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NONLINEAR 3D SEISMIC SITE RESPONSE ANALYSIS CONSIDERING SPATIAL VARIATION OF GEOLOGICAL CONDITIONS

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Site response analysis is important for assessing ground motions and seismic hazards at a specific location by given an earthquake event. 1D site response analyses have been widely used in engineering applications due to its simplicity and computational efficiency by assuming the soil strata is horizontally layered. However, a real site may have diverse and complex geologic conditions, such as irregular topography, highly variable rockhead, varying soil profiles, and formation of sedimentary basin etc., leading to complexed 3D wave prorogation and ground distribution at different locations. Therefore, 3D seismic site response analysis is much needed to incorporate these geological features for better simulation of ground motions. In this study, we develop a large-scale 3D geological model for Ma On Shan area in Hong Kong for seismic site response analysis in order to assess the influence of complex geology on ground motion distribution. The detailed 3D geological model is 1.3 × 1.6 km with a spatial resolution of 10 m. Through the study area, fills are underlain by alluvium, marine deposit, weathered granitic rock etc. A fault zone crosses the study region. Higher weathering in the fault zone results in a deep rockhead up to 120 meters, while marble and granite on both sides of the fault zone have much shallower rockhead. This rockhead feature significantly enhances the ground motion, which cannot be captured by 1D site response analysis. Another feature of this study is to develop a fully nonlinear constitutive model into the large-scale situation to capture the nonlinearity of soils undergoing large strains. The nonlinear 3D site response analysis shows that the spatial variation of geological condition contributes significantly to site amplification of ground motions.

Keywords: Site response, numerical simulation, 3D site effects, spatial variation, nonlinear soil model.

1. Introduction

A major task in geotechnical earthquake engineering is assessing ground motions during seismic events. The evaluation of local site effects is crucial in site response analysis. One commonly used approach is 1D site response analysis, which models the seismic wave propagation assuming that waves are vertically propagating through infinite horizontal layers without lateral heterogeneity. It has been widely adopted in earthquake engineering due to simplicity, for instance, site response calibration, seismic hazard assessment, and soil-structure interaction.

However, 1Dsite response analysis is unable to simulate wavefield incurred by real earthquakes while considering complex spatial variation of geological conditions, such as irregular topography, highly variable rockhead, varying soil profiles, and formation of sedimentary basin etc. Researchers examined seismic downhole arrays and found many of them were not suitable for 1D site response analysis because of the large lateral variations of the soil profile (Pilz and Cotton 2019, Thompson *et al*. 2012). Advances in computational efficiency and power have led to the wider use of 3D large-scale numerical simulations (Chen *et al*. 2022). With the capability to capture complex geological conditions, 3D simulations give better insight into site response analysis. One of the numerical methods used for the 3D regional physics-based simulation is the spectral element method (SEM). The SEM is an effective and powerful approach for solving 3D seismic wave propagation problems with high performance of parallel computing (Stupazzini *et al*. 2009).

In the following section, we implemented a bounding surface plasticity model in an open-source spectral element program SPEED (Mazzieri *et al*. 2013), and validation is performed by a series of numerical experiments. Then, a 3D geological model for Ma On Shan area in Hong Kong was constructed based on the borehole data. Subsequently, a nonlinear 3D large-scale simulation for Ma On Shan area is conducted, and the result is presented comparing with 1D site response analysis to assess the 3D site effects.

2. Nonlinear soil modelling

The use of nonlinear soil constitutive models in engineering can be challenging due to the high computational costs and mathematical complexities associated with parameters calibration. A bounding surface plasticity model is proposed by Borja and Amies (1994), and its nonlinearity is modelled by smoothly changing the secant shear modulus from small strains to large strains. This bounding surface model has shown good performance in both the small-scale and large-scale ground motion simulation problems (Wang and Sitar 2011, Seylabi *et al.* 2020).

The present bounding surface model only needs a few hardening parameters, and it can successfully capture essential soil behavior characteristics. The required hardening parameters (h and m) can be calibrated by shear modulus reduction curves and soil shear strength using the following equation.

$$\left(\frac{G}{G_{max}}\right)^{-1} = 1 + \frac{3}{h\gamma_0}\int_0^{\tau_0}\left(\frac{\tau}{R/\sqrt{2}-\tau}\right)^m d\tau$$

We performed a 1D site response analysis for the layered soil column on a rigid bedrock (figure 1 a) in SPEED with the implemented bounding surface model. The same problem was also modelled using OpenSEES where a similar plasticity model is available. The soil column has three layers with total height of 256m. The properties and parameters for each soil model are shown in figure 1 (a). Figure 1 (b) shows the shear modulus reduction curves at layer 1 and layer 2 calculated by the above equation. The rigid base excitation is shown in figure1 (c). The surface acceleration time history and hysteresis loops for shear stress and strain at depth of 25m are shown in figure1 (d) and (e). As shown, the SPEED results are in excellent agreement with their OpenSEES counterparts.

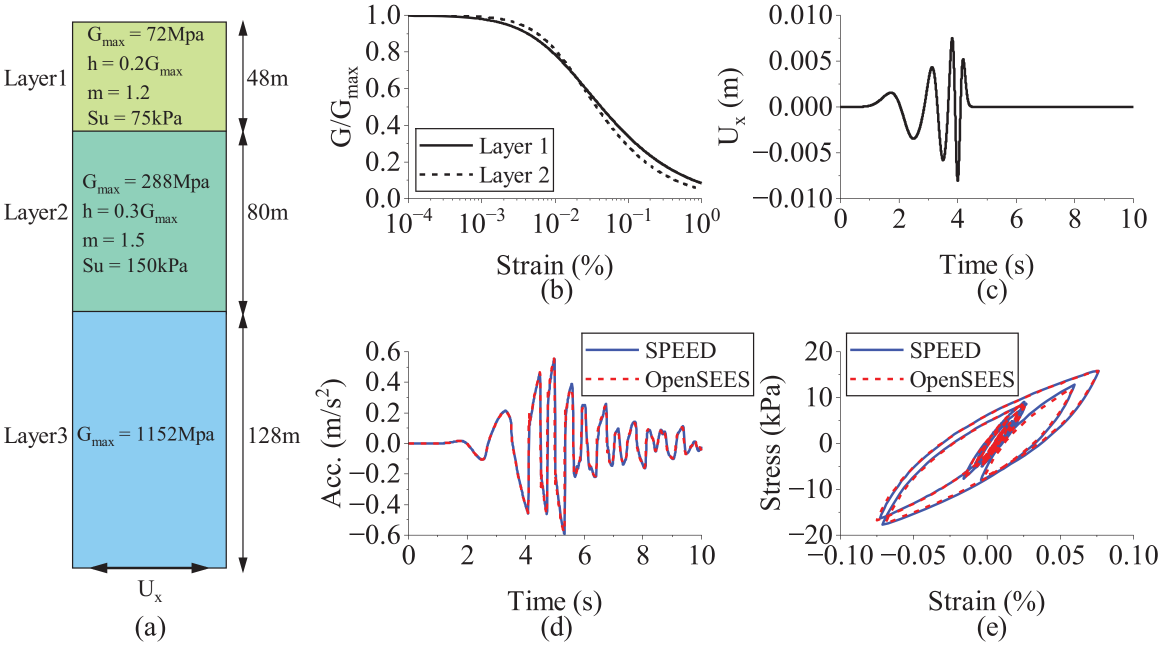


Fig. 1. (a) Layered soil column model; (b) shear modulus reduction curves at layer 1 and layer 2; (c) rigid base excitation; (d) acceleration response at surface; (e) hysteresis loops at depth of 25m.

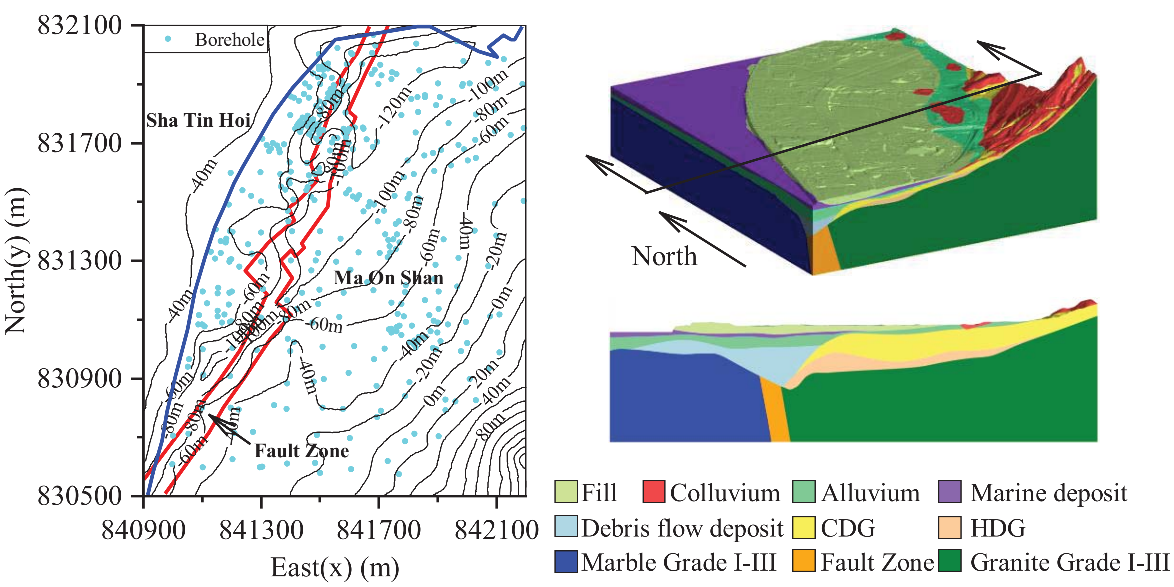
3. 3D Geological Model Construction

The study area Ma On Shan is by Sha Tin Hoi. As shown in the geological model (figure 2b), the middle part of the study region is plain and the southeastern is Ma On Shan mountain. The soil profiles are extracted from around 400 boreholes (figure 2a). The borehole data shows that the base rocks are marble, granite and fault zone, and soils mainly consist of fill, colluvium, alluvium, marine deposit, debris flow deposit, completely decomposed granite (CDG) and highly decomposed granite (HDG). In Hong Kong, the grade of soils and rocks is divided into six catalogues: fresh (I), slightly decomposed (II), moderately decomposed (III), highly decomposed (IV), completely decomposed (V) and residual soil (VI). Grade III and above can be regarded as rock.

After collecting and processing the borehole data, we interpolate the rockhead level contour map (figure 2a), which indicates the deep and steep rockhead in the fault zone. The depth of the rockhead varies from 10 to 120 meters with deepest area in the fault zone. The geological model is constructed based on soil profiles (figure 2b). Apart from soil profiles, standard penetration test (SPT) values extracted from borehole data can be used for shear wave velocity calculation based on the correlation proposed by Sze *et al.* (2016). Then the shear wave velocity structure of the 3D model is constructed by interpolating the SPT-V_s correlation.

4. Nonlinear 3D site response analysis

The complex 3D geological configurations make the ground motion distribution complicated, which cannot be accurately evaluated by 1D site response analysis. Therefore, 3D simulation is conducted for Ma On Shan area to incorporate 3D site effects by considering the irregular rockhead depth and spatial variation of soils. The spectral element program SPEED (Mazzieri *et al.* 2013) is used for numerical simulation.



(a) (b)

Fig. 2. (a) Rockhead level contour map and boreholes distribution;(b) 3D geological model

4.1 Model settings

The 1D soil profile is derived from 3D geological model (Figure 3) by assuming soil strata are horizontally layered at each location. A total of 5400 1D simulations are performed on a grid of 20m×20m for each ground motion. As for the 3D site response analysis, an SEM model of 1.3 km × 1.6 km is developed with an element size of 10 m and 4th order shape function, which is accurate to simulate wave frequency up to 8 Hz. The rock materials are assumed to be elastic, and soils are modelled by using the aforementioned bounding surface plasticity in both 1D and 3D simulations, with material density, shear wave velocity (Vs), nonlinear parameters *h* and *m*, and undrained shear strength Su listed in table 1. We calibrate the nonlinear parameters for each soil type based on the shear modulus reduction curves obtained by Sze *et al.* (2016). The input motion has a peak ground acceleration (PGA) of 0.19g, corresponding to the rock outcrop motion of 2450 year return period, which is deconvoluted and input from the base of the 3D model. The numerical simulation, encompassing a physical duration of 30 seconds, required 182 hours on Intel® Core™ i9-10900 CPU with 10 cores.

Table 1. Soils and rocks parameters for simulation.

Layers	Density (kg/m^3)	V_s range (m/s)	*h*	*m*	*Su* (kPa)
Fill	2000	105-290	0.55Gmax	1.15	60
Colluvium	2000	200-300	0.3Gmax	1.1	60
Alluvium	1900	115-280	2Gmax	1.15	30
Marine deposit	1700	100-200	1.2Gmax	1.05	25
Debris flow deposit	2200	200-450	0.3Gmax	1.05	250
CDG	2000	150-500	0.3Gmax	1.1	300
HDG	2000	380-520	2Gmax	1.1	400
Granite (rock)	2600	1280			
Marble (rock)	2800	1110	Elastic model		
Fault zone	2600	800			

4.2 Results

In this section, we compare the 3D simulation results with 1D cases based on spectral acceleration (SA) over the whole computational domain. We present the comparison result over a 20m × 20 m grid on the ground surface.

We use the ratios of SA obtained from the 3D case over that from 1D to compare the 3D versus 1D site effect. Figure 3(a) shows the SA ratio at the period of 1 sec. As for SA(1s), the maximum SA ratio is around 2.0, which is located at the fault zone with sharply varying rockhead. Large amplification also happens in the area with rockhead of bowl-like shape. These 3D effects are caused by the trapping and focusing of seismic waves. Other areas with slowly changing rockhead depth show smaller amplification for 3D cases. Figure 3 (b) compares the SA for the 1D and 3D cases at a monitoring location in the fault zone, which shows 3D has a larger SA over a wide range of periods compared with the 1D case. Figure 3 (c) shows the surface acceleration time histories for the 1D and 3D cases, which also shows the large amplification of acceleration due to 3D effects.

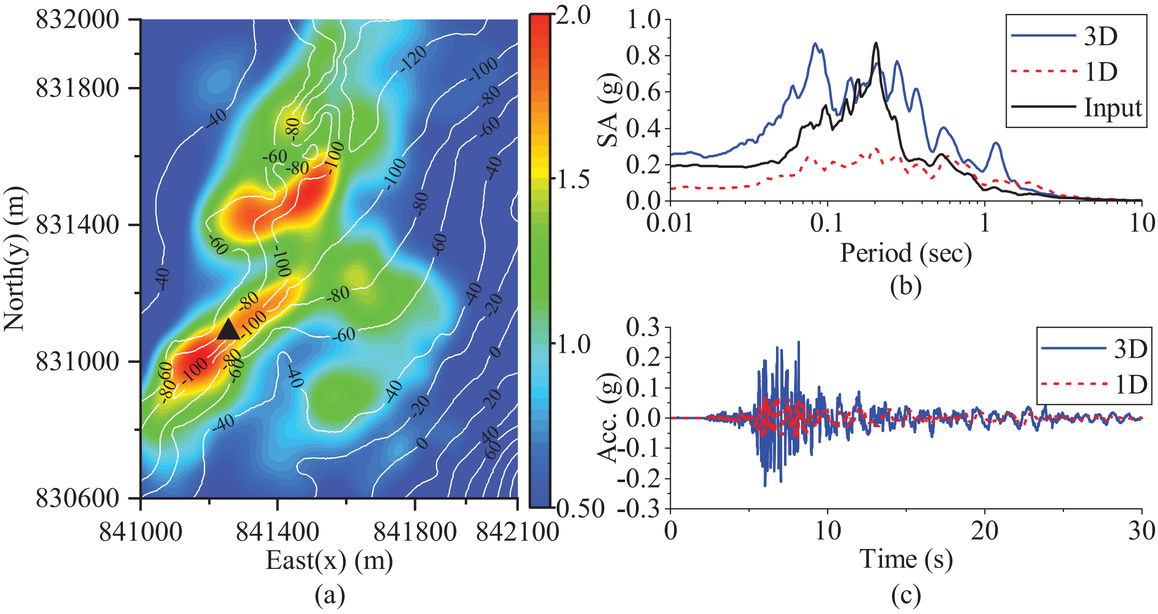


Fig. 3. (a) 3D/1D map for SA(1s), where contour lines show rock head levels; (b) SA for input motion, 3D and 1Dresponses at a monitoring location (841300,831100) shown as ▲ in (a); (c) acceleration histories of 3D and 1D at the monitoring location.

5. Conclusion

In this paper, we conducted a large-scale 3D physics-based simulation of site response with a nonlinear soil constitutive model implemented in spectral element method. Based on geologic borehole data, a 3D geological model of Ma On Shan area was constructed, and the nonlinear model parameters were calibrated based on different soil types. The constructed model shows a great spatial variation in rockhead depths and soil profiles, which results in significant 3D site effects in seismic site response analysis. To qualify the 3D site effects, the ratios of spectral acceleration are obtained for the whole region. Significant 3D effects can be identified at areas with rapidly varying rockhead, where the spectral ratio is up to 200%.

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