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Response spectra for long distance subduction earthquakes on soft soil sites

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A stochastic seismological model has been developed for simulating earthquake ground shaking on rock sites in Singapore and the adjoining Malaysian Peninsula. Simulations from the model have been compared with recent earthquake events (12th September 2007) of M8.4 and M7.8 generated by the Sunda Arc Subduction Trench from a long distance in the range 600 km – 1000 km. It was concluded that existing attenuation models developed for worldwide applications may not provide realistic representation of such extreme magnitude-distance combinations. In this study, ground motion simulations for rock sites were extended to simulations for the more hazardous soft soil sites conforming to Class C and D of IBC 2006. Accelerograms recorded in downholes from recent major earthquake events along with borehole records of selected soil sites have been collated and archived. Response spectra and drift demands calculated from the recorded accelerograms have been compared with those simulated by program GENQKE (incorporating the attenuation behaviour of the region) and program SHAKE (incorporating the amplification effects of the individual soil sites). This comparative study could form the basis for the development of a realistic and reliable seismic demand model for the Singapore and Malaysian peninsular region.

1. Introduction

The Malay Peninsula inclusive of Singapore is located within the stable Sunda plate (Figure 1). However, this region has experienced seismic tremors generated mainly from (i) the Sunda-Arc subduction source off-shore of Sumatra on the Indian Ocean side of the island and (ii) the Sumatran fault source which has a closest distance of 400 km from this region. Generally tremors due to long distant earthquakes are notorious for damaging long period structures (typically 1 s and above). The effect could be more pronounced if the structures were founded on deep soil sites underlain by a hard rock-soil interface. Such soil sites would filter the long period component of the ground motion and amplify it several times (due to soil resonance phenomenon) and impose severe displacement demand on structures. Thus there are three important components in predicting seismic displacement demand in these regions: a) modeling the effects of long distant earthquakes, b) modeling associated soil resonance effects (focusing on deep or soft soil sites) and c) estimating displacement demand for structures which could be vulnerable. Ground motion simulations from the above subduction zone for key earthquake scenarios have been presented by Lam et al. (2008), Kafle et al. (2008) and Venkatesan et al (2005). In this paper, these simulations have been extended to include the effects of soil resonance in predicting the associated seismic displacement demand.

The largest subduction earthquake that has occurred in the Sunda Arc subduction trench is the Aceh earthquake of 26th December 2004 (also known as the "Great Sumatra earthquake" which caused the Boxing Day Tsunami). Details of this earthquake event and other recent great earthquakes that have been felt in the whole region including Singapore and parts of the Malaysian Peninsular are listed in Table 1.

Table 1 Major recent earthquake events in the Singapore- Malaysian Peninsular region

Location of epicentre	Moment magnitude (M_w)	Epicentral distance from Singapore (km)	Date of occurrence
Aceh	9.3	1000 - 1200	26th December 2004
Offshore of Bengkulu	7.9	700	4 June 2000
Nias Island	8.6	700 - 800	28 March 2005
Offshore of Bengkulu	8.4	700	12 September 2007
Mentawi Strait	7.9	550	12 September 2007

Lam *et al.* (2008) compared the recorded motions from the above events with those simulated by the stochastic seismological model (GENQKE) and found the comparisons to be satisfactory. The model has been used in this study with design earthquakes of Mw=9, 9.3 and 9.5 at a distance of 600 km.

Soil sites with natural periods in the range between 0.5 sec and 1.5 sec have been collated from the region which is presented in Section 2 of the paper. Site response analyses carried out using SHAKE (Schanbel, et al. 1972) and the key response spectral properties on deep soil sites have been presented in Section 3 whilst seismic displacement demand on structures have been modeled, estimated and presented in Section 4. Conclusions from this research are presented in Section 5 of this paper.

Figure 1. Location of Sumatran fault and the Sunda-Arc subduction zone

2. Soil profile data

About 15 soil sites with (initial low-strain) natural periods in the range of 0.5 s to 1.5 s have been collated for this research. The natural period is calculated as shown in equation 1.

$$T_i = \frac{4H}{V_s} \tag{1}$$

where T_i is the initial low-strain natural period in seconds
H is the total depth of the soil medium in m
V_s is the weighted average Shear Wave Velocity (SWV) in m/s
and V_s can be estimated using equation 2.

$$V_s = \frac{\sum_i h_i}{\sum_i \frac{h_i}{V_{si}}} \tag{2}$$

where,

i = layer number,
h_i = thickness of layer i and
V_{si} = SWV of layer i

It is noted that International Building Code (IBC 2006) recommends classifying soil sites based on their weighted average SWV over the upper 30 m of the site. According to this classification, soil sites are classified as `C' (with $V_s$ in the range 180 m/s - 360 m/s) or `D' (with V_s in the range 120 m/s - 180 m/s). It is generally believed that these site classifications would cover the practical range of interest and exceptional cases be classified as Site E. Sites chosen for analysis herein belong to either Site – C or Site – D of the above classifications and also confirm to the natural period in the range of 0.5 sec and 1.5 sec. It is important to observe that resonance in soil medium would occur close to their natural periods. Thus a comprehensive range of soil sites that may impose significant displacement demands on structures have been chosen for analysis as shown in Table 2. (The complete details of the borehole log of these sites are shown in Appendix -1).

Table 2. List of sites selected for soil response analysis

Site name	**Natural period (s)**	**Average shear wave velocity SWV (m/s)**	**Total depth (m)**	**IBC site classification**
Pulau Retan Laut BH6	0.6	340	51	Site - C
Cassia Drive BH1	0.6	230	36	Site - C
Chapel close BH1	0.65	280	46	Site - C
Marine Parade	0.7	220	39	Site - C
Katong Park	1.0	190	48	Site - C
Katong	1.2	170	53	Site - D

From the above table, it is clear that the Katong site would have been classified as a site-C according to IBC (2006). However when the natural period is chosen as the basis of site classification, the site would be classified as type D for reflecting a deep or flexible soil site. This observation is very consistent with the displacement demands estimated in this paper.

3. Site response analysis

Input motions for projected earthquake scenarios of M = 9.5, 9.3 and 9 at a distance of 600 km were simulated using program GENQKE (Lam et al. 2000). Six synthetic accelerograms were simulated for each event and site response analyses for all sites in Table 2 were carried out using SHAKE-91.

The ensemble average velocity response spectrum (5% critical damping) of the two sites with natural period of 1 sec and 1.2 sec are presented in Figure 2. Lines corresponding to a constant acceleration of 1% g and 5% g are shown in Figure 2a. The response spectral behavior of structures possessing a natural period less than 1 sec could be characterized by these two acceleration limits. Structures possessing a natural period close to 1 sec pertain to the upper limit of 5% g, whilst structures possessing a lower natural period pertain to the lower limit. Seismic displacement demands imposed on the above selected sites were then inferred from the SHAKE-91 simulations.

Figure 2a. Ensemble averaged velocity response spectra for 1 second site

Borehole log

7.9 m	Very stiff silty sand
27.9 m	Sandy clay
17.4 m	Silty sand

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