

# Site-Dependent Response of Singapore Buildings to Long-Distance Sumatra Earthquakes

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## Summary

Singapore is believed to be located in an aseismic region. However, tremors caused by distant Sumatra earthquakes have reportedly been felt in Singapore for many years. Based on previous studies for Singapore, the maximum credible earthquakes (MCEs) from Sumatra have been hypothesized to be a subduction earthquake ( $M_w = 9.0$ ) and a strike-slip earthquake ( $M_w = 7.5$ ). Response at a soft soil site in Singapore to the synthetic bedrock motions corresponding to these MCEs are simulated using a one-dimensional wave propagation method based on the equivalent-linear technique. A typical high-rise residential building in Singapore is analyzed to study its responses subjected to the MCE ground motions at both the rock site and the soft soil site. The results show that the base shear force ratios would exceed the local code requirement in terms of the notional horizontal load for buildings.

## 1. Introduction

In the 1985 Michoacan earthquake, a large earthquake ( $M_s = 8.1$ ) along the coast of Mexico caused destructions and loss of lives in Mexico City 350 km away from the epicenter. Learning from the Michoacan earthquake, it has been recognized that urban areas located rather distantly from earthquake sources may not be completely safe from the far-field effects of earth tremors. Singapore is located in a low-seismicity region, where the closest active seismic sources are located more than 300 km away, along and off the western coast of Sumatra. Earthquakes in Sumatra, some of which had magnitudes as low as 6.0, have frequently shaken high-rise buildings in Singapore, especially those founded on Quaternary marine clay deposits and reclaimed lands. No structural damage, however, has been recorded (Pan, 1995, Pan, et al. 2001). Currently, building design codes for structures in Singapore and Malay Peninsula have been developed largely based on the BS8110 Code (BSI, 1987), which does not provide for seismic loadings. This paper studies the ground motions at a soft soil site first, followed by the structural response of a typical high-rise building subjected to the ground motions.

## 2. Subsurface Soil Properties of Singapore Island

The soft soil site is located at Katong Park (KAP) along the south-east coast of Singapore island (Figure 1). The site rests on the Kallang Formation which consists of late Pleistocene and recent deposits of marine, alluvial, littoral and estuarine origin. The most important unit of the Kallang Formation is the marine clay. It occurs over an area covering one quarter of the island, but no surface outcrops exist. Its thickness is

extremely variable with a maximum depth of 35 m recorded (Pitts, 1984). The marine clay is pale grey to dark blue in colour, soft, silty, kaolinite-rich and has shell fragments disseminated throughout.

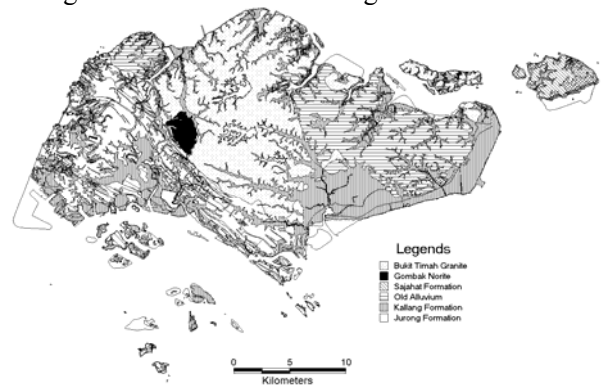


Figure 1. Surficial geological map and location of the KAP site

The subsurface profile of the KAP site consists of 6.5 m of fill material, followed by 24 m of marine clay unit. The marine clay unit consists of upper and lower members separated by a weathered crust on top of the lower member. This weathered crust is much stiffer than either the upper or the lower member, as can be deduced from the much larger recorded shear wave velocity. Following the marine unit is 4 m of soft organic clay, 5 m of residual soil and the last 8 m consists of slightly weathered silty sand of which the shear wave velocity reaches a maximum value of around 500 m/s.

## 3. The Maximum Credible Ground Motions

Megawati and Pan (2002), Pan and Megawati (2002) and Megawati et al. (2003) identified that the

maximum credible ground motions in Singapore are likely to be caused by two large earthquakes of different source mechanisms. One is a strike-slip earthquake (Sumani segment) with an epicentral distance of around 425 km and a moment magnitude of 7.5. The other is a Sumatra subduction earthquake with an epicentral distance of 723 km and a moment magnitude of 9.0. The bedrock motions in Singapore due to these two earthquakes have been simulated using the extended reflectivity method (Kohketsu, 1985), taking into account uncertainties in the source rupture process. One set of the simulated motions is used in this study.

The equivalent-linear site response analysis is carried out for the soft soil site using the larger horizontal components of the two MCE ground motions selected. In this study, the EERA program (Bardet, et al. 2000) for equivalent-linear earthquake site response analysis of layered soil deposits is used. The simulated surface acceleration time-history and its Fourier spectra for the strike-slip tangential component are compared with those of the corresponding input rock motion (Figures 2). We observe an increase in the peak acceleration by around 2.2 times from 22.3 gals to 49.8 gals. In the Fourier domain, a distinct predominant frequency occurs at around 1.0 Hz for the surface motion as compared with the rock motion which does not display a distinct peak. Similar results for the subduction perpendicular components are shown in Figures 3. For the subduction event, we observe an increase in the peak acceleration by around 2.6 times from 17.5 gals to 45.6 gals (Figure 3). In the Fourier domain, a distinct predominant frequency occurs at around 0.8 Hz for the surface motion as compared with the rock motion which again does not display a distinct peak.

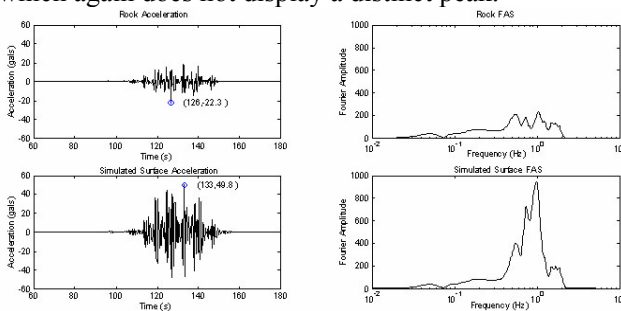


Figure 2. Comparison of rock and surface acceleration time-histories and Fourier spectra for the Mw = 7.4 Sumatra strike-slip earthquake

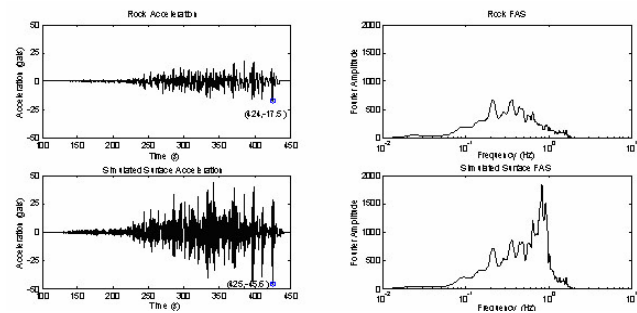


Figure 3. Comparison of rock and surface acceleration time-histories and Fourier spectra for the Mw = 9.0 Sumatra subduction earthquake

#### 4. Building Response to Long-distance Earthquakes

In this section, the seismic responses of a typical high-rise residential building under the ground motions previously discussed are studied. The structure is a typical 15-storey, reinforced concrete (RC) residential building. The building has a dual lateral force resistant system of RC frames and shear walls. A three-dimensional finite element (FE) model was constructed to study the dynamic responses of the building (Figure 4).

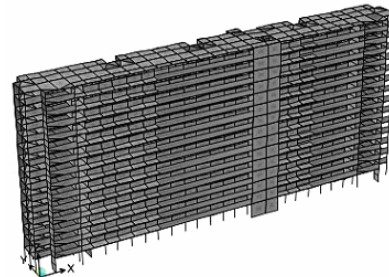


Figure 4. Perspective view of the FE model

The total base shear forces of the FE model subjected to the ground motions are investigated in both the longitudinal and the transverse directions. The maximum base shear force is 14,056 kN, caused by the soft soil ground motion of the strike-slip earthquake in the transverse direction. The force is about 9.2% of the total building dead weight, which is 152,563 kN. Even though the total base shear forces of the model are greater than 1.5% of the total building weight, which is the notional lateral load resistant capacity as required by BS8110 (BSI, 1987), they are all well below the base shear capacities of the building. The base shear capacities of the building are 22.4% and 35.3% of the building weight for the longitudinal and the transverse directions, respectively.

The analysis results also show that, when the ground motions change from the bedrock motions to the soft soil motions, the base shear forces are amplified by two to four times. For example, when the building is subjected to the bedrock motion of the strike-slip earthquake, the total base shear force is

only 6,014 kN, while when subjected to the soft soil motion of the same earthquake, the total base shear force increases to 13,544 kN. Therefore, the typical building would function very well during the MCE events when it is located at the rock sites. However, the MCE events might cause some local damages to the building located at the soft soil site, such as overstressing on some column and cracking on the infill walls.

#### 4. Conclusions

Ground motions at a soft soil site in Singapore due to the maximum credible earthquakes from Sumatra have been computed using a one-dimensional equivalent-linear ground response analysis technique. Due to the large input rock motions, soil stiffness degradation has been observed. This results in a consequent shift of the site fundamental frequency towards a lower value as compared with the linear case of the recorded weak earthquake motion. The responses of a typical high-rise residential building subjected to the ground motions of MCEs have also been investigated. Even though the base shear forces caused by the earthquake ground motions would exceed the nominal code requirement as stated in BS8110, the vertical members designed under the gravity loads are sufficient to resist them. The responses of the building are highly site-dependent. At the rock site, the earthquake ground motions are hardly a problem to the building. However, at a soft soil site, the MCEs may cause some vertical elements being overstressed and cracking on the infill walls.

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