Simple model accounting for the soil resonance phenomenon

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Abstract

The site natural period as a parameter for site classification has the attribute of providing an objective, and direct, representation of the risk of a soil site developing resonance behaviour. This parameter has definite advantages over the conventional approach of classifying soil based mainly on description of the sediments close to the ground surface (eg. the upper 30m of the sediment). This is particularly so if the site is characterised by high impedance contrast at the rock-soil interface, and more so in regions of low and moderate seismicity where non-ductile, lightly damped, systems are particularly prone to resonance behaviour. However, site natural period alone will not be able to accurately characterise potential soil amplification behaviour. This paper presents the recently developed Extended Component Attenuation Model (ECAM) which incorporates component factors to account for the effects of the shear wave velocity profile of the soil, damping properties of the soil, impedance contrasts with the bedrock (ie. radiation damping) and the frequency content of the earthquake excitation as transmitted from the bedrock. The presented model, due to its simplicity and generality, could potentially become standard manual calculation procedures that can be codified for widespread practical applications.

Keywords: Soil amplification, site factor, resonance, seismic.

Introduction

The importance of the modification effect of earthquake ground shaking by soft sediments and reclamation fill has been well recognised. The speculation of increased significance of site effects in areas of low and moderate seismicity like Australia is open to different interpretations depending on the perspectives from which research evidences were developed and presented.

The most well known mechanism that is responsible for the soil amplification phenomenon is that of the conservation of energy which causes an increase in amplitude of seismic waves entering from a medium of low impedance (rock or stiff soil sediments) to that of a higher impedance (soft soil) where impedance of the medium is represented by the product of density (r) and shear wave velocity (V). Site factor provisions in major seismic design standards including the current Australian Earthquake Loading Standard (AS 1170.4: 1993) and the International Building Code (IBC, 2000) could be interpreted using the conservation of energy principles to explain the trend.

Another important contribution to site hazards is that of conditions pertaining to resonance behaviour which is particularly important in areas where soft soil sediments are deposited directly on top of the bedrock which has a much higher shear wave velocity. The high impedance contrasts at the soil – rock interface is potentially hazardous in an earthquake due to the containment of energy within the soil medium (seismic waves reflected from the soil surface back down onto the soil – rock interface would be mostly reflected back into the soil medium). Significantly, the periodic reflected waves would superpose with incident waves entering the soil medium. The effects of wave superposition tend to be more pronounced with low intensity shaking as the reflected waves would tend to attenuate at a lower rate in such conditions. The 1985 Mexican earthquake is a notorious example of seismic destruction by soil resonance. The catastrophic destruction of the city was attributed to the long duration ground shaking and resonance between the medium-rise reinforced concrete buildings (typically of about 10 storey) and the deep soft soil deposits of the lake bed which has a natural period of about 2 seconds.

Despite the Mexican earthquake experience, contemporary site factor provisions in major international codes and standards including the International Building Code (IBC, 2000) and the current Australian Earthquake Loading Standard (AS 1170.4, 1993) do not explicitly parameterise the natural period of the site which characterises potential resonance behaviour. The site factors in IBC (2000), based on NEHRP recommendations, were originally developed from regression analyses of recorded ground motion parameters on different site classes. Again, the natural period of the recording stations had not been parameterised in the regression analyses.

The engineering significance of soil resonance has been a subject of debate. The opinion of some investigators is that soil resonance only occurs in the "exceptional" circumstances of the natural period of the structure coinciding with the natural period of the site. Flowing from this argument is the normal recommendation that the natural period of the structure should always be checked to ensure that the condition of resonance would not develop in the first place. This approach is distinguished from the intention of designing a structure which could accommodate the potential effects of high site amplification caused by resonance behaviour. It is also argued, quite rightly, that resonance could be suppressed effectively by energy dissipation in both the soil and the structure during the course of response to strong ground shaking.

Importantly, the capacity of a typical building structure in Australia to dissipate energy must not be assumed to be comparable to that of a code compliant building in a region of high seismicity such as California. The destructive effect of resonance mainly stems from the periodic nature of the waveform causing the amplitude of response of the structure to significantly exceed the amplitude of response of the ground. The amplification is highly selective. Thus, in theory, resonance can be circumvented by ensuring that the natural period of the building is not close to that of the site. However, in reality, the natural period of a building can be very difficult to determine and would often vary with the intensity of the response. For example, a structure with initial natural period significantly lower than the site natural period might risk being subject to the conditions of resonance (as the lateral secant stiffness of the building might deteriorate with increasing displacement amplitude). The reduction in stiffness would cause the natural period of the building to increase and hence its natural period shift closer to the natural period of the site. This period shift phenomenon adds to the scope of structures that are exposed to the risk of resonance behaviour; however, the potential amplification is offset against the non-linear behaviour that intervenes the damping.

In the new Australian Standard for Seismic Actions (DR 04304, 2004), the natural period of the site has been incorporated as a site classification criterion. However, site natural period alone will not be able to accurately characterise potential soil amplification behaviour. This paper presents a recently developed model which accounts for other important factors including shear wave velocity profile of the soil, damping properties of the soil, impedance contrasts with the bedrock (i.e. radiation damping) and the frequency content of the earthquake excitations as transmitted from the bedrock. The presented model, due to its simplicity and generality, could potentially become standard manual calculation procedure that can be codified for widespread practical applications.

Description of the model

A simple site factor predictive model which accounts for the effects of soil resonance has been developed recently at the University of Melbourne based on a parametric study of results obtained from one-dimensional quasi-nonlinear analyses of real borehole records (collected from Melbourne and from international sources) using program SHAKE (Idriss & Sun, 1992). This model, which is given the name the Extended Component Attenuation Model (ECAM), should provide more accurate predictions of the site factor than current code provisions which are mostly based on a prescriptive scheme of soil classification. However, the ability of ECAM to simulate real behaviour in the soil is limited by the capability of one-dimensional quasi-nonlinear analyses (which were employed for the development of the model in the first place). Nevertheless, ECAM is expected to accomplish the intended practical purpose of enabling site factors to be predicted with reasonable accuracy using only manual calculations rather than involving dynamic analysis of the soil column. ECAM is about predicting the soil amplification factor (S) which is defined as the ordinate of the soil response spectrum at the fundamental natural period of the site divided by the respective response spectrum ordinate of the rock outcrop. Since the model is intended to fully account for the effects of soil resonance, the predicted factor is expected to be generally higher than that stipulated by current standards.

In ECAM, the soil amplification Factor (S) is expressed as the product of four component factors as shown by equation 1 (Venkatesan, 2006).

$$S = S\xi .\ S\lambda .\ S\psi .\ S\tau \qquad (1)$$

where, $S\zeta$ represents the effects of hysteretic and viscous damping within the soil medium, and is a function of the intensity of ground shaking as defined by the peak ground velocity of the bedrock (PGV) and the plasticity index (PI); refer Table 1;

$S\lambda$ represents the effects of the impedance contrasts between soil and bedrock which controls the extent of radiation damping, and is mainly a function of the shear wave velocity of the bedrock (half-space); refer Table 2.

$S\psi$ and $S\tau$ both represent the effects of the form of the shear wave velocity profile as illustrated in Tables 3 & 4 respectively.

Table 1: $S\psi$ factor

PGV (mm/sec)	PI-0	PI-15	PI-30	PI-50	PI-100
20	2.6	2.7	3.2	2.9	2.6
40	2.3	2.5	3.0	2.7	2.5
60	2.2	2.5	2.8	2.6	2.4
80	2.1	2.5	2.7	2.5	2.4
100	2.1	2.5	2.6	2.5	2.3

Table 2: $S\lambda$ factor

Bedrock SWV in m/sec (half-space)	Impedance contrast Factor $S\lambda$
750 m/sec	0.96
1000 m/sec	1
1500 m/sec	1.08
2000 m/sec	1.15
2500 m/sec	1.22
≥3000 m/sec	1.3

Table 3: Sψ factor

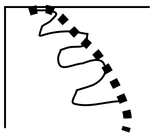
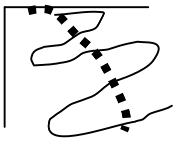
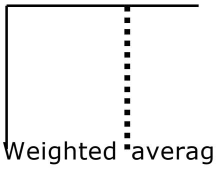
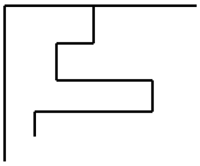
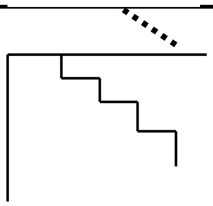
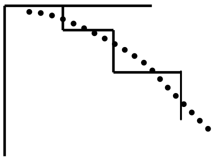
Lateral spread of SWV → Generic classification of Soil SWV Profile ↓	S_ψ Lower Bound (consistent with the generic profile within ± 20%) Example: 	S_ψ Upper Bound (variations in SWV is greater than ± 50%) Example: 
 Weighted average uniform profile (reference profile)	1	1
 Irregular profile	1.45	1.7
 Linear profile	1.55	1.8
 Polynomial profile	1.65	1.95

Table 4: Sτ factor

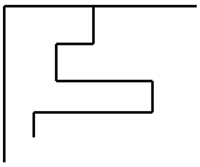
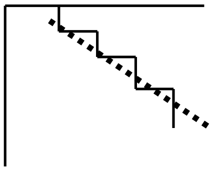
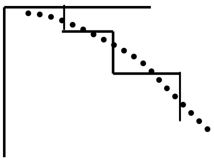
Soil SWV Profile Modification factor	 Irregular profile		 Linear profile		 Polynomial profile	
	Sand	Clay	Sand	Clay	Sand	Clay
S_τ	0.	1.1	0.95	1.05	0.85	1.15

Illustration of ECAM by example

The proposed ECAM model is illustrated by the analysis of an example site (denoted herein as "Site – 1") which has the shear wave velocity profile as defined by Figure 1 below.

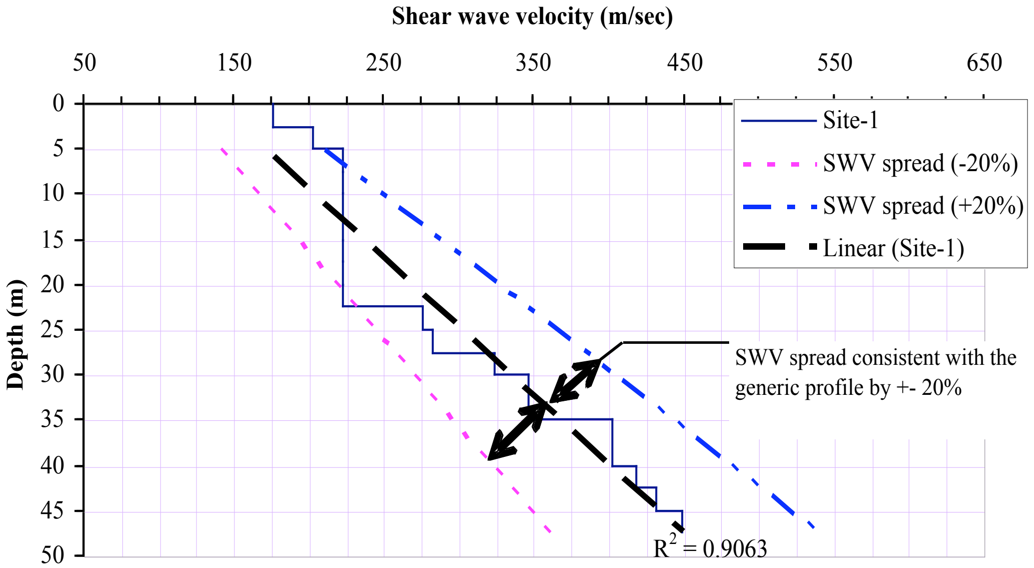


Figure 1 : Shear wave velocity profile for "Site – 1" used in the illustration

Generic classification of SWV profile of site-1 is basically a "linear" profile.

Site – 1 consists mainly of sand (PI=0%) and is subject to a notional peak ground velocity on bedrock of 60 mm/sec approximately.

From Table 1 , Sζ = 2.2; from Table 2 , Sλ =1.08 based on a bedrock shear wave velocity of 1500 m/sec ; from Table 3, Sψ =1.55 ; and from Table 4, Sτ = 0.95 for sand.

Finally, from equation (1), the value of S = 2.4 x 1.08 x 1.55 x 0.95 = 3.5

Comparison of ECAM with results from SHAKE analyses

Three additional example sites with shear wave velocity profiles shown by Figure 2 were analysed by both ECAM and SHAKE for comparison. Calculations for the individual component factors for each case are presented in Table 5.

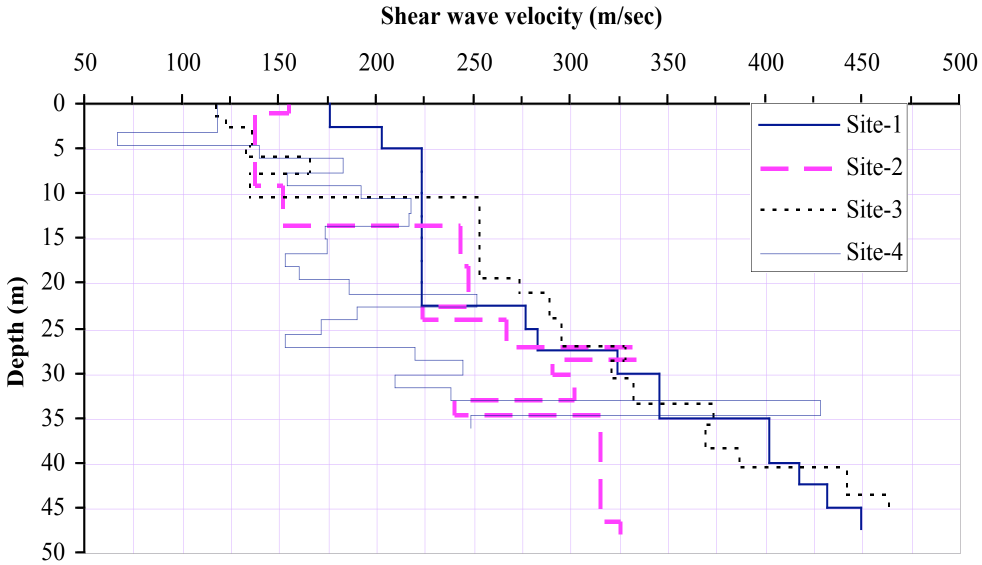


Figure 2: Shear wave velocity profiles for the four example sites

Table 5: Component factors and S value for the four example sites

Site Number	Sξ	Sλ	Sψ	Sτ	"S"
Site-1	2.2	1.08	1.55	0.95	3.5
Site-2	2.5	1.08	1.55	1	4.2
Site-3	2.35	1.08	1.55	1	3.9
Site-4	2.8	1.08	1.55	1.1	5.2

One-dimensional quasi-nonlinear analyses were undertaken on the shear wave velocity models of site 1 - 4 using program SHAKE and bedrock excitations simulated for the earthquake scenario of magnitude (Mw) 7 at 90 km distance which has a peak ground velocity on rock of approximately 60 mm/sec (Lam et al, 2005). The velocity response spectra calculated for each of the soil sites and bedrock are plotted in Figure 3. The site factor for comparison with the ECAM predictions is based on measurement at the natural period of the site (as indicated in the figure).

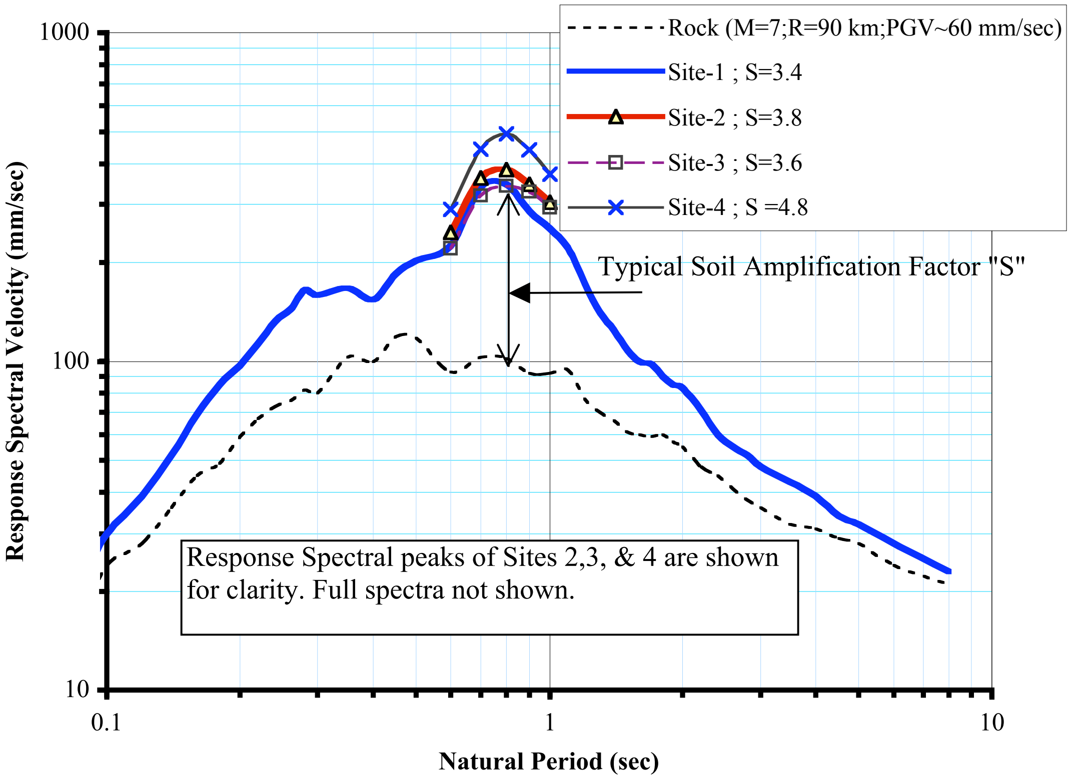


Figure 3: Velocity Response Spectra and soil amplification factors for case study soil sites computed using SHAKE-91

The site factors inferred from Figure 3 (based on SHAKE analyses) are compared with the ECAM predictions in Figure 4 (with the percentage error shown in Figure 5). It is not the intention here to use these four example sites to verify ECAM. Full details of the development of ECAM and a much more extensive verification of the model can be found in Venkatesan (2006).

Closing remarks

A simple manual procedure called ECAM for estimating the soil amplification factor which accounts for the effects of resonance behaviour is presented in the paper. Limited comparisons of ECAM with results obtained from SHAKE analysis revealed that the proposed model provides estimates which were comparable to that obtained from one-dimensional non-linear dynamic analyses of the soil columns.

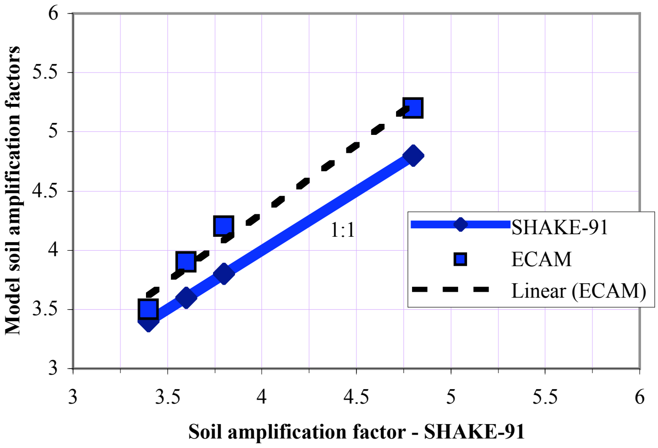


Figure 4: Comparison of soil amplification factor "S" computed using ECAM model with computations using SHAKE-91

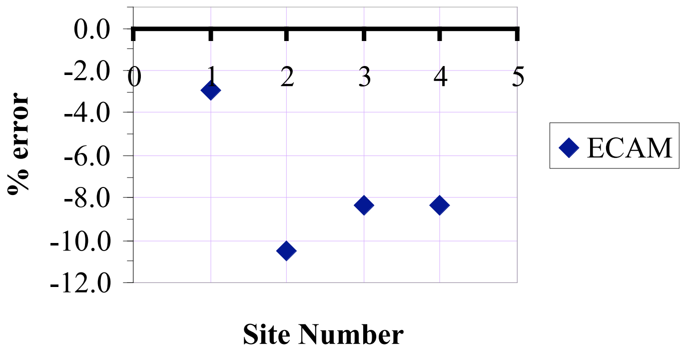


Figure 5. Percent error of soil amplification factor "S" computed using ECAM with computations using SHAKE-91

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