Are Current Design Spectra Sufficient for Soil-Structure Systems on Soft Soils?

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ABSTRACT: Seismic codes have universally adopted smooth design acceleration spectra, on the basis of averaging of a large number of elastic response spectra of actual recordings. Such spectra have, for each soil category, an essentially constant acceleration plateau, S_a , usually equal to 2.5A, followed by a descending acceleration branch. The period range of the constant-acceleration plateau is larger for softer soils. However, such a flat shape of spectra has little resemblance to an actual soil-amplified spectrum. The unrealistic shape stems basically from the fact that the spectra of motions recorded on soft soils belonging to one soil category attain their maxima at different well-separated periods; thereby, averaging them eliminates their peaks and leads to a (spurious) flat spectrum. Through an extensive analytical parametric study we demonstrate that by normalizing the period of the spectra with the predominant period of motion, and then averaging, results in a bi-normalized spectrum ($S_d/A : T/T_p$) which has a sharp peak at $T/T_p = 1$. It is found out that this spectrum has peak value $S_d/A \approx 3.75$ (rather than 2.5), for a narrow range of normalized periods. The effect of such a spectrum especially on SSI studies may be drastically different from the beneficial effect of a (conventional) code spectrum.

1. THE PROBLEM: CODE SPECTRA VERSUS REALITY

It is well known how important soil effects are on the intensity and frequency content of ground motions. In civil engineering practice these effects are often computed theoretically (wave propagation analysis assuming equivalent-linear or nonlinear soil behavior). Yet, the seismic codes have universally faced the problem of soil amplification in *a purely empirical and (unavoidably) oversimplified way*:

- The soil deposits were classified in a few broad categories, each of which encompasses a wide range of soil layer stiffness and thickness down to bedrock.
- The response spectra $S_a(T)$ from numerous world wide accelerograms recorded on top of soils belonging to each category, were statistically processed. The shape of the design spectrum for the particular soil category was based on the average of the normalized spectrum, $S_a(T)/A$, for each period *T*, after some "conservative smoothening".

The design spectra that have thus resulted share a crucial characteristic : *the more "flexible" a soil deposit* (i.e. the smaller its stiffness and/or the larger its thickness), the flatter the design spectrum. If this were the reality, ignoring SSI for a structure on soft ground would have led to conservative results : SSI effect would always be helpful.

Yet, reality has repeatedly shown the opposite trend ! Numerous records in "soft" soils have produced response spectra of a sharp rather than flat shape, with well defined peaks around the site fundamental period. Fig. 1 highlights the discrepancy between seismic codes and reality. The consequences of such a disparity, especially on SSI systems may be significantly detrimental.

2. WHY THIS DISCREPANCY?

As illustrated in the sketch of Fig. 2, the culprit behind the discrepancy is the averaging of *dissimilar* response spectra; its accomplish: the very broad range of stiffness and thickness of each soil category. A range of natural periods in the ratio of 1 to 4 is quite possible within one single category, say category D (according to NEHRP). The actual seismic motions in a number of (soft) soil profiles belonging to category D but with so vastly different fundamental periods are likely to have response spectra with sharp peaks at well-separated periods. Thus, at the period for which one spectrum has a peak the spectra on sites with different values we simply "annihilate" the real sharp peaks. In other words, *spuriously and against safety, we disregard (or rather depress) the resonance between soil deposit and excitation!*

The topic has already been brought to light by Mylonakis & Gazetas (2000) and Gazetas (2006), in an attempt to reevaluate the importance of soil-structure in-

teraction (SSI). They showed that the effects of SSI have been incorrectly predicted on the basis of the Code Spectra as being always beneficial ; and recalled many failures in Mexico (1985) and Kobe (2005) that have persuasively been shown to be to a large extent the (detrimental) effect of SSI (Gazetas et al 1986, 2004). More recently, Xu & Xie (2004) along similar lines developed a unique average bi-normalized spectrum for 206 strong-motion records of the Chi-Chi (1999) earthquake. Each and every individual acceleration response spectrum was doubly normalized : the ordinate, S_a , with respect to the peak ground acceleration, A; the abscissa, T, with respect to the predominant period T_p of the spectrum. The average of the individual " $S_a/A : T/T_p$ " spectra exhibited indeed a sharp peak, at $T/T_p =$ 1, with a maximum value of the order of 4, rather than the 2.5 of the code spectra. The practical indirect conclusion from the above studies was that the increase of the period of a structure-soil system with decreasing soil stiffness would not necessarily lead to reduced intensity of shaking, as presently implied by the code spectra.

3. SUMMARY OF THE ANALYTICAL ("REMEDIAL") STUDY

In contrast with the purely empirical method with which the Code Spectra have been developed, we follow an analytical methodology which comprises the following steps :

- For a particular soil category (for example C according to EC8, or D according to NEHRP) we "construct" a number of idealized generic soil profiles having the following characteristic parameters:
- velocity : $V_{S,30} = 180$ m/s, 260 m/s, 360 m/s. $V_{S,30}$: average shear wave velocity from the ground surface down to a depth of 30 m
- distribution of V_s with depth : uniform, trapezoidal, with-crust (see Fig. 3)
- depth to "rock" : H = 30 m and 60 m.
- "rock" to soil wave velocity ratio : $V_{S, ROCK} / V_{S,30} = 1.5$ and 5
- Seven accelerograms recorded on "rock" are utilized as ("rock-outcrop") excitation after being scaled (up or down) to achieve peak ground acceleration : A = 0.20 g, 0.40 g, 0.60 g. The names and earthquakes of these records are :

Stone Canyon Reservoir, Northridge 1994 Aegion-Rock, Aegion 1995 Sakarya, Izmit 1999 Dayhook, Tabas 1978 Gilroy-1, Loma Prieta 1989 Lucerne, Landers 1992 Superstition Mountain, Imperial Valley 1979.

• By exciting all the aforesaid soil profiles with each record in all possible combinations we obtain results in 1009 cases. The analysis is first done, with the well-known equivalent-linear method of Schnabel et al, 1972 (SHAKE)

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and, second, with the inelastic method introduced by Gerolymos & Gazetas, 2005 (NL-DYAS).

Fig. 1: The discrepancy between a Code Design Spectrum typical for soft soils and the response spectra of two actual soil amplified motions.



Fig. 2: Sketch illustrating the derivation of code spectra from the average (for each specific period) of the S_a/A values of all recorded spectra. The three individual idealized spectra are from possible motions in three soft soil profiles, all belonging to the same Soil Class (Category), and all bearing the effects of resonance but at different periods. The resulting spectrum spuriously suppresses the soil–excitation resonance.

The response spectra of the ground surface motions resulting from each of the 2x1009 analyses are utilized in two different ways :

- (a) We normalize only the spectral accelerations by dividing with the corresponding peak ground acceleration, S_a/A --- the established conventional normalization used for deriving the current design spectra (S_a/A :T).
- (b) We normalize both the spectral acceleration, S_{α}/A , and the period, T, by dividing it with the predominant period T_p of the ground surface motion. We call the plot $S_{\alpha}/A : T/T_p$ Bi-Normalized Spectrum (BNS).
- The average for each period T of the 1009 simply normalized spectral values (type (a)) give a mean response spectrum $(S_{\alpha}/A : T)$ which is expected to be quite similar with the current code spectrum for this soil category.
- The average for each period ratio T/T_p of the 1009 doubly normalized spectra (type (b)) give a mean response spectrum ($S_a/A : T/T_p$) which is expected to differ both in shape and in amplitude from the conventional spectrum.

4. RESULTS: TOWARDS A MORE RATIONAL SPECTRUM

All the 1009 response spectra obtained with the equivalent-linear soil response analyses and simply or doubly normalized as afore-explained, are portrayed in Fig. 5(a) and 5(b) respectively. Their average response spectra, after some "*conservative smoothening*" could serve as the design spectra. The following conclusions emerge from the two figures :

- (a) Regarding the conventionally derived spectrum as anticipated, its shape is indeed quite similar with the smooth shape of the code spectrum for this soil category : a nearly constant ordinate, approaching (from below) $S_a/A \approx 2.5$, for the range of periods from 0.15 sec to 0.60 sec, approximately. (Of course, if more excitations had been employed, and additional and more realistic soil profiles had been considered, the period range of nearly constant S_a would have likely increased, and the spectrum would have been even smoother.)
- (b) Regarding the Bi-Normalized Spectrum its shape is vastly different from the conventional spectrum : a sharp peak at $T/T_p \approx 1$ dominates. Its maximum value, max (S_a/A), reaches 3.75, i.e. it is 50% greater than the peak value of the conventional spectrum.

Evidently, the (true or pseudo) resonance between soil and excitation is well preserved only in the bi-normalized spectrum. The conventional Spectrum does not reflect the physics of the problem, while being unsafe for many structures (with $T \approx T_p$) and leading to erroneous conclusions on the possible effects of soil-structure interaction.

5. THE UNIQUENESS OF THE BI-NORMALIZED SPECTRUM

Several interesting attributes of the Bi-Normalized Spectrum (BNS) have been demonstrated analytically by Ziotopoulou and Gazetas (2009). Specifically,:

- The BNS is hardly influenced by soil category, i.e., it is practically the same for all soil categories! The same conclusion was drawn by Xu & Xie (2004) for the strong records of the Chi-Chi (1999) earthquake. (Of course, T_p may change significantly from soil to soil, decreasing with soil stiffness ; and moreover, it is often affected by the nature of seismic excitation. Its estimation is a totally different ball game.)
- The BNS is only marginally influenced by the nature of the performed wave propagation analysis : equivalent-linear and truly nonlinear analyses differ appreciably only in the low-period range ($T/T_p < 0.5$), not in the basic shape of the spectrum.
- The BNS is only marginally influenced by the nature of seismic excitation. (Of course, again, the above argument does not extend to T_p which is affected by the dominant excitation periods.)

Indicative of the uniqueness of this BNS is Fig. 6, which reveals the practical independence of BNS from the soil category — contrary to the behavior of the conventional spectrum.



Fig. 3: The three types of generic soil profiles used in our parametric investigation



Fig. 4 "Rock" accelerograms used as excitation (scaled to 0.40 g).



Fig. 5: Compilation of response spectra of ground surface motions from all the equivalent-linear analyses. (a) Conventionally normalized spectra; (b) Bi-Normalized spectra. The thick curves are the mean response spectra.

6. CONCLUSION, LIMITATIONS

One unique Bi-Normalized Spectrum (BNS), for all soil categories and most likely seismic excitations, emerged from the comprehensive set of wavepropagation analyses reported in this article. This unique spectrum is sketched in Fig. 7 and is approximated with the following algebraic expressions :

$$S_a/A = exp\left(1.35\left[T/T_p\right]\right) \quad \text{for } T/T_p < 1$$
$$S_a/A = 3.75\left(T/T_p\right)^{-1.2} \quad \text{for } T/T_p \ge 1$$

The potential benefits from adopting this simple spectrum have been highlighted in the article. However, the imprecise definition of T_p and the profound difficulty in predicting T_p in reality remain serious obstacles in adopting it at present. And of course, empirical support from recorded motions must be (statistically) significant, to arrive at a robust such design spectrum.



Fig. 6: Comparison of the mean spectra of Figure 5 (Soil: $V_{S,30} = 180 - 360 \text{ m/s}$), with the mean spectra for a much softer soil ($V_{S,30} = 100 \text{ m/s}$). The differences of the conventionally normalized spectrum (top) almost disappear in the normalized spectra (bottom)



Fig. 7: Mean Bi-Normalized Spectra (BNS) from the equivalent linear wave propagation (SHAKE) and from the inelastic wave propagation (NL-DYAS) studies, and the idealized smooth spectrum proposed for design. The algebraic expressions for two branches of this spectrum are given in the text.

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