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A design spectrum model for flexible soil sites in regions of low-to-moderate seismicity

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ABSTRACT

Design spectrum (DS) models in major codes of practice for structural design of buildings typically stipulate empirical site factors for each of the five, or six, site classes. Although the phenomenon of resonant like amplification behaviour of the structure caused by multiple wave reflections is well known, the potentials for such periodic amplification behaviour are not explicitly considered in code models. This is partly because of expert opinion that such effects are very "localised" in the frequency domain and can be suppressed readily by damping. However, investigations into the risk of collapse of non-ductile, and irregular structural systems, common in regions of low-to-moderate seismicity, revealed the extensive influence of periodic base excitations on flexible soil sites (with initial small-strain natural period T_i > 0.5 s). In this paper, an alternative DS model which addresses the important phenomenon of soil resonance without the need of computational site response analysis of the subsurface model of the site is introduced.

1. Introduction

Seismic action models in major codes of practice for structural design of buildings typically stipulate empirical site factors for each of the five, or six, site classes. The value of the empirically derived site factor is expressed simply as a function of the site class each of which is identified with a range of shear wave velocity (SWV) values. These site factors are applied uniformly over the flat (constant acceleration) and the hyperbolic (constant velocity and constant displacement) sections of the spectrum. As different site factors are applied to the two sections, the corner periods in the DS model can vary a great deal between site classes. The International Building Code (IBC) of the United States [1] also stipulates different sets of site factors for different intensities of ground shaking in order that different levels of seismicity are covered in one model.

This simple format for modelling site effects is widely accepted albeit that in reality the modification of seismic waves through soil sediments is well known to be highly frequency selective and under the influence of many factors. The concept of "frame analogy" [2] can be used to explain the phenomena that certain wave components in a range of frequencies are amplified. It has also been shown that the extent of the amplification can be very dependent on the energy absorption behaviour of both the soil sediments and the superstructure. Thus, the amount of shear strains (i.e. non-linearity) imposed on the soil material and (for cohesive soils) the plasticity index are amongst the controlling parameters.

Resonant-like amplification behaviour of the structure found on the soil surface can occur as a result of superposition of reflected waves. Thus, factors such as seismic impedance ratio at the soil-bedrock interface and thickness of the soil layers can also have important influences on the behaviour of ground motions on the soil surface [3,4], given that these factors control the reflections of shear waves within the soil medium.

The wave modification mechanisms as described are well known and can be simulated by simple one-dimensional equivalent-linear dynamic analysis of the soil sediments [5]. However, periodic amplification behaviours as described have not been well represented in code provisions for the modelling of site effects, given that factors such as soil depth and impedance contrast at the interface between soil and bedrock are usually not parameterised. The decision adopted by codes of practice not to model the effects of resonance is partly because of a preference for simplicity and partly because of expert opinion that such effects are only "localised" in the frequency domain and can be suppressed readily by energy dissipation in the form of damping of the soil layers and ductile behaviour of the structure.

It is noted that non-ductile, and irregular, structural systems are

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common in regions of low-to-moderate seismicity. The priority in design, and retrofitting, in such built environments is to safeguard these structural systems from total, or partial, collapse in a rare event for avoiding loss of lives and for minimizing casualties. Until recently, the post-elastic behaviour of these systems in ultimate conditions featuring significant strength degradation and P-delta effects could only be modelled by rigorous non-linear time-history analyses. Reliable predictions can now be made using simple hand calculation techniques which employ displacement-based principles [6]. Importantly, investigations into the risk of collapse (overturning) of this type of structure employing a kinematic-based calculation technique revealed significant influence by the peak displacement demand of the ground motions irrespective of the exact dominant frequency of the ground excitations [7]. Although the effects of resonance on elastically responding systems are very localised, the effects on structures approaching the state of collapse, or overturning, can be widespread. This peak displacement demand has been shown to be amplified to a very high value by periodic excitations on a flexible soil site. Central to the calculation technique is the use of response spectrum in the displacement (RSD) format or acceleration-displacement response spectrum (ADRS) format which shows more clearly the amplified displacement demand behaviour of the ground motion than a response spectrum in the conventional acceleration format.

Fig. 1(a)–(e) presents the results of a case study of a flexible soil site (T_i~1.0 s) experiencing resonant-like amplification behaviour. Clearly, the frequency contents of ground motions have been dramatically modified by the flexible soil sediments as revealed by the displacement response spectrum (Fig. 1(d)) and ADRS diagram (Fig. 1(e)). In contrast, the phenomenon is not as clearly shown on response spectra presented in the conventional acceleration (RSA) format (e.g. Fig. 1(a)). Furthermore, it should be noted that the resonant phenomenon as illustrated in Fig. 1 can be easily masked by averaging response spectra from a suite of accelerogram records (except when all the recordings are from one soil site or from soil sites with very similar site natural period properties which is usually not the case). Resonant-like soil amplification behaviour is therefore not well represented in empirically developed codified models which were usually derived by statistical analyses of averaged response spectral values from accelerograms recorded on a diversity of soil sites.

A DS model in the displacement format which takes into account the described amplification phenomenon as depicted in Fig. 1(d) for flexible soil sites ($T_i > 0.5$ s) is introduced in this paper. Relationships for estimating the site factor and the site natural period (with considerations for a shift in the site natural period value) are presented in the form of algebraic expressions and design charts in order that a representative DS model can be constructed readily which can mimic results from computational dynamic analyses. The important effects of site natural period have been parameterised whereas the effects of damping in the soil and impedance ratio at the soil-bedrock interface have also been taken into account.

2. Appraisal of existing codified DS models

DS models in five codes of practice as listed in below (in alphabetical order of the abbreviated names shown in bold fonts) have been included in the review to be presented in this section:

1. Australian Standard (**AS** 1170.4–2007) [8].
2. Eurocode 8 (**EC**) (EN 1998-1:2004) [9]: a. Type 1, b. Type 2.

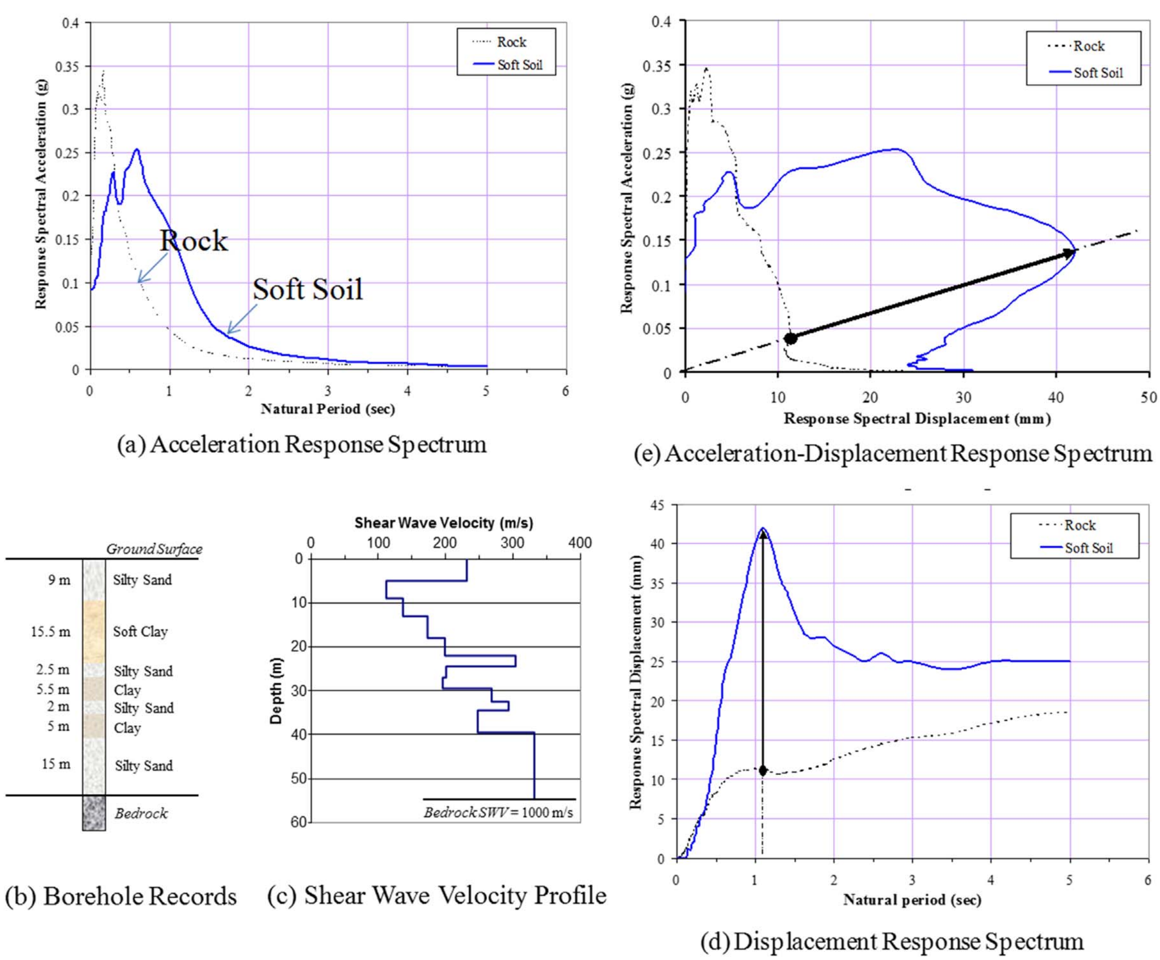

Fig. 1. Response spectra showing the effects of resonant-like soil-amplification behaviour.