Seismic Hazard Analyses of Northern Metropolis and Kau Yi Chau Artificial Islands in Hong Kong

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ABSTRACT

Northern Metropolis and Lantau Tomorrow are two major projects to alleviate the acute shortage of land in Hong Kong. The Northern Metropolis is a planning area consisting of North District and Yuen Long District in northern New Territories to provide an integrated living and economic region, while the Lantau Tomorrow targets to create a third core business district by constructing artificial islands with a total area of around 1,000 hectares through land reclamation near Kau Yi Chau. Hong Kong is a densely populated city with a moderate level of earthquake risk; however, there is still a lack of seismic hazard study and yet no seismic design code. In this study, seismic hazard assessment is conducted for Northern Metropolis and Kau Yi Chau Artificial Islands, based on Hong Kong uniform hazard spectrum for the 2% probability of exceedance in 50 years. For Tuen Mun and Yuen Long, 591 drilling boreholes are collected and interpreted to build the 3D regional geological model (20km × 20km); the physics-based simulation of wave propagation is performed to investigate the complicated effect of deep sedimentary layers and mountainous terrains. On the other hand, 104 boreholes around the Kau Yi Chau Artificial Islands are collected and interpreted, and 1D nonlinear site response analyses are conducted to evaluate the seismic hazard level before and after land reclamation.

1 INTRODUCTION

1.1 Northern Metropolis at Tuen Mun - Yuen Long

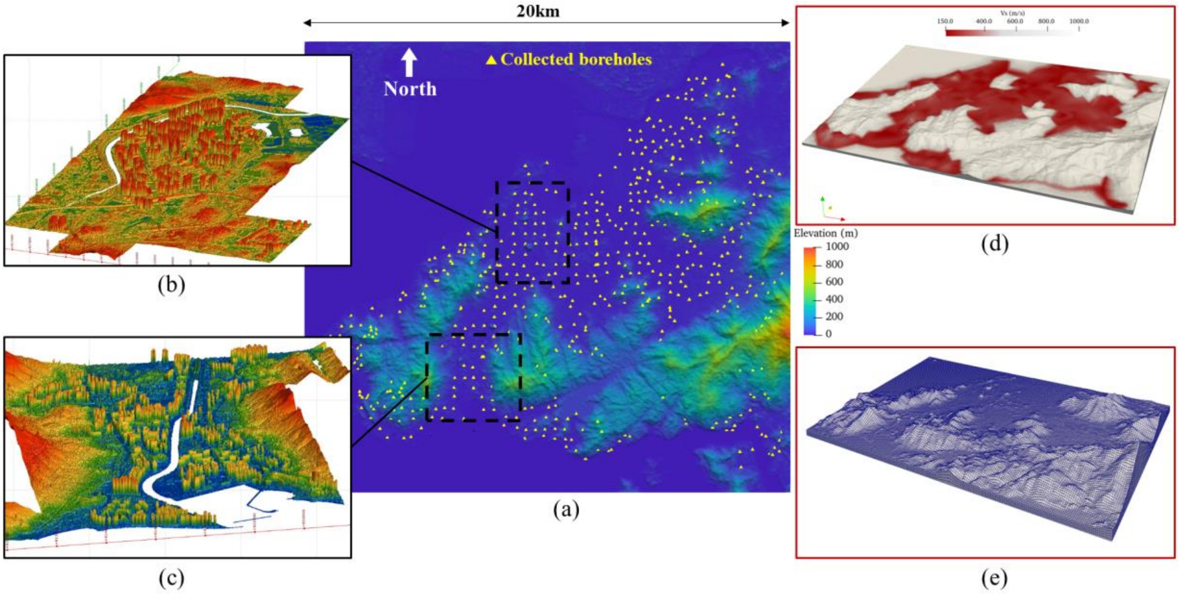

Figure 1. (a) Collected boreholes in the study region; (b) buildings located at Yuen Long; (c) buildings located at Tuen Mun valley around Tuen Mun river; (d) shear wave velocity distribution; (e) 3D physics-based model.

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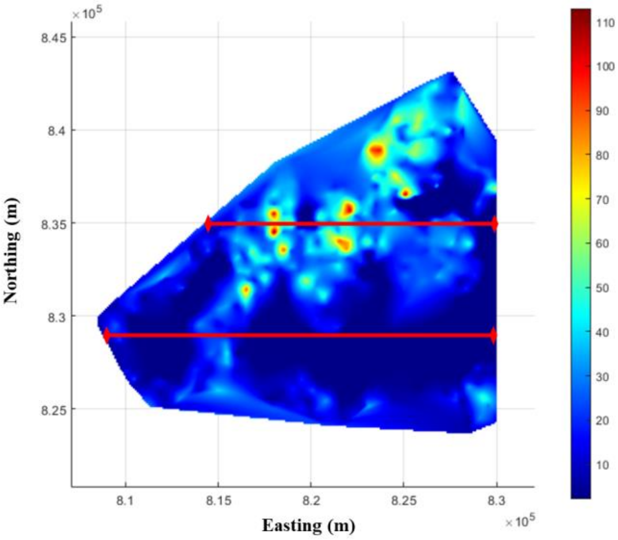
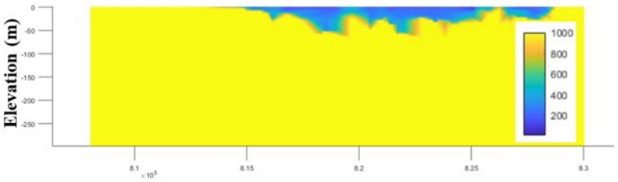
The Tuen Mun-Yuen Long in the North-West New Territories are mainly formed of late Jurassic to Cretaceous granitic and volcanic rocks surrounding Quaternary deposits (basin) (GEO, 2012). The Yuen Long formation in the north consists of siltstone and karstic marble with large sinkholes, while to the east of it is the Lok Ma Chau formation consisting of sandstone and siltstone. The Quaternary deposits on the top of the basin mainly consists of the alluvium around the Tuen Mun river.

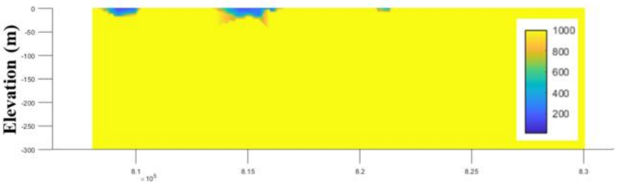
The study region is 20km (north-south) × 20km (east-west), as shown in Figure 1(a). A total of 591 boreholes are collected in the study region, each of the selected borehole stations contains the underlaying strata as well as the standard penetration test (SPT) results. Figure 1(b)&(c) show the densely distributed buildings along the Tuen Mun river, at the Yuen Long and Tuen Mun districts respectively. The SPT-N values at each borehole are used to estimate the shear wave velocity V_S, based on the correlation between V_S and SPT-N provided in (GEO, 2012). The available V_S values are adopted to interpolate the 3D V_S distributions shown in Figure 1(d). Usually SPT-N smaller than 15 are estimated with a V_S less than 200 m/s, and SPT-N of 50 are assigned with a V_S of around 300 m/s, based on the empirical correlation. SPT-N=100 is regarded as the boundary between the grade IV and grade III rocks with V_S of 400 m/s. Fresh or slightly decomposed rocks are assigned a V_S of 1000 m/s for simplicity. Note that the compressional wave velocity $V_P = 2V_S$ is adopted for our simulation model. Figure 1(e) shows the constructed physics-based model using the spectral element method, which will be discussed in the following sections.



(a) Soil depth (m)



(b) Shear wave velocity at northing = 835000m



(c) Shear wave velocity at northing = 829000m

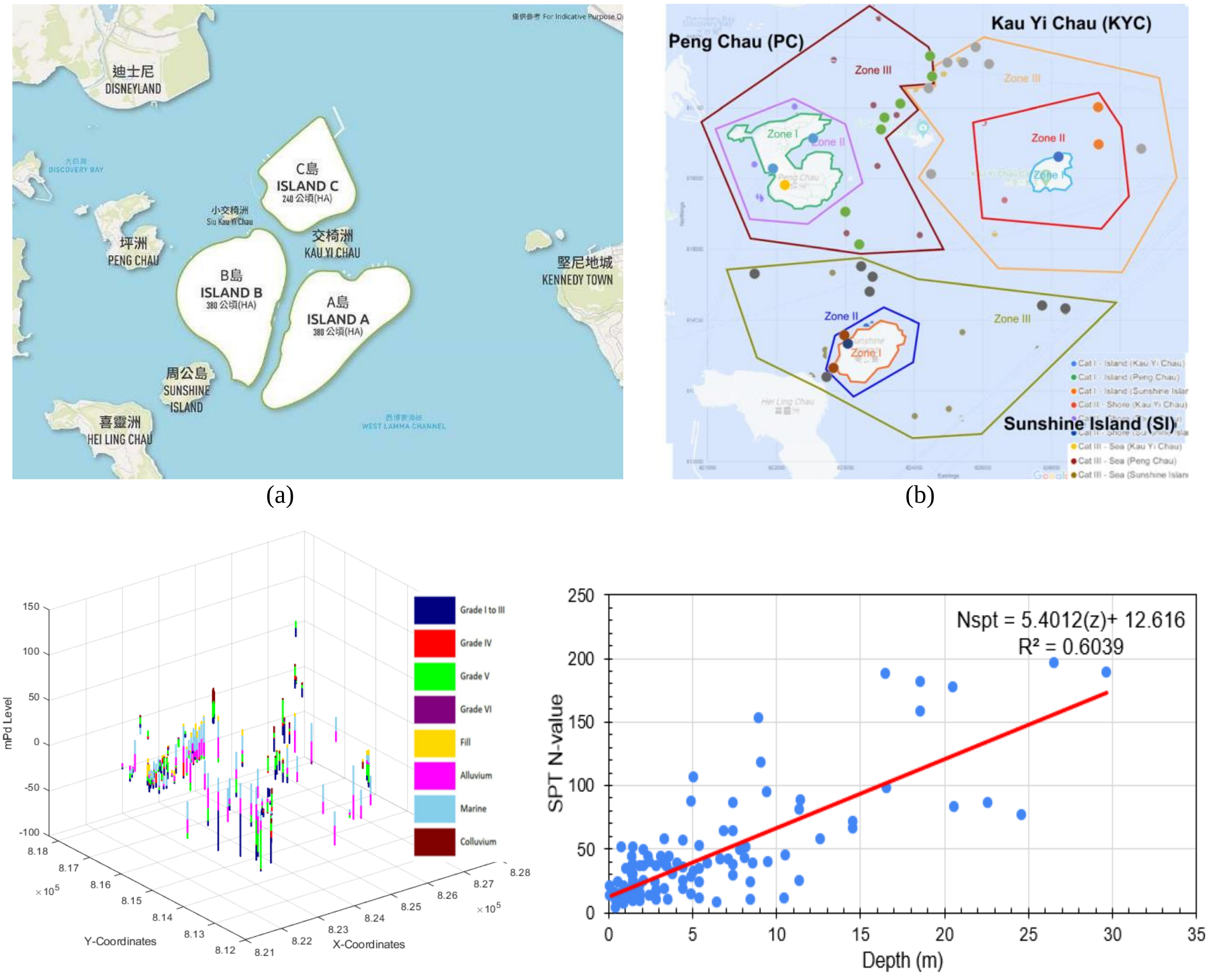
Figure 2. (a) soil depth distribution across the study region; Shear wave velocity distributions at two cross sections (b) northing = 835000 and (c) northing = 829000.

Figure 2 shows the detailed interpolation of soil structure within the study region. The soil depth distribution is depicted in Figure 2(a). At the Tuen Mun region, the two major mountain groups, Tsing Shan and Kau Keng Shan, have very shallow soil layers; the soil layer at the valley between them is approximately 20m, as shown in Figure 2(c). Yuen Long has a soil depth at around 30-50m, with a few sinkholes as deep as around 100m (Figure 2a&b). The complicated topography and soil distributions at the study region could significantly affect the ground motion responses during seismic activities. Mountains could amplify the ground motions due to the focusing effect of the convex terrains (Chen et al., 2023a, 2023b); on the other hand, the subsurface soils will further give rise to the ground seismic level due to the soil amplification (Huang et al., 2020).

1.2 Kau Yi Chau Artificial Islands in Central Waters

In June 2021, the Civil Engineering and Development Department (CEDD) and Planning Department of Hong Kong began a joint consultancy agreement to investigate artificial islands in the central waters. The study aims to conduct a detailed planning and engineering analysis for around 1,000 hectares of artificial islands near Kau Yi Chau (Figure 3a).

The three islands in our studied area are divided into three subzones based on the Island (I), the shore (II) and the sea (III) areas surrounding the three islands and a total of 104 boreholes have been collected from the ground investigation database archive at GEO as shown in Figure 3 (b). To perform 1D site response analysis, 30 representative boreholes (RBHs) have been chosen based on its locations, ground/seabed levels and BHs that have minimum values of SPT-N. The locations of these 30 representative boreholes are shown in Figure 3 (b) by big dots (the rest shown by small dots).



(a) (b)

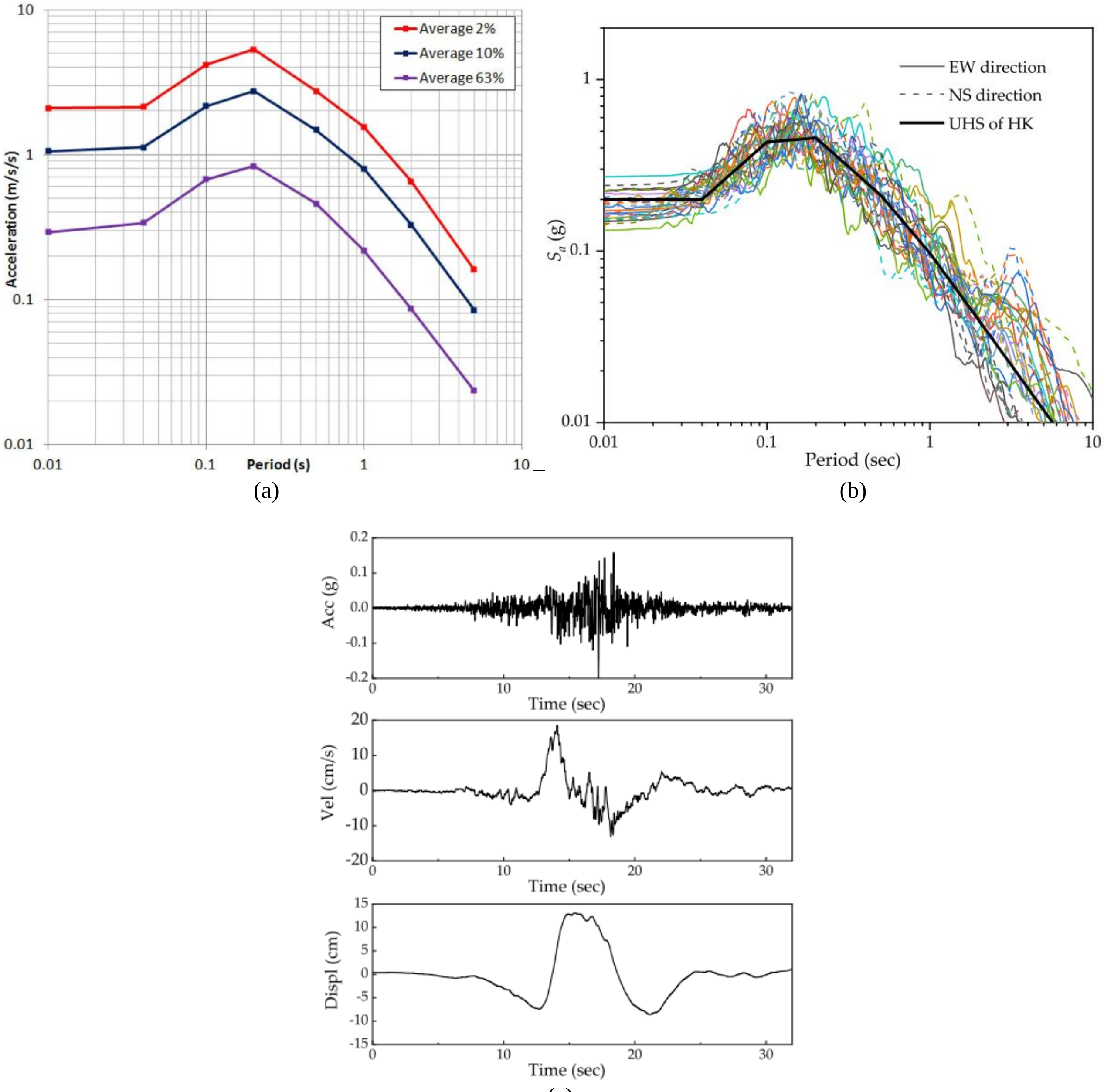
(c) (d)

Figure 3. (a) Lantau Tomorrow reclamation scheme (CEDD); (b) zones classifications, all BHs and representative BHs (big dots) at the reclamation site; (c) 3D visualization of all collected boreholes; (d) SPT-N vs Depth.

The main geological formation, based on these boreholes, consists of volcanic rocks and rhyolites from grade I to grade VI, fills, alluvium, and marine deposit. The 3D visualization of all boreholes showing top, bottom levels and type of rock and soil is shown in Figure 3 (c). The number of blows, SPT-N, of the standard penetration test results have been collected for all the soil layers at different depth and a relation between the SPT-N and depth has been developed to depict the variation of shear-wave velocity with depth, as shown in Figure 3 (d). The relationship between SPT-N value and shear-wave velocity is used to construct the 1D nonlinear seismic model to calculate the ground response under seismic excitations. Both the Equivalent Linear (EQL) model via Strata software and the nonlinear (NL) model via DEEPSOIL, are used to evaluate the ground response and to study the soil nonlinear effect. Note that for zones in the sea (II and III in Figure 3b), ground responses before and after land reclamation (to +7 mPD) are both investigated.

1.3 Seismic input in the study region

Figure 4(a) shows the uniform hazard spectrum (UHS) at the rock outcrop of Hong Kong, based on the probabilistic seismic hazard analysis, for 2%, 10%, and 63% probabilities of exceedance in 50 years (GEO, 2018). In this study, seven sets of ground motions (14 recordings in total) have been selected and applied as rock-outcrop input motion and its mean spectral accelerations (of two horizontal components) are fitted with the UHS of 2% probability of exceedance, as shown in Figure 4(b). Figure 4 (c) shows an example of the selected earthquake motion as the seismic input for this study; this motion is recorded along the east-west direction at LPCC station during the Darfield earthquake in New Zealand in 2010. The peak ground acceleration of this motion is approximately 0.2 g and the peak ground velocity is 0.19 m/s showing a clear velocity pulse.



(a) (b)

(c)

Figure 4. (a) Uniform hazard spectra of Hong Kong at 2%, 10% and 63% probabilities of exceedance in 50 years; (b) Selected earthquake motions fitting 2% probability of exceedance in 50 years; (c) acceleration, velocity and displacement time-histories.

2 3D SEISMIC ANALYSIS AT TUEN MUN - YUEN LONG

2.1 Spectral element model

The spectral element method (SEM) is a high-order finite element method, with specially designed interpolation points and integration scheme. It combines the advantages of FEM for the geometrical flexibility and the Pseudo Spectral Method for accuracy of wavefield simulation (Poursartip et al., 2020). The SEM discretizes the elements using high-order Lagrange interpolants, and integrates over elements based on the Gauss-Lobatto- Legendre integration rule (Komatitsch and Vilotte, 1998). This scheme yields a systematic diagonal mass matrix, suitable for parallel computation. The SEM was first introduced into the seismology by Komatitsch and Vilotte (1998) in the early 1990s. As for the time integration, SPECFEM3D adopts the second-order classical explicit finite difference scheme, benefited from the systematic diagonal mass matrix. The constructed SEM model for the study region has a resolution of 40m × 40m horizontally, with more than 2 million high-order spectral elements and over 100 million grid points (Figure 1e).

The Lysmer-Kuhlemeyer transmitting boundary is implemented as the bottom boundary, which is composed of two terms: (1) the absorbing term that dissipates waves outward the domain; (2) the second term can be regarded as a force acting at the bottom, to simulate waves travelling into the study region (Lysmer and Kuhlemeyer, 1969). In this study, the selected earthquake recordings as introduced in the previous section have been adopted as the seismic input.

2.2 Seismic responses considering topographic and site effects

Firstly, the SEM model is adopted to examine the topographic effect on ground motion distribution, without considering the soil amplification at the basin region. The topographic amplification factor (*TAF*) is calculated through dividing the S_a on topographies by S_a on flat ground (Wang et al., 2018). It reflects the focusing effect of mountain terrains on seismic waves that leads to unexpectedly severer ground responses.

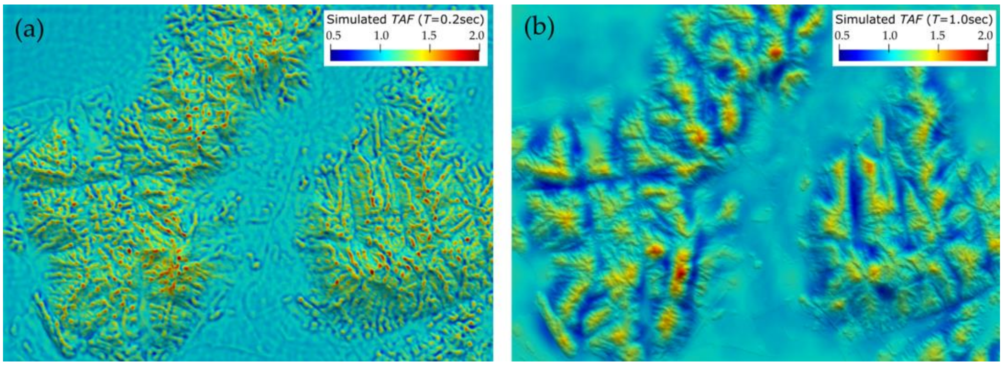


Figure 5. Ground amplification due to the topographic effect at periods of (a) 0.2 sec and (b) 1 sec.

Figure 5 shows the topographic amplification factor of two local mountain groups around Tuen Mun and Yuen Long, at two periods of 0.2 sec and 1 sec. Note that when studying the topographic effect, the soil effect is yet not considered and the region is simulated as uniformly distributed grade V rocks. It is found that both periods have a similar range of *TAF* between 0.5 and 2.0. However, the S_a at 1 sec (Figure 5b) shows significantly larger terrain features of amplification and de-amplification than S_a at 0.2 sec (Figure 5a). This is because larger periods correspond to larger wavelengths, and thus show stronger focusing effect from regional terrains. On the other hand, smaller periods indicate shorter waves that respond to more locally terrain features (Figure 5a). This is consistent with another seismic study for Hong Kong Island by Wang et al. (2018).

Secondly, the soil amplification at the basins is studied, by using the interpreted borehole data to construct a 3D SEM model (Figure 2). Figure 6 shows the ground spectral acceleration S_a distributions at a wide range of periods from 0.05 sec to 5 sec. It is found that S_a at different periods show significantly different patterns, which is attributed to different soil depths, as illustrated in Figure 2(a). Sites with deeper soil thickness (H) have greater soil amplification at larger periods, with site period equaling to $4H/V_S$. S_a at 0.05 sec shows more amplification at areas with shallower soil (~20m) like the edge of basins (Figure 6a). S_a at 0.2 sec shows the largest area of amplification, because site period of 0.2 sec takes the largest proportion within the basins with depth between 20 m and 50 m (Figure 6b). On the other hand, only a few deep-soil areas (with soil > 50 m) show notable amplification at larger periods of 1 sec and 5 sec (Figure 6 c&d). Overall, the soil amplification factors (S_a on soil divided by S_a on rock outcrop) can be as high as 3 to 5 (5 for 0.2 sec and 1 sec).

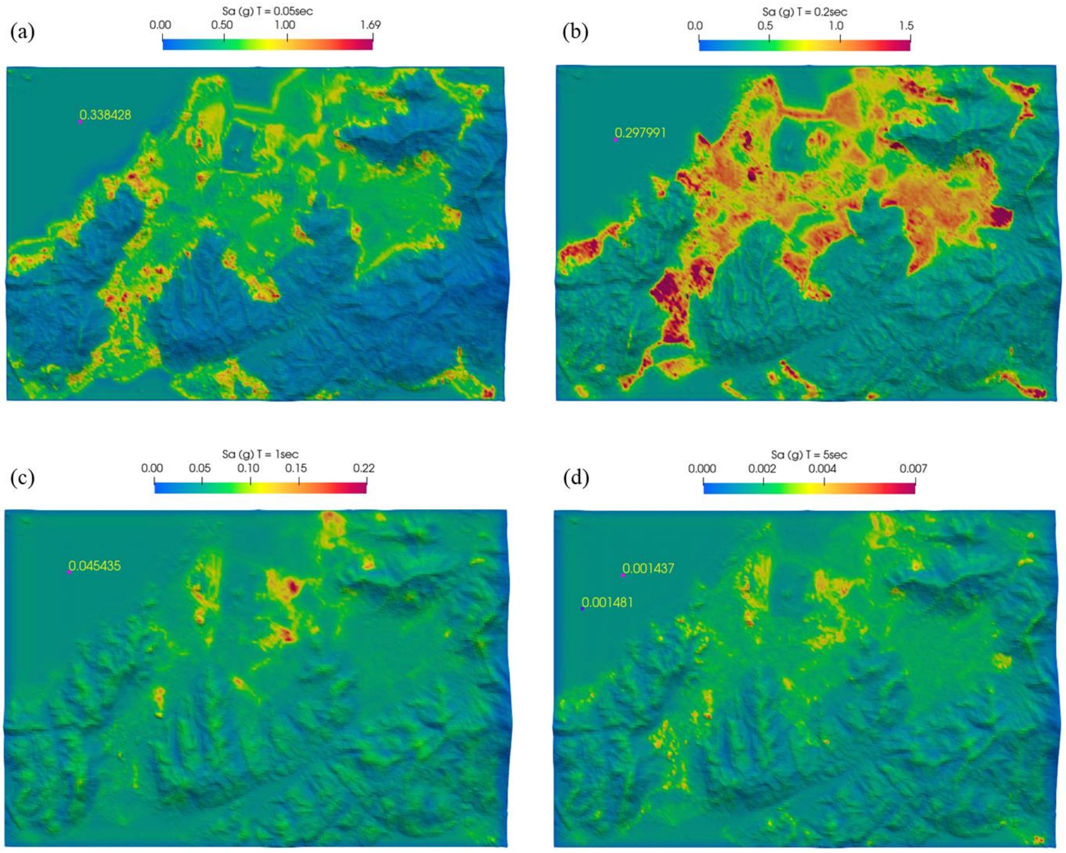
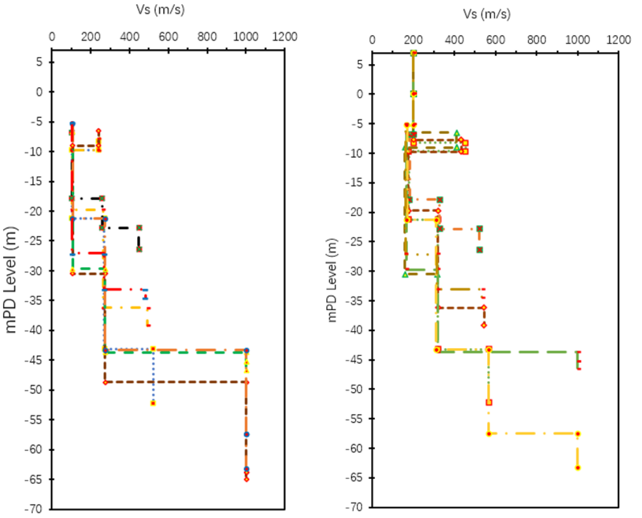


Figure 6. Ground response spectra at periods (a) 0.05 sec, (b) 0.2 sec, (c) 1 sec, and (d) 5 sec.

3 NONLINEAR SITE RESPONSE ANALYSIS AT KAU YI CHAU ARTIFICIAL ISLANDS

3.1 Soil strata



(a) (b)

Figure 7. Shear wave velocity profile of boreholes within the sea near Kau Yi Chau (a) before and (b) after reclamation

Figure 7 presents the shear wave velocity profiles before and after reclamation for the seven representative borehole samples in the sea. The original seabed level is around -10 mPD (before reclamation), whereas the final formation level is set as + 7 mPD assuming 200 m/s as the shear-wave velocity for fill materials. The analyzed soil profiles extend deep to rock with grade III or better and represented by V_S of 1000 m/s (at a level of -40 mPD to -70 mPD). Both strata before and after reclamation will be used to conduct seismic analysis. The degradation G/G_{max} and Damping Ratio (D%) with shear strain are selected for the studied soils (both cohesive and non-cohesive), depending on: over consolidation ratio, confining pressure, plasticity index (PI), number of cycles and frequency, and details can be found in Darendeli (2001). In this study, we adopted a plasticity index of 30 for marine deposit to determine the degradation and damping ratio curves.

3.2 Nonlinear seismic analysis

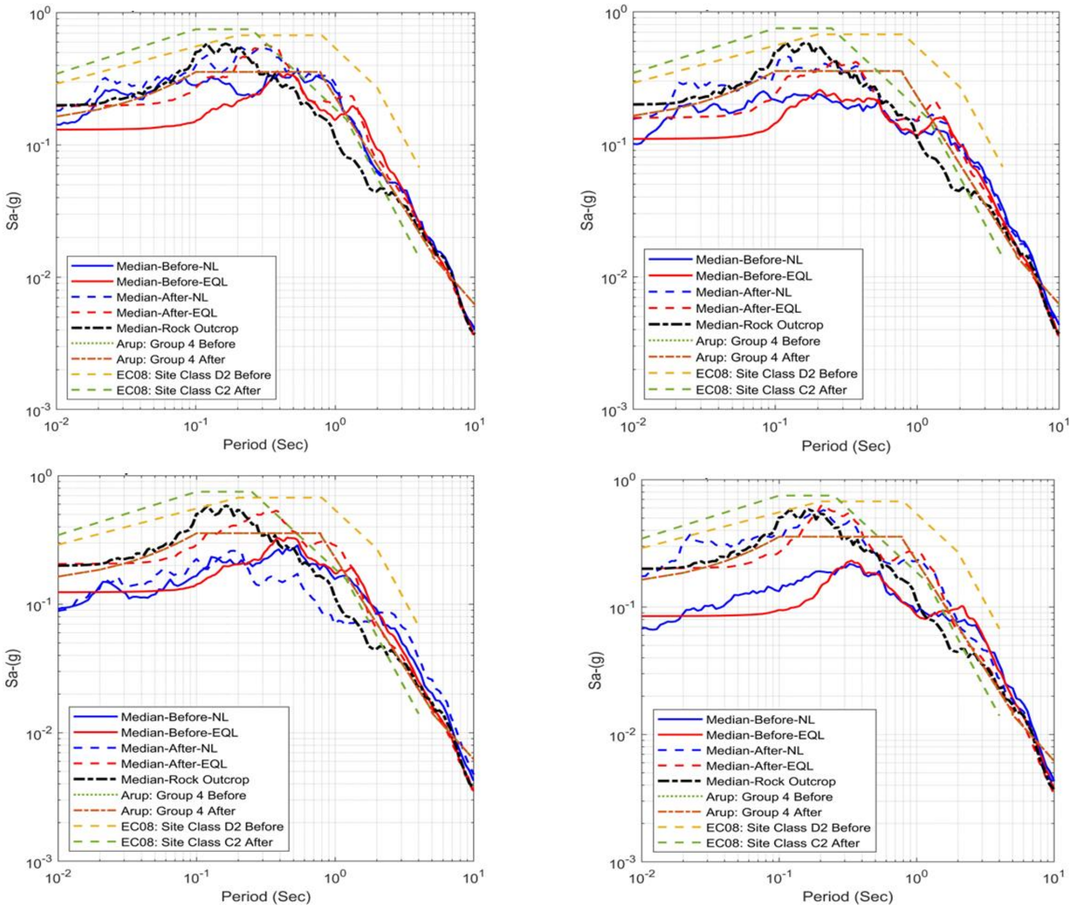


Figure 8. Spectral acceleration in the sea around the Kau Yi Chau island, before and after land reclamation.

Figure 8 shows the ground spectral responses (median results from the 14 earthquake recordings) at sea regions near Kau Yi Chau island, before and after reclamation. Note that seismic analysis results from Euro Code type 2 (denoted by EC2, for low to moderate seismic zones) and Arup are also presented for comparison (Pappin et al., 2015). Both EC2 and Arup estimate seismic hazard levels based on site classifications V_{S30} which represents the average shear wave velocity within 30 m below ground level. Detailed classifications criteria can be found in Pappin et al. (2015). The results show that compared to rock outcrop, the studied sites show de-amplification at short periods (< 0.5s) before reclamation for both Equivalent Linear (EQL) and nonlinear (NL) analyses, but not in the same trend (EQL and NL) especially in very short periods <0.1s; the spectral acceleration is amplified at longer periods > 0.6s. After reclamation, the spectral acceleration sees notable amplifications, mainly at periods of 0.1 sec to 1 sec.

In general, EC2 over-estimates the seismic hazard level over the studied period ranges at both before and after reclamation. On the other hand, Arup over-estimates seismic hazard level before reclamation, but under-estimates seismic hazard level after reclamation at period between 0.1 sec and 0.4 sec.

4 CONCLUSIONS

In this study, seismic hazard assessment is conducted for Northern Metropolis and Kau Yi Chau Artificial Islands, based on Hong Kong uniform hazard spectrum for 2% probability of exceedance in 50 years. In-situ borehole data have been collected to interpret the geological model at the study regions. The 3D physics-based model (20km × 20km) is constructed to perform regional scale seismic wave propagation at Tuen Mun and Yuen Long regions (Northern Metropolis), to investigate the effects of local topographies and basins on ground seismic responses. Besides, 1D nonlinear seismic analyses are performed to study the seismic levels at the Kau Yi Chau Artificial Islands in Central Waters. It is found that topographies at Tuen Mun and Yuen Long regions contribute to a topographic amplification factors of 0.5 – 2.0, and larger periods show ground amplification at larger terrain scales. The deep sedimentary soil layers at the Yuen Long regions contribute to a soil amplification factor as high as 3-5 depending on the studied period. On the other hand, studies on the Kau Yi Chau artificial island show similar ground responses by using equivalent linear and nonlinear soil models, due to the relatively moderate seismic level in Hong Kong. The soil deposits around Kau Yi Chau artificial islands lead to de-amplification at short periods (high frequencies) before reclamation due to large damping ratio from the marine deposits, while the filling material would lead to notable amplification of ground responses at period between 0.2 sec and 2sec. Besides, the obtained seismic responses are compared against those estimated by Euro Code and Arup.

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