Bi-normalized Response Spectrum for a Rational Soil-Structure Interaction Analysis

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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. An extensive analytical parametric study is summarized here to demonstrate that by normalizing the period of the spectra with the predominant period of motion, and then averaging, results in a bi-normalized spectrum ($S_a/A : T/T_p$) which has a sharp peak at $T/T_p = 1$. It is found out that this spectrum has peak value $S_a/A \approx 3.75$ (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. INTRODUCTION

The importance of soil – structure interaction (SSI) in seismic design has been seriously under-rated in the last 30 years, following publication of the ATC-3 guidelines. For most structures SSI meant primarily increased natural period and damping which led invariably to reduced inertia forces in the structure a direct consequence of the shape of the design response spectra. In this paper we argue that the basic shape of the design spectra is incorrect for all soil categories, but that the "error" is significant primarily for soft soils. The effects of SSI may thus prove detrimental rather than invariably-beneficial as the current "wisdom" asserts.

2. THE PROBLEM: THE SHAPE OF CODE SPECTRA CONTRADICTS REALITY FOR SOFT SOILS

In earthquake engineering practice soil amplification effects on the intensity and frequency content of ground motions are often computed theoretically (wave propagation analysis assuming equivalent-linear or nonlinear soil behavior). The seismic codes by contrast have universally followed *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 from numerous 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 .

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.

The culprit behind the discrepancy is the averaging of *dissimilar* response spectra, and 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) ; or C (according to EC8). The actual seismic motions in a number of soft soil profiles belonging to this category D may have so vastly different fundamental periods that actual (of motions recorded on them) may have sharp peaks at well-separated periods. Thus, at the period for which one spectrum has a peak the spectra on sites with different periods are likely to have very small values. Hence, by averaging all these 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 interaction (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 PARAMETRIC ANALYTICAL STUDY

In contrast with the purely empirical method with which the Code Spectra have been developed, we followed 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.
  - 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) and, second, with the inelastic method introduced by Gerolymos & Gazetas, 2005 (NL-DYAS).

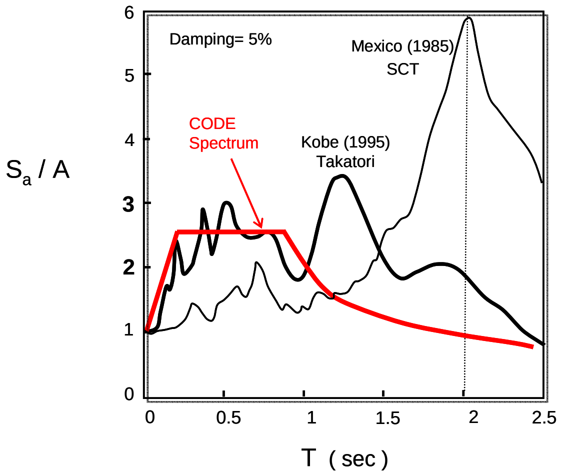

Fig. 1: *The discrepancy between a Code Design Spectrum, typical for soft soils, and the response spectra of two actual soil amplified motions.*

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_a/A, and the period, T, by dividing it with the predominant period T_p of the ground surface motion. We call the plot $S_a/A : T/T_p$ Bi-Normalized Spectrum (BNS).

- The average for each period T of the 1009 simply normalized spectral values (type (a)) give a mean response spectrum $(S_a/A : T)$ 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 ("BI-NORMALIZED") 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. 3(a) and 3(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.

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.)

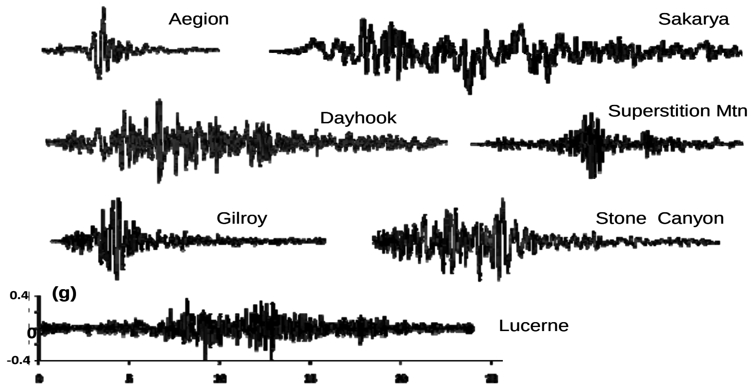

Fig. 2 *"Rock" accelerograms used as excitation (scaled to 0.40 g).*

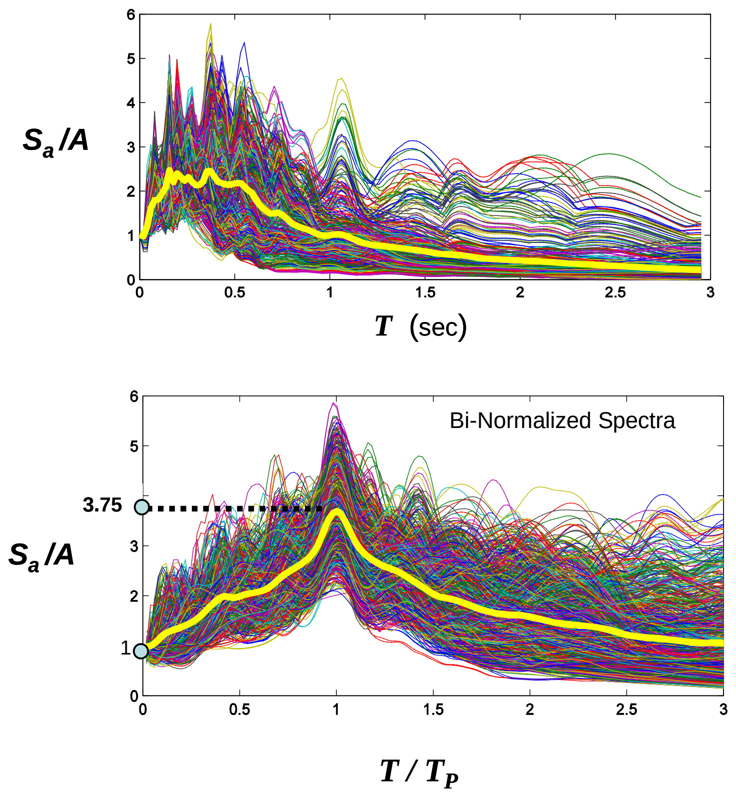

Fig. 3: *Compilation of response spectra of ground surface motions from all the equivalent-linear analyses. (a) Conventionally normalized spectra; (b) Bi-Normalized spectra. The thick curves are the mean response spectra.*

5. CONCLUSION

One unique Bi-Normalized Spectrum (BNS), for all soil categories and most likely seismic excitations, emerged from the comprehensive set of wave-propagation analyses reported in this article. This unique spectrum is sketched in Fig. 4 and is approximated with the following algebraic expressions :

$$S_a/A = exp\left(1.35\ [T\,/\,T_p]\right) \qquad \text{for} \quad T/T_p < 1$$

$$S_a/A = 3.75\left(\,T/T_p\right)^{-1.2} \qquad \text{for} \quad T/T_p \geq 1$$

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.

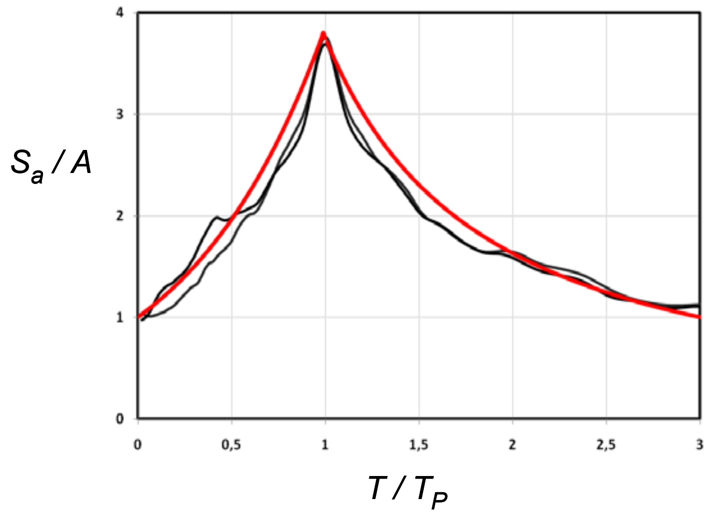

Fig. 4: *Mean Bi-Normalized Spectra (BNS) from the equivalent linear wave propagation (SHAKE) and from the inelastic wave propagation (NL-DYAS) studies, and the idealized smooth spectrum proposed for design. The algebraic expressions for two branches of this spectrum are given in the text.*

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