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Site response analyses using downhole arrays at various seismic hazard levels of Singapore

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ABSTRACT

Local site conditions can significantly influence the characteristics of seismic ground motions. In this study, site response analyses using one-dimensional linear elastic (LE), equivalent-linear (EQL) and nonlinear (NL) approaches are performed at different seismic hazard levels of Singapore. Two seismic stations, namely, the KAP and BES stations located at soft soil sites, are selected from the national network of Singapore. Firstly, site response estimates using the LE, EQL (SHAKE04) and NL (DEEPSOIL) approaches are compared with the borehole recordings. Results show favorable matches between the predictions and the observations at the KAP site, while under-predictions are observed for all the three site effect approaches at the BES site. Secondly, the applicability of the LE, EQL and NL models is examined at different hazard levels of Singapore. It is found that for the hazard level at a return period of 475 years, the computed maximum strain (γ_{max}) is 0.06% and then the EQL model can provide accurate site response predictions. However, for the hazard level at a return period of 2475 years, the calculated γ_{max} is larger than 2%, resulting in notable differences in the predictions of different site response models. This study highlights the importance of site effects in seismic hazard analysis of Singapore.

1. Introduction

Although Singapore is located in low-to-moderate seismicity regions, seismic risk should be an important concern due to its strong economy, dense population and numerous high-rise buildings. Nowadays there are more than five million residents in Singapore, and most of them live in middle or high-rise buildings. These high-rise buildings have frequently experienced shakings by far-field Sumatran earthquakes. One of the major sources of ground shakings felt in Singapore is the Great Sumatran fault (at a distance of about 400 km from Singapore). It has been identified as a 1,900-km long right-lateral strike-slip fault consisting of 20 major segments [1]. Several studies have shown that the Great Sumatran fault, which is well known to produce earthquakes larger than moment magnitude (M_w) 7, may potentially affect Singapore regions by some major earthquakes [2,3]. In the new seismic design code of Singapore [4], the bedrock peak ground acceleration (PGA) value is given as 0.0178 g for a return period of 475 years (10% probability in 50 years). Besides, based on the Southeast Asia PGA hazard maps by U.S. Geological Survey (USGS), the rock PGA value with 10% probability of exceedance in 50 years is in the range of 0.04-0.06 g, while the rock PGA with 2% probability of exceedance in 50 years is about 0.15-0.2 g [5]. It should be noted that the rock PGA value provided from the USGS hazard map is slightly greater than that of the seismic design code of Singapore.

Local site conditions play an important role in the characteristics of surface seismic waves. In general, soft soil sites tend to increase ground motion amplitudes compared to rock sites. The earthquakes of 1985 Michoacan event [6], 1989 Loma Prieta event [7] and 2010 Haiti event [8] have shown the significant influence of local site conditions. For instance, the Mexico City, although it was located 400 km away from the epicenter, suffered severe damages and human losses due to strong site amplifications. Therefore, in view of a similar situation compared with the Mexico City, more attentions should be drawn to the high-rise buildings built on soft clays or reclaimed lands of Singapore.

The surface ground motions are usually estimated by one-dimensional linear elastic (LE), equivalent-linear (EQL) frequency domain analysis [9] or fully nonlinear (NL) time domain analyses [10]. Downhole seismometer arrays are commonly used to compare and validate site response analyses, e.g. [11–20]. For example, Kwok et al. [13] performed blind site response predictions at the Turkey Flat array site using ground motions from the 2004 Parkfield earthquake. Kottke [15] evaluated the performance of equivalent-linear and fully nonlinear analyses using borehole sites

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in California and Japan, and Kaklamanos et al. [16] compared the accuracy of linear and equivalent-linear method using 100 KiK-NET arrays. These results show that the suitability of different methods is strongly associated with ground motion intensities, one-dimensional assumptions as well as maximum strain levels.

The objective of this paper is to perform a comprehensive site response analysis using two seismic downhole arrays of Singapore. Two major issues are addressed in this study. First, the computed ground motions by various methodologies (LE, EQL and NL) at different depths are compared with the recorded data at each vertical array. The computations are based on two recent earthquake events: the September 30, 2009 event (M_w 7.6 and rupture distance 470 km) and the October 1, 2009 event (M_w 6.6 and rupture distance 460 km). These events can be regarded as frequently felt earthquakes in Singapore. Second, site response analyses using the three aforementioned methods (LE, EQL and NL) are performed at various earthquake intensity levels: (i), the seismic design level of Singapore with a bedrock PGA 0.0178 g (10% probability of exceedance in 50 years); (ii), one ground motion with PGA 0.04 g from the 1985 Mexico earthquake which can be regarded as a rare event of Singapore due to the similar fault mechanisms and rupture distances; (iii), the up-scaled Mexico time history with PGA as 0.15 g (2% probability of exceedance in 50 years in Singapore); and (iv), the up-scaled Mexico motions with a series of target PGA values (from 0.05 g to 0.2 g with interval as 0.01 g). To sum up, the presented paper plans to quantitatively evaluate the site amplifications of the two soft clay sites in Singapore, and further clarify the suitability of the LE, EQL and NL methods at different intensity levels. It is to be noted that through this study, the LE and EQL analyses are performed in the frequency domain by SHAKE04 [21], and the fully NL approach is implemented in the time domain by DEEPSOIL v5.1 software [22].

2. Geology and seismic stations of Singapore

Recently, the Defence Science and Technology Agency [23] provided detailed geological formations of Singapore, as shown in Fig. 1. The geology of Singapore can be broadly classified into five major formations i.e., Gombak Norite (GN), Bukit Timah Granite (BTG), Jurong Formation (JF), Old Alluvium (OA) and Kallang Formation (KF). In particular, KF is the youngest formation, and it is located most abundantly on the coastline of the island with larger area coverage at the southeast part. The KF category consists of marine and littoral sediments with silt and clay lenses. In addition, a large portion of Reclaimed Land (RL) has been extended outwards to coast. Based on ground types classification of Eurocode 8 [24], the dominant site classifications in Singapore are mainly ground types B, C, D and S_1, and the corresponding values of shear wave velocity in the top 30 m (V_{s30}) are in the range of 360-800 m/s, 180-360 m/s, 100-180 m/s and less than 100 m/s, respectively.

Seven seismic stations were set up in 1996 by the Meteorological Services Singapore. They are located at Bukit Timah Dairy Farm (BTDF), Fruit Tree Center (FTC), Nanyang Technological University (NTU), Pulau Tekong (PTK), Saint John's Island (SJA), Beatty Secondary School (BES), and Katong Park (KAP). The distribution of these stations is shown in Fig. 2. The stations have successfully captured hundreds of ground motions till now. The recorded ground motions have been used for some research topics, such as the development of ground motion prediction equations ([25,26]). More information about the national network of seismic stations can be found by Pan and Lee [27].

Among these stations, the KAP and the BES sites are located mainly on soft soils, and therefore they are particularly valuable for site response study. More importantly, both the two stations were built associated with downhole arrays, making it easier to capture the ground motions at multiple depths. It is noted that only these two stations have drilled boreholes to install seismometers at various depths and to perform geotechnical investigations. At the KAP site, the soil profile mainly consists of very soft marine/organic clay layers (about 6.5-34 m), and stiff silty clay and silty sand layers below 34-m depth. The soil profile of the BES site mainly consists of soft organic/marine clay layers (3.5-21.5 m), a 5-m thick poorly-graded loose sand layer and highly/moderately weathered granite layers below 26.5-m depth. A suspension P-S velocity logging method was used to measure the seismic wave

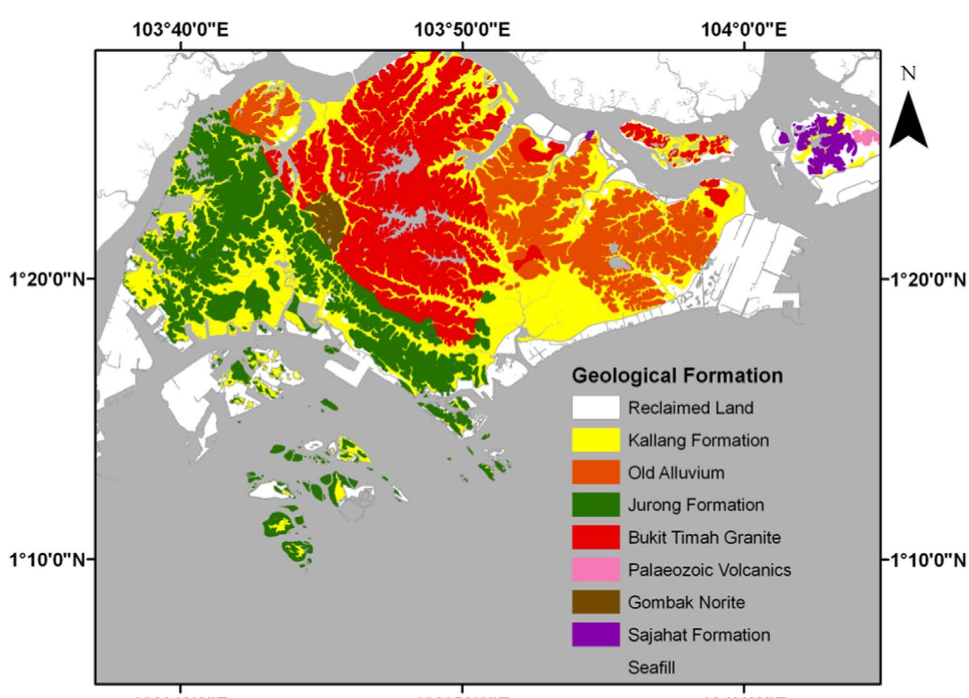

Fig. 1. Geological map of Singapore [18].