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Site effect assessment via dynamic analysis – Bukit Timah Granite

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ABSTRACT: This study aims to assess the site effect of the Bukit Timah Granite area in Singa-pore via 2D dynamic numerical modeling and further comparison with previous geophysical testing results. A 3D geophysical model was created via combining geophysical investigation data with borehole data and geological maps of the region, and then several 2D geological cross-sections were extracted. Those cross-sections were used for dynamic numerical modeling of seismic ground motion and for calculating site amplification using the Universal Distinct Element Code (UDEC). The results show that the fundamental frequency (f_0) is in a good agreement between dynamic numerical modeling and horizontal to vertical spectral ratio (HVSR). Thus, the dynamic numerical models would be used for site effect analysis in the seismic hazard assessment.

1 INTRODUCTION

The local effects that amplify the seismic waves are generally due to the surface topography, the presence of an alluvial/lake, or any other soft deposits, including artificial fills (Wald & Allen, 2007). Therefore, the territory targeted is divided into several microzones to consider seismic amplification effects based on the dynamic soil properties of the site.

Site effect analyses can be conducted using information from geological investigations, borehole drilling, and geophysical surveys (Hakimov et al., 2021). Borehole drilling, an invasive method, is commonly practiced among the listed methods. Drilling will provide data on the thickness of each layer, bedrock depth and layers' stiffness. The latter data can then be empirically used for estimating shear wave velocity (V_S). Despite its popularity, the method contains huge drawbacks, such as being destructive, expensive, and time-consuming. For these reasons, their wide application is not always possible (Zhang et al., 2019, Moon & Ku, 2017), e.g., in Upper Missisipi Embayment, where the bedrock depth can reach up to 1000m (Moon et al., 2017). Geophysical surveys (e.g., multichannel analysis of surface waves (MASW) or horizontal to vertical spectral ratio (HVSR) from microtremor measurements (MM)) are practiced as a fast and cost-effective alternative to deriving dynamic soil properties.

This study aims to evaluate the site effects at the Bukit Timah Granite area in Singapore using 2D dynamic numerical modeling. 2D numerical models are selected from 3D Geomodel in such a way as to contain locations with geophysical and borehole information. The

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numerical modeling technique generates a layered digital representation of a Bukit Timah Granite region to improve interpolated data further. The available geophysical survey data with the region's borehole data and geological maps are combined to create a 3D Geomodel. From the resulting numerical model, 2D cross-sections close to available geophysical data are selected for further data validation.

2 STUDY AREA

The Bukit Timah Granite is the most predominant rock formation in Singapore, comprising about 1/3 of the land area, and is one of the five major geological formations. Bukit Timah Granite is considered a base rock formation for the central part of Singapore. In a local context, in accordance with weathering degree, Bukit Timah Granite is graded from G(I) for hard intact rock to G(VI) for fully weathered residual soil. Bedrock depth is considered the depth of G(III), in which gradual stiffness is noticeably increased (Moon & Ku, 2017). The thickness of residual soils in Bukit Timah territory reaches 70 m, with a mean thickness of 30 m (Zhao, 1996).

Previous studies have demonstrated that the MASW test and microtremor measurement (MM) are applicable for bedrock depth estimation in the Bukit Timah Granite (Moon et al., 2019, Ku et al., 2021). Moreover, further works on HVSR inversion in Bukit Timah Granite performed with constrained borehole information resulted in V_S profiles similar to MASW test results (Abdialim et al. (2021). This work compiles the results of all the aforementioned studies for generating and demonstrating a dynamic numerical model in an example of a 2D cross-section. Figure 1 shows test site locations, including MASW results, MM, and borehole data.

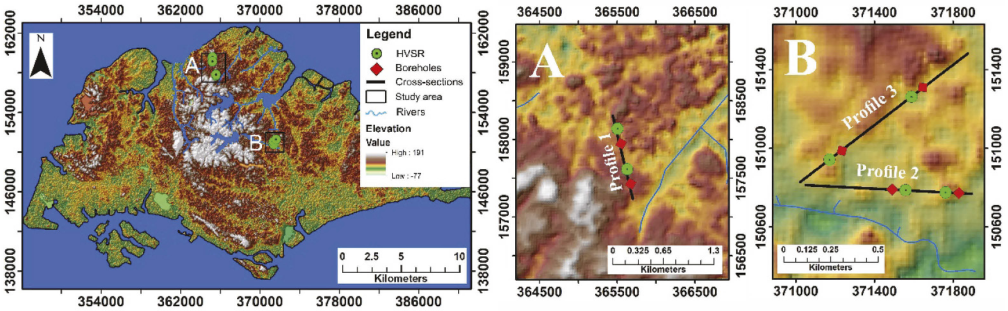

Figure 1. The study area of the Bukit Timah Granite with an indication of three 2D cross-sections (Note: Green circles indicate HVSR points on the profiles, and the red rhomboid shows borehole locations on the profiles).

3 NUMERICAL MODELLING

A 3D geomodel for the Bukit Timah area was generated based on combined MASW, HVSR, and borehole data. This model was obtained using Leapfrog Geo software (version 4.5 from Seequent Limited). The thickness of soil layers (h) susceptible to site amplification was estimated and mapped by the 1-D soil model assumption using the following equation: $h = V_S/4f_0$, where V_S = average shear wave velocity of 30m, f_0 = fundamental frequency. Since the relationship between f_0 and h assumes a high impedance contrast between two underlying layers, only clear peak HVSR curves with high amplitudes were used for Geomodel generation. 3D Geomodel was split into three layers to consider the weathering: soft layer, weathered granite layer, and granite. Thicknesses of soft and weathered layers were introduced following borehole, MASW, and HVSR information. From the 3D geomodel, we extracted three 2D cross sections from the points where HVSR measurements were taken (Figures 1 and 2). Dynamic numerical simulations of the site effect were performed and compared with HVSR measurements. UDEC software developed by the Itasca Consulting Group was used as the distinct element method-based tool. 2D section consists of a basement, a weathered granite layer, a surface layer, and synthetic receivers. Site effect analysis was performed in an elastic domain for all profiles. Input data were selected from the literature (e.g., stiffness properties of bedrock from Zhao (1996), V_S values from MASW data, densities from Sharma et al. (1999)). Bulk and shear moduli (K and G) data converted from V_P and V_S data. Joint properties of the model, such as joint normal and shear stiffnesses (j_{kn} and j_{ks}) and joint cohesion (j_{coh}), were maximized for the prevention of deformations along the discontinuities (Havenith et al., 2003). Ricker wavelet was used as input signal at the base. Elastic properties of numerical model materials are listed in Table 1.

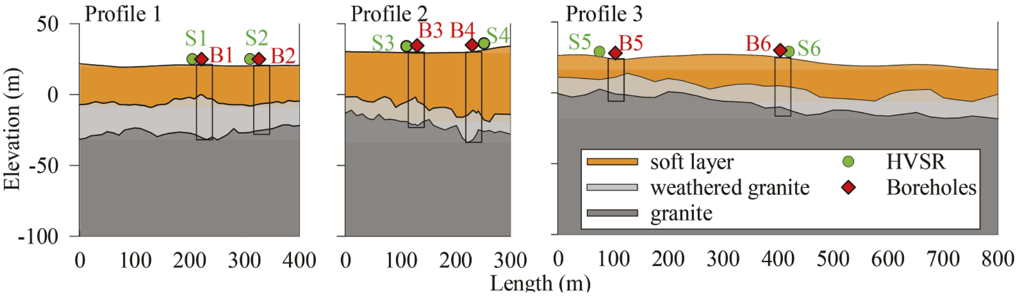

Figure 2. 2D Cross-sectional profiles taken and extracted from 3-D geomodel.

Table 1. Soil engineering properties.

	K (Mpa)	G (Mpa)	ρ (kg/m^3)	H(m)	j_{fric}	j_{tens}
Soft layer	1387	384.75	1900	10-20	–	2e20
Weathered granite	10208	4776	2200	20-30	38	–
Granite	14208	7776	2600	30-50	38	–

4 2D NUMERICAL MODELING PROCESSING

Figure 3a shows the locations of synthetic receivers for dynamic analysis. Standard spectral ratios (SSRs) were obtained for site amplification evaluation at each synthetic surface receiver by the following procedure: The acceleration-time histories generated on the surfaces were compared with those recorded on a synthetic receiver at the model's base. Signals were then multiplied by two to account for the flat surface reflection effect and filtered, respectively (Havenith et al., 2003). By gathering such time histories on the surface, synthetic three-component records were generated. The surface receivers (synthetic receivers) represent the two horizontal components in this set, and base records replace the vertical component. This synthetic data was further processed by following the HVSR analysis procedure. As a result, much like in the HVSR technique, a spectral ratio versus frequency graph would be generated.

5 RESULTS AND DISCUSSION

3D Geomodel construction relies mainly on borehole readings and geophysical test results. Among geophysical tests, HVSR measurements significantly contribute to the modeling because the relationship between f_0 and peak amplitude is directly correlated with the site amplification. For our simulation, we considered the relative changes and shape of the peak rather than the absolute amplitude value. In Figure 3b, we compared the results of simulated

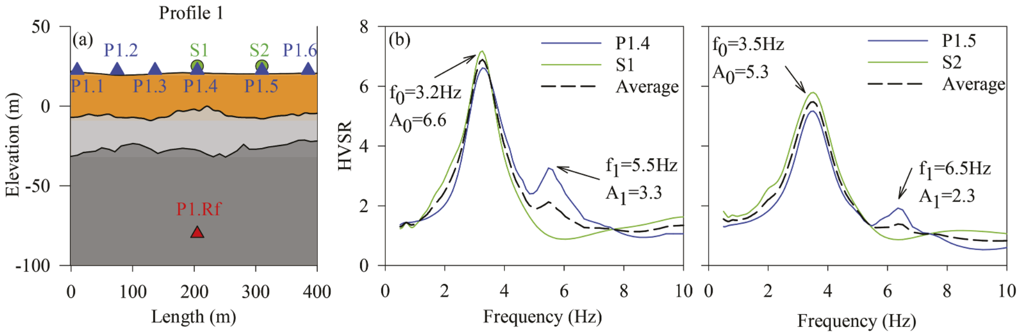

Figure 3. (a) 2D Cross-section with an indication of locations of synthetic receivers and HVSR measurements (green) at Profile 1. The base receiver (red) was a reference for surface receivers (blue). (b) Simulated SSR (P1.4 & P1.5) and HVSR measurements (S1 & S2) in Profile 1.

and real HVSR at profile 1. The comparison shows that both curves have the same trend for low frequencies, especially close to the f_0. At high frequency, simulated SSR had a low amplitude corresponding to a weathered granite layer. A peak frequency match was observed for the frequency range of 2-7 Hz. The extra peak can be because of differences in impedance contrast between weathered granite and soft soil in numerical modeling compared with actual measurements. The numerical model was generated by grouping different granite layers into "soft layer" and "weathered granite" based on weathering degree. Thus, there might be a sudden rise in impedance contrast. In reality, the number of layers will be higher with slowly increasing stiffness, resulting in the absence of an intense surge in impedance contrast between layers. Thus, we believe that this method allows us to detect the resonant frequency of deep deposits and highlight the presence of surface deposits. However, HVSR measurements have clear limitations in application: (1) HVSR data will not be able to estimate soft layer thickness, and other geophysical data, such as V_S., will be needed. (2) the interpretation of peak amplitudes: correlation between site amplification factor and HVSR amplitudes has not been fully proven. These results provide a basis for further research on Geomodel modification and implementation of more geophysical results (e.g., MASW) to minimize the limitations.

6 CONCLUSIONS

To assess the site effects of the Bukit Timah Granite region, 2D cross-sections were generated from 3D Geomodel. Response to the horizontal Ricker wavelet input signal at the base of the model was used to estimate the region's SSR and further comparison with actual HVSR data. In an example of Profile 1, it was demonstrated that both simulated and measured spectral curves had the same shape close to the f_0. It was also mentioned that only the shape of the simulated spectral curve was used for the data analysis of the curve. Moreover, simulated curves contained extra peaks at higher frequencies corresponding to the impedance contrast between the soft and weathered granite layers. A possible reason for such differences at high frequencies was discussed. Known limitations of the method can be minimized in the future by using extra geophysical data, especially when generating 3D Geomodel. The clear trend between synthetic and measured data demonstrates the possibility of using numerical modeling for seismic microzonation works at Bukit Timah Granite formation.

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