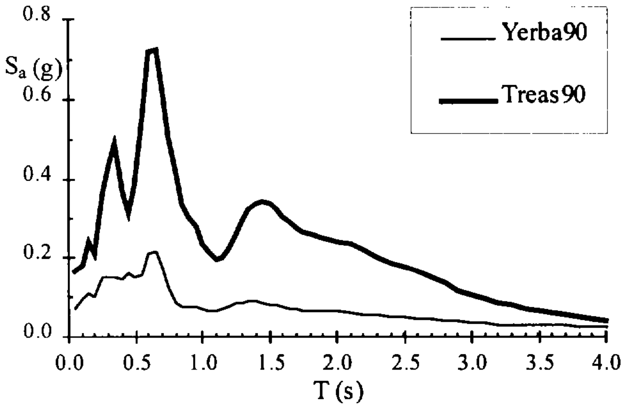

Fig. 4 Loma Prieta earthquake, 1989. Response spectra, S_a (g), at Yerba Buena Island and Treasure Island stations.

The energy spectrum of the Treasure Island motion (Fig. 5) shows remarkable amplification at T=0.65s and in the period range between 1.5 and 2.5 s. Unlike the response spectrum, the energy spectrum indicates high amplification in the long period range, of the same order of magnitude than at shorter periods. This particular behavior in the long period range, which is not apparent form the consideration of response spectra only, is the most striking difference between the energy and the response spectra.

The second pair of stations is part of the Gilroy array. These stations, named Gilroy #1 and Gilroy #2, are located approximately 30 km east of the Loma Prieta epicenter and 2 km from each other. Gilroy #1 is a rocky outcrop and Gilroy #2 is constituted by stiff soils up to a depth of about 170 m.

Fig. 6 shows the best estimate of the shear wave velocity profile for Gilroy #2 (EPRI, 1993). From the geotechnical point of view, Gilroy#2 can be considered as a deep stiff soil deposit. The fundamental period at Gilroy #2 is estimated about 1.2 s while the second and the third mode periods are about 0.4 and 0.24 s, respectively. These estimates are based on the given soil properties of the site (EPRI, 1993).

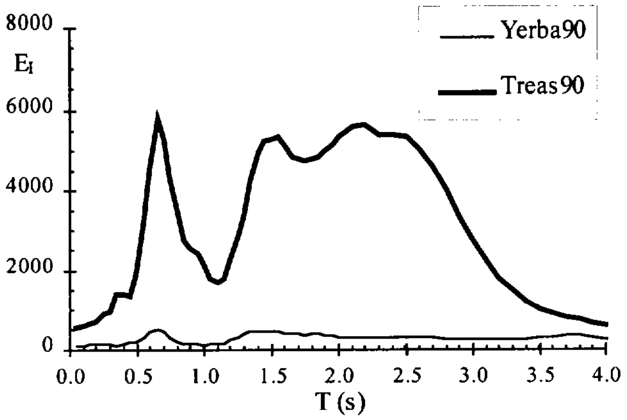

Fig. 5 Loma Prieta earthquake, 1989. Input energy, E_I [cm^2/s^2], *at Yerba Buena Island and Treasure Island stations.*

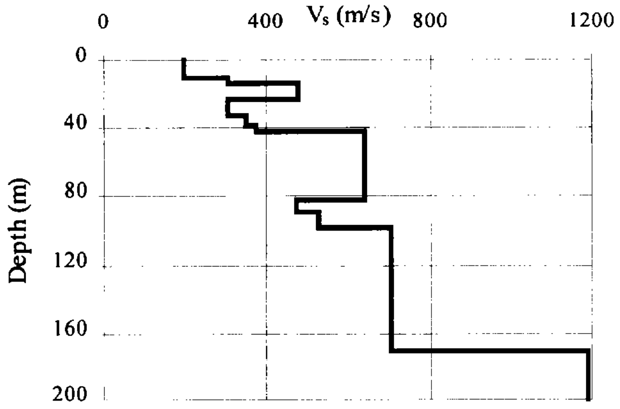

Fig. 6 Shear wave velocity profile at Gilroy #2 site.

The response spectra and the input energy spectra of the horizontal components (90 component) of the motion are shown in Figs. 7 and 8, respectively. In both figures it can be seen that the ground motion of the soft-soil site relative to the rock site is amplified at longer periods while the reverse occur at shorter periods. The response spectrum of the Gilroy #2 station (Fig. 7) shows two distinct peaks at T=0.4 and T=1.3 s, with the first peak being larger than the second. These peaks approximately correspond to the first and the second mode periods of the soil deposit. The energy spectrum of the Gilroy #2 station (Fig. 8) shows peaks at similar periods than the response spectrum. Unlike the response spectrum, the peak at longer period is much larger than that at shorter period. Again, the occurrence of high energy demand in the long period range, much greater than the demand at shorter periods, is the most important difference between energy and response spectra.

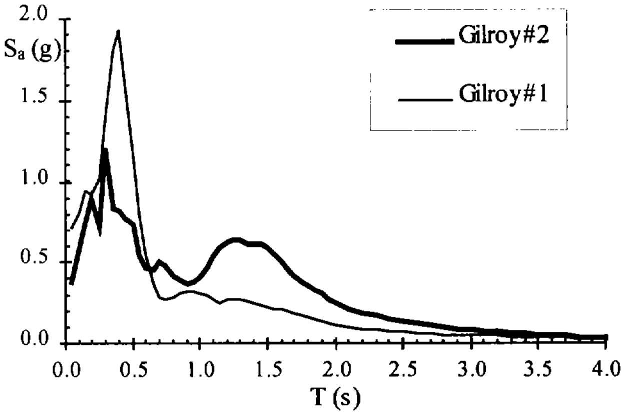

Fig. 7 Loma Prieta earthquake, 1989. Response spectra, S_a (g), at Gilroy #1 and Gilroy #2 stations.

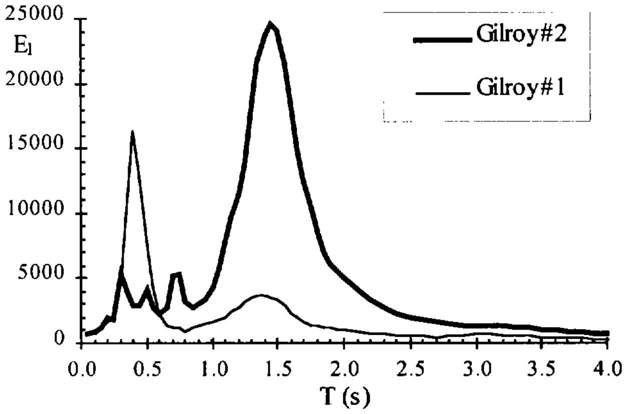

Fig. 8 Loma Prieta earthquake, 1989. Input energy, E_I [cm^2/s^2], *at Gilroy #1 and Gilroy #2 stations.*

The Northridge Earthquake

The near-source strong motions recordings at the soil USC station No. 55 from the mainshock and some of its aftershocks are examined. The USC station No. 55 is located 13 km from the epicenter, at the bottom border of the rupture surface projection of the causative fault, according to the model proposed by Wald *et al.* (1996). The two horizontal components of the strong motion records are rotated into strike-normal (SN) and strike-parallel components (SP) because of the near-source effects due to directivity which are most pronounced on the fault normal component. Five aftershocks (Todorovska *et al.*, 1999), of magnitude between 5.2 and 5.9, were also considered for the study (Table 1). In the vicinity of USC station No. 55 is not available a rock site. Thus, the indications of possible site effects derive from considerations on energy spectra only. Fig. 9 shows the shear wave velocity profiles at station USC station No. 55 (Gibbs et al., 1996).

Table 1 Northridge aftershocks.

Event	Date	Time (GMT)	M
Aftershock1	1994/01/17	12 31 58.12	5.9
Aftershock2	1994/01/17	12 40 36.12	5.2
Aftershock3	1994/01/17	23 33 30.69	5.6
Aftershock4	1994/01/18	00 43 8.89	5.2
Aftershock5	1994/03/20	21 20 12.26	5.2

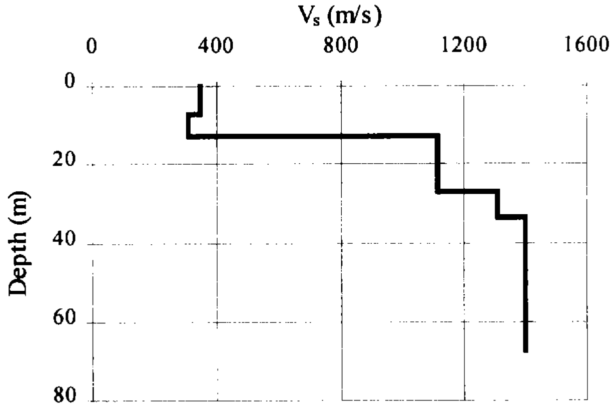

Fig. 9 Shear wave velocity profile at USC55 site.

The station is characterized by a soil layer of limited thickness (H=12m) and an average shear wave velocity V_S=337 m/s, above a bedrock with V_S=1100 m/s. The impedance ratio is approximately 4. From the geotechnical point of view, USC station No. 55 can be considered as shallow stiff soil deposit. The fundamental period of the site is about 0.2 s.

The energy spectra of both the mainshock (Fig. 10) and the aftershocks (Fig. 11) records show distinct peaks in the short period range. In particular, the peaks in the aftershocks records are always located at T≅0.35 s, while those in the mainshock record at somewhat longer periods. This lengthening of the predominant period in the mainshock may be attributed to non-linear soil effects because of the level of strain generated during the earthquake. However, the occurrence of the peaks both in the mainshock and in the aftershocks at short periods, similar to the fundamental period of the site, may be interpreted as an effect of the local soil conditions. Peaks at similar periods are also present in the response spectra.

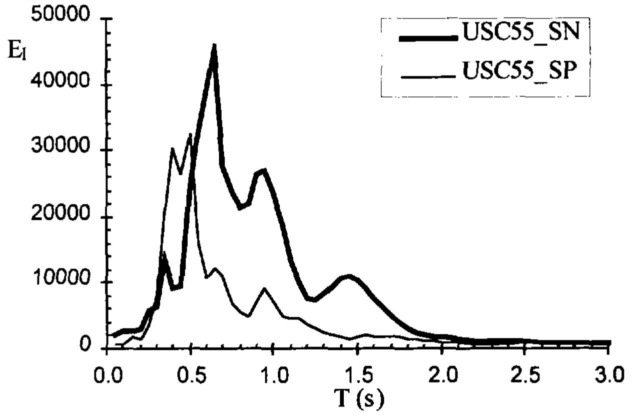

Fig. 10 Northridge earthquake, 1994. Response spectra, S_a (g), at USC55 station.

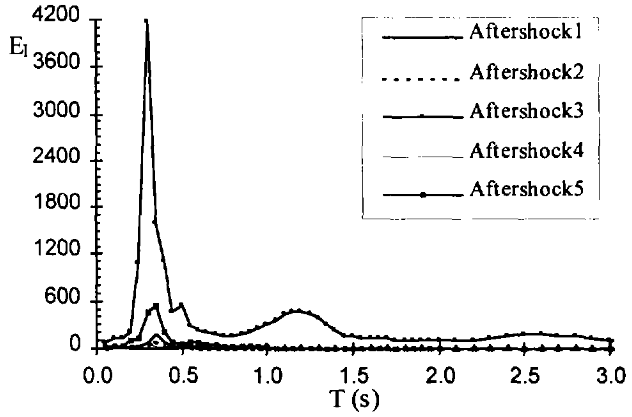

Fig. 11 Northridge earthquake, 1994. Input energy, E_I [cm^2/s^2], *at USC55 station.*

CONCLUSIONS

The input energy spectra of selected strong motion records from recent destructive earthquakes at different rock and soil stations were evaluated. It has been found that energy spectra depend largely on site specific conditions. It has been shown that peaks in energy spectra reflect the natural periods of a site. Shallow deposits show peaks in the short period range while deep deposits show peaks in the longer period range. Generally, peaks in energy spectra are in agreement with those obtained in response spectra.On the other hand, input energy spectra generally exhibit maximum spectral amplitudes in the long period range, of the same order of magnitude than those at short periods.

This high energy demand in the long period range does not emerge from the consideration of response spectra only and have significant engineering implications for long period structures.

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