THE EFFECT OF FAR-FIELD EARTHQUAKES ON THE BEHAVIOUR OF SHALLOW TUNNELS IN STRUCTURED CLAYS

L.T. Cabangon[1], G. Elia[2], M. Rouainia[3], S. Keawsawasvong[1] & T. Ornthammarath[4]

[1] Thammasat School of Engineering, Pathum Thani, Thailand

[2] Technical University of Bari, Bari, Italy (gaetano.elia@poliba.it)

[3] Newcastle University, Newcastle Upon Tyne, UK

[4] Mahidol University, Nakhon Pathom, Thailand

Abstract: *Far-field earthquakes are typically characterised by their low peak ground acceleration, peak ground velocity and Arias intensity, having far lower damage potential than near-field signals. In places like Bangkok and Singapore, where known active seismic faults lie at considerable distance, the effects of far-field earthquakes on tunnels are frequently ignored. However, far-field motions have relatively longer duration and a greater probability of containing long-period waves which can result in a higher response in the low-frequency region of the acceleration spectrum. When thick layers of structured clay deposits, such as those found in Bangkok, are subjected to far-field earthquakes, they can significantly amplify a long-period ground motion. This can result in large ground deformations and generate high shear strains, which in turn induce large forces in geotechnical structures such as tunnel linings. In this paper, a set of two-dimensional finite element simulations have been conducted to predict the behaviour of a shallow tunnel built in a thick Bangkok soft clay deposit and subjected to both far-field and near-field earthquake motions. A kinematic hardening model developed for natural clays has been used to capture the essential features of the dynamic soil behaviour. The results clearly demonstrate that, despite having less intensity, a far-field, long-period, long-duration earthquake can induce equally destructive forces in the tunnel lining as those generated by a strong, near-field, short-duration motion. This highlights the importance of considering the effects of far-field earthquakes in designing seismic-resistant shallow tunnels in soft clays and reduce the risk of geotechnical infrastructure systems.*

1. Introduction

The destructive nature of near-field earthquakes on underground structures is extensively documented and studied in literature while the number of real-life cases highlighting the effects of far-field earthquakes on engineering structures is relatively low. In places like Bangkok and Singapore, where known active seismic faults lie at considerable distance, the effects of far-field motions on tunnels are simply ignored.

Unlike near-field earthquakes, which have high intensity (i.e., high peak ground acceleration (PGA), high peak ground velocity (PGV) and high Arias intensity), and, therefore, have high damage potential, far-field ground motions attenuate slowly with distance and are perceived to have low damage potential due to their low PGA and PGV. However, far-field earthquakes are characterised by relatively longer duration than near-field ones (Koketsu and Miyake, 2008), thus having a greater probability of containing long-period waves which can result into a higher response in the low-frequency region of the response spectrum (Tavakoli et al., 2012).

When imposed on thick layers of soft structured clays, these far-field ground motions can be significantly amplified in the long-period range and can generate large soil displacements/shear strains, thus inducing substantial forces in underground structures, which can be as large as those generated by near-field earthquakes. Amplification can occur within soft soil deposits, particularly when the long-period component of the motion is equal or close to the first natural period of the soft soil layer. Furthermore, tunnels at shallow depth are more vulnerable and suffer more damages from earthquakes than deep ones (Hashash et al., 2001). As more tunnels are currently built in shallow soft soil deposits, it is imperative to assess the seismic vulnerability of these tunnels during far-field earthquakes. To this aim, a case study of an existing shallow tunnel of the Mass Rapid Transit (MRT) Blue Line in Bangkok has been investigated through numerical simulations using real long-duration ground motions recorded in the city after recent strong far-field earthquakes occurred in the region.

2. Bangkok seismicity

Bangkok, Thailand's capital, is located on the stable Sunda plate of Eurasia and situated at remote distance from active seismic sources (Ornthammarath et al., 2011), the closest of which, the Three Pagoda and Si Sawat faults in Kanchanaburi province, are about 120 to 300 km away from the city. There is no history of notable seismic activity recorded close to the city during the last century, hence, Bangkok is widely perceived to have low seismic hazard. However, several studies (Ashford et al., 2000; Poovarodom and Jirasakjamroonsri, 2016; Poovarodom et al., 2017) show that the soft soils underlying Bangkok have the ability to considerably amplify both extremely low intensity, long-period ground motions (PGA less than 0.02g) and relatively stronger seismic actions (PGA greater than 0.02g). Therefore, Bangkok has a substantial risk from distant earthquakes that can be generated by the Three Pagoda and Si Sawat faults. Although their current rate of seismic activity is rather low, it was estimated that they can generate a maximum earthquake magnitude of 7.5 ± 0.3 based on their expected rupture dimensions (Warnitchai et al., 2000). Therefore, any potential strong earthquake triggered from these faults should not be underestimated, as it can have significant impact and cause huge damage in the Bangkok Metropolitan area.

The first probabilistic seismic hazard assessment (PSHA) map of Thailand was proposed by Hattori (1980). Since then, the PSHA in Thailand has been progressively modified during the last four decades. The most recent PSHA study by Pailoplee and Charusiri (2016) has used the most up-to-date seismicity and paleo-seismological data, including recent strong earthquakes, such as the 2011 Tarlay (Mw = 6.8) and the 2014 Mae Lao (Mw = 6.2) earthquakes that occurred far north of Bangkok, with epicentral distances of 775 km and 670 km, respectively (Subedi et al., 2021). This PSHA considered site-specific studies for ten major provinces within Thailand, accounting for 75 earthquake sources (seismogenic faults and seismic source zones). It has been based on the attenuation models deemed to be most suitable for Thailand (Chintanapakdee et al., 2008), calibrated using 163 ground motions of 45 earthquake events recorded by the Thai Meteorological Department. The results of the PSHA for Bangkok indicate a PGA of 0.03g for 2% POE in 50 years.

3. Depot approach tunnel and soil profile

The city of Bangkok, being a centre of business, tourism and education, has been investing massively in transport services for the last two decades. On the 3rd of July 2004, the MRT Blue line, the city's third rapid transit line and first underground railway line, started its operation. The line runs from Hua Lamphong to Bang Sue.

As shallow tunnels are found to be most vulnerable under seismic loading, particularly in soft clay soils where a strong resonance of long-period seismic waves may occur, this study focuses on shallow tunnels along the MRT Blue line alignment embedded in Bangkok clays. One of such underground structures along the alignment is the depot approach tunnel, which runs from Thailand Cultural Centre Station to the depot. The tunnel is located at its shallowest depth at about 7.5 m below ground, has a diameter of 6 m and a 300 mm thick lining. The known soil profile at the tunnel location, shown in Figure 1 (modified after Ove Arup & Partners International Ltd, 1998b), is about 40 m deep and consists of made ground, Bangkok soft clay, Bangkok 1st stiff clay, clayey sand, Bangkok 2nd stiff clay and dense sand. The dense sand is underlain by a 12 m horizon of hard clay and at least 11.5 m of a weaker dark grey clay layer. The exact depth of the bedrock is unknown, but its level in the Bangkok area is thought to vary between 400 to 1800 m depth (Surarak, 2011). A typical description of these soils is summarised in Table .

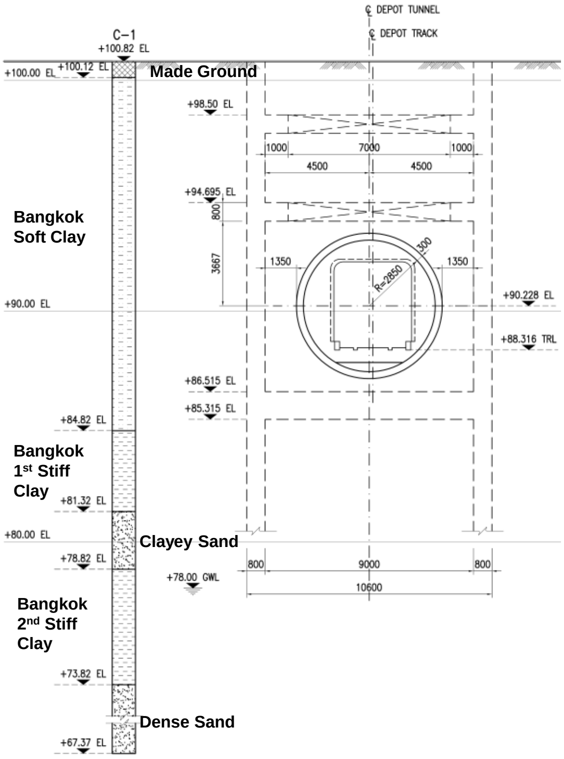


Figure 1. Soil profile at MRT Blue Line Depot Approach [modified after Ove Arup & Partners International Ltd, 1998b].

Table 1. Typical soil profile at the MRT Blue Line [Surarak, 2011; Ove Arup & Partners International Ltd, 1998a].

Stratum	Level of top of Stratum (m ISD)	Thickness (m)	Typical Description
Made Ground	100.7 to 101.9	0.1 to 4.0	Loose sands or soft clay and construction materials.
Bangkok Soft Clay	98.2 to 100.7	9.0 to 15.8	Very soft to soft, occasionally medium stiff at depth, dark grey clay. Medium stiff crust at surface in some locations.
Bangkok 1st Stiff Clay	83.4 to 88.4	3.5 to 14.4	Stiff to hard greenish or brownish grey, or yellowish brown silty clay often sandy towards the base of the strata. Often fissured.
Clayey Sand	72.0 to 82.0	0.3 to 7.5	Dense alluvial non-uniform sand, occasional interbedded with stiff clay.
Bangkok 2nd Stiff Clay	78.8 to 79.5	2.0 to 6.0	Stiff to hard light grey brown, occasionally dark brown or grey, silty occasionally sandy, clay. Often fissured.
Dense Sand	72.0 to 77.0	12.0 to 17.5	Medium to very dense clayey and silty sand, with a yellowish to greyish brown in colour.
Hard Clay	59.4 to 60.25	10.0 to 12.0	Very stiff to hard clay layer, with a thickness of 10 to 12 m, and its colour varies from light grey to greyish brown.

4. Soil constitutive models

The advanced constitutive model RMW, formulated within the framework of kinematic hardening multi-surface plasticity by Rouainia and Muir-Wood (2000), has been employed in the numerical analysis to simulate the mechanical behaviour of the Bangkok soft and stiff clays. The RMW model can effectively reproduce the key features of the cyclic behaviour of natural clays, such as the decay of the shear stiffness with strain amplitude, the corresponding increase of hysteretic damping and the related accumulation of excess pore water pressure and structure degradation under undrained conditions (Elia and Rouainia, 2016). The model performance in cyclic/dynamic conditions has been previously explored by Elia and Rouainia (2012), Elia and Rouainia (2014), Elia and Rouainia (2016), Cabangon et al. (2019). The reader is referred to Rouainia and Muir Wood (2001) and Zhao et al. (2005) for the details of the mathematical formulation and implementation of the RMW model into finite element (FE) codes.

The Bangkok soft clay is geologically overconsolidated, with an overconsolidation ratio (OCR) between 1.1 and 1.7. It generally comprises of very soft to soft inorganic clays of intermediate to very high plasticity (i.e., plasticity index (PI) between 26 and 70%) with a typical unit weight of 16 kN/m^3 (Ove Arup & Partners International Ltd, 1998a) and sensitivity ratio ranging from 3 to 6 (Shibuya et al., 2001). On the other hand, the Bangkok stiff clay generally comprises of medium to very stiff silty clays, which are often fissured, with a PI ranging from 35 to 59% and an OCR between 1.1 and 2.1. The typical unit weights of the 1st stiff clay and the 2nd stiff clay are 19 and 20 kN/m^3, respectively.

A series of laboratory/in situ results from undrained monotonic triaxial compression tests, cyclic torsional shear, oedometer, seismic cone, direct shear box and bender element tests performed by Shibuya et al. (2001) on the Bangkok soft and stiff clays within the study area have been used for the calibration of the RMW parameters, not shown here for brevity. A summary of the model parameters adopted in the FE non-linear dynamic simulations undertaken in this work is reported in Table. The reader is also referred to Cabangon et al. (2023) for the definition and details of the calibration of RMW parameters adopted in the simulations. The well-known equation proposed by Viggiani and Atkinson (1995) has been adopted to describe the small-strain shear stiffness of the deposit with depth. For the Bangkok soft clay, the dimensionless parameters A, n and m in the Viggiani and Atkinson equation have been set equal to 210, 0.86 and 0.29 respectively, while the corresponding values are 500, 0.83 and 0.26 for the Bangkok stiff clays.

Table 2. RMW parameters for Bangkok clays.

Material	λ^*	κ^*	M	R	B	ψ	r_0	A^*	k
Soft Clay	0.12	0.012	1.05	0.07	5.00	5.25	3.0	0.50	3.0
1st Stiff Clay	0.045	0.009	1.05	0.06	0.80	2.75	1.5	0.30	6.0
2nd Stiff Clay	0.045	0.009	1.05	0.06	0.80	2.75	1.2	0.30	0.4

For the remaining soil strata of the Bangkok deposit (i.e., made ground, clayey sand and dense sand), the same parameters of the Hardening Soil Model (HSM) derived by Surarak (2011) and previously implemented in several works (Likitlersuang et al., 2013a, Likitlersuang et al., 2013b, Likitlersuang et al., 2014, Chheng and Likitlersuang, 2018, Likitlersuang et al., 2018, Pisitsopon et al., 2018) have been adopted in this paper. HSM, however, cannot accurately reproduce the stiffness degradation and hysteretic damping in the small-strain range. Therefore, the Hardening Soil Model with Small-Strain Stiffness (HSS) has been used to simulate the dynamic behaviour of the clayey sand and dense sand, by adding the reference small-strain shear modulus G_0^{ref} and shear strain amplitude $\gamma_{0.7}$ to the HSM parameters. G_0^{ref} has been derived from the SPT N_{60} correlation with depth proposed by Ove Arup & Partners International Ltd (1998a) and the correlation between N_{60} and G_0 proposed by Stroud (1988) for overconsolidated sands, while $\gamma_{0.7}$ has been obtained from Vucetic and Dobry (1991). As limited data are available for the made ground, the HSM model has been considered sufficient for this stratum. The parameters for the made ground, clayey sand and dense sand layers are listed in Table 3 and commented in details by Cabangon et al. (2023). The typical values of the other design parameters adopted in this study, including OCR and coefficient of earth pressure at rest K_0 for each soil strata, have been extracted from Ove Arup & Partners International Ltd (1998a).

Table 3. HSM parameters for made ground and HSS parameters for clayey sand and dense sand.

Material	ϕ'	c'	ψ'	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	ν_{ur}	m	K_0^{nc}	R_f	G_0^{ref}	$\gamma_{0.7}$
Made ground	25°	1 kPa	0°	45.6 MPa	45.6 MPa	136.8 MPa	0.2	1.0	0.58	0.9	-	-
Clayey sand & dense sand	36°	1 kPa	0°	38.0 MPa	38.0 MPa	115.0 MPa	0.2	0.5	0.41	0.9	from corr.	0.000093

5. Numerical model

The depot approach tunnel, 6 m in diameter with 7.5 m overburden, was excavated within the Bangkok subsoil as indicated in Figure 1. It has been analysed in this work using the soil constitutive models and parameters described above and the 2D FE code PLAXIS (Brinkgreve and Broere, 2021). The depth of the soil deposit implemented in the FE simulations has been limited to 41m below ground where the interface between the hard clay stratum and the dense sand layer is found. This base level matches the depth of the borehole accelerometer in the BKKA seismic station where the ground motions have been recorded. The 300 mm thick lining has been modelled as a linear visco-elastic material with Young's modulus equal to 38 GPa, Poisson's ratio equal to 0.25 and damping ratio equal to 5%.

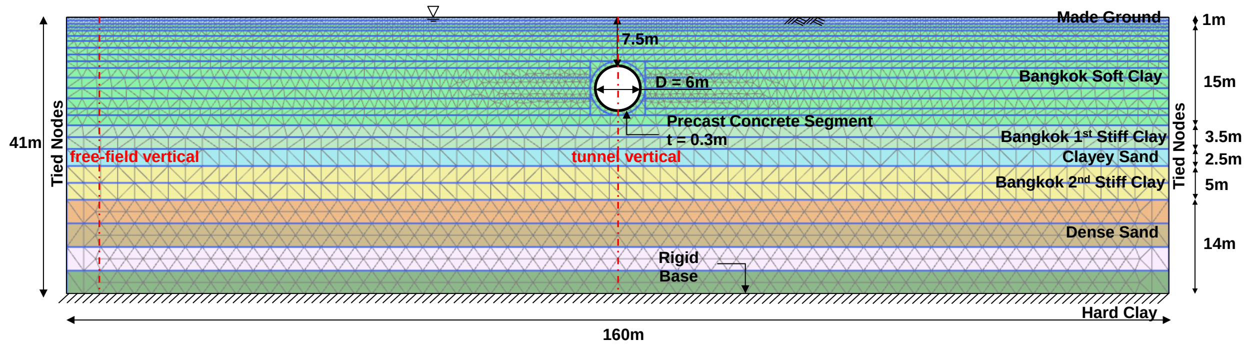


Figure 2. FE model and boundary conditions adopted for the dynamic simulations.

The 2D model has been discretised with a total number of 6,650 plane strain 15-noded triangular elements, with the mesh refined in the region around the tunnel to avoid mesh sensitivity due to the softening behaviour predicted by the RMW model. The vertical distance between adjacent element nodes has been limited to satisfy the condition recommended by Kuhlemeyer and Lysmer (1973). Standard boundary conditions have been adopted for the static analyses. In the dynamic simulations, the bottom of the model has been assumed rigid, while tied-nodes boundary conditions have been imposed along the lateral sides of the mesh to effectively absorb the energy induced by the seismic action, as proven by Zienkiewicz et al. (1999), thus avoiding spurious wave reflections into the FE model. The assumed rigid base condition is based on the study by Yanuviriyakul (2009), which indicates that a bedrock-like condition in Bangkok subsoil is achieved the at the hard clay layer depth. Moreover, parametric studies have been conducted to optimise the lateral extent of the 2D model to ensure that the boundaries are significantly far enough to avoid any influence on the tunnel, as well as to properly reproduce the free-field conditions at the edges of the model. To this aim, the 2D results obtained far from the tunnel have been compared to agree with those from one-dimensional soil response simulations. In this work, the groundwater level has been assumed coincident with the ground surface to consider the worst-case scenario for the design. Figure 2 shows the FE model implemented in PLAXIS.

One of the most recent strong, long-distance earthquakes felt in Bangkok, the 6.8M_w Tarlay earthquake, which occurred at the Nam Ma fault near the border of Myanmar, Laos and Thailand, has been used as input in the dynamic simulations of the depot approach tunnel. The ground motion signals (i.e., the E-W and N-S components) were recorded at the BKKA seismic station in Bangkok from the sensors in a borehole about 40 m below the ground surface (Subedi et al., 2021). The two components of the event have been scaled up to a PGA of 0.03g for 2% POE in 50 years (MCE), in accordance with the most recent and updated PSHA for Bangkok (Pailoplee and Charusiri, 2016), and have been filtered to prevent frequencies higher than 10Hz. To compare the effects of far-field earthquakes against near-field ones, the seismic signals of the same Tarlay earthquake recorded near the epicentre at the Mae Sai (MSAA) seismic station have been similarly applied to the base of the model. The corrected acceleration time histories of the E-W and N-S components of the Tarlay earthquake for the far- and near-field events are shown in Figure 3 and Figure 4, respectively, while their corresponding response spectra are illustrated in Figure 5. Table gives general information about the input earthquakes in terms of magnitude (M_w), Arias in-tensity (I_a) as proposed by Arias (1970), epicentral distance (D_e), duration, peak ground acceleration, peak ground velocity and peak ground displacement.

Table 4. Main characteristics of the selected earthquake signals.

Station	Event	M_w	D_e (km)	Component	I_a (m/s)	Duration (s)	PGA (g)	PGV (m/s)	PGD (m)
BKKA	Tarlay (2011)	6.8	775	E-W	0.19806	427	0.03	0.1247	0.1469
				N-S	0.17407	425	0.03	0.1142	0.0953
MSAA	Tarlay (2011)	6.8	28	E-W	0.57150	50	0.204	0.1570	0.1890
				N-S	0.50480	50	0.199	0.1020	0.1500

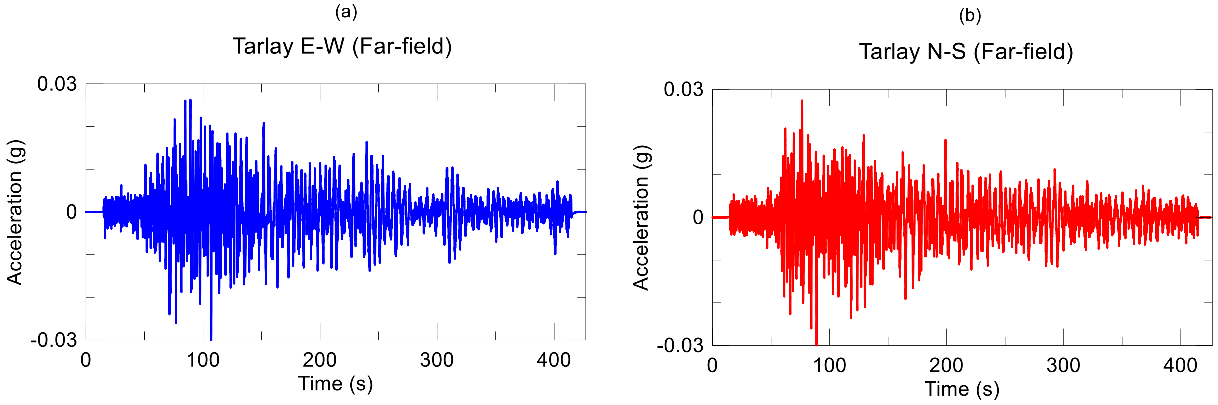


Figure 3. Acceleration time history of (a) E-W component and (b) N-S component of the 2011 Tarlay earthquake recorded at BKKA seismic station.

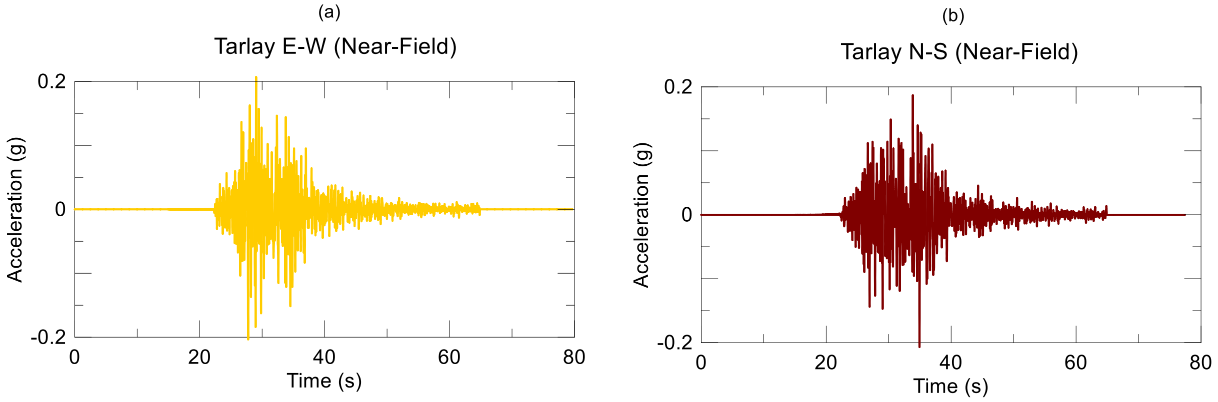


Figure 4. Acceleration time history of (a) E-W component and (b) N-S component of the 2011 Tarlay earthquake recorded at MSAA seismic station.

6. Results and discussion

In this section, the dynamic soil–tunnel interaction response has been investigated to highlight the impact of far-field, long-duration, strong earthquakes on the performance of an existing tunnel located within the Bangkok clay deposit with shallow overburden. The results of the dynamic analyses are presented in terms of propagation of the seismic waves within the deposit, mechanical response of the soil surrounding the tunnel and distribution of lining forces induced in the tunnel by the earthquake actions. The output from the far-field event are also compared to those obtained considering its near-field counterpart.

6.1. Accelerations and displacements

The profiles of maximum horizontal acceleration $|a_x|$ recorded along the tunnel vertical and in free-field conditions (located as shown in Figure 2) during the earthquake events (E-W and N-S components applied independently) are presented in Figure 6. As expected, the accelerations from the near-field earthquake are higher than far-field. For the far-field event, the FE analyses predict an overall amplification of the input motion from the Bangkok 2nd stiff clay layer upwards, but more pronounced from the Bangkok soft clay to ground surface by as much as 0.075g, which is 2.5 times the peak acceleration of the base motion. The amplification of the bedrock motions (black lines) is clearly discernible in the Bangkok soft clay (red lines) and made ground (blue lines) layers in Figure 7a, where the response spectra of the accelerations predicted at the mid-depth of each soil strata along the free-field vertical are plotted. On the other hand, the near-field earthquake appears to deamplify in the Bangkok soft clay layer (Figure 7b).

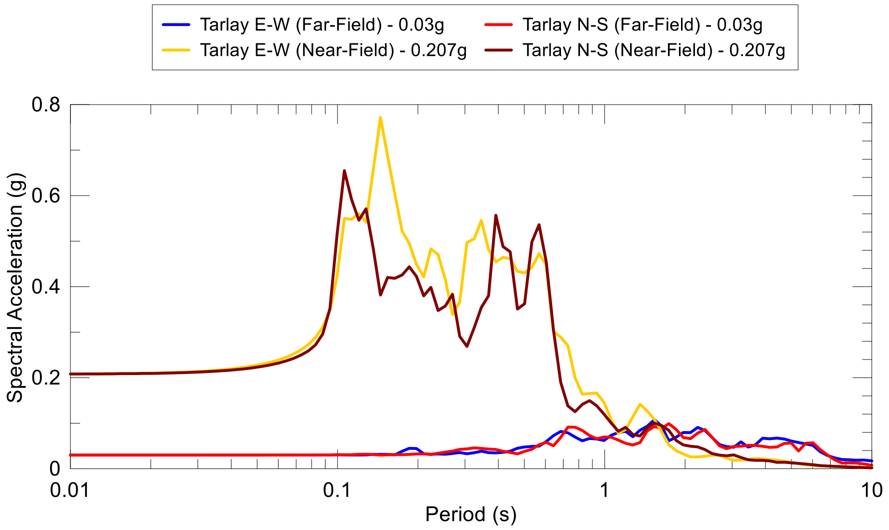


Figure 5. Response spectra of the near-field and far-field Tarlay input motions.

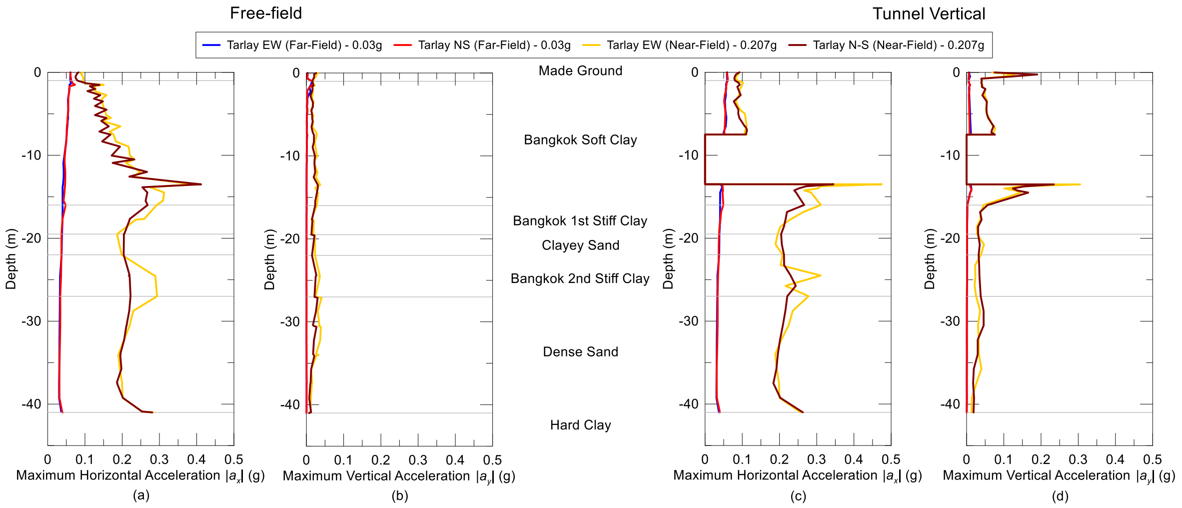
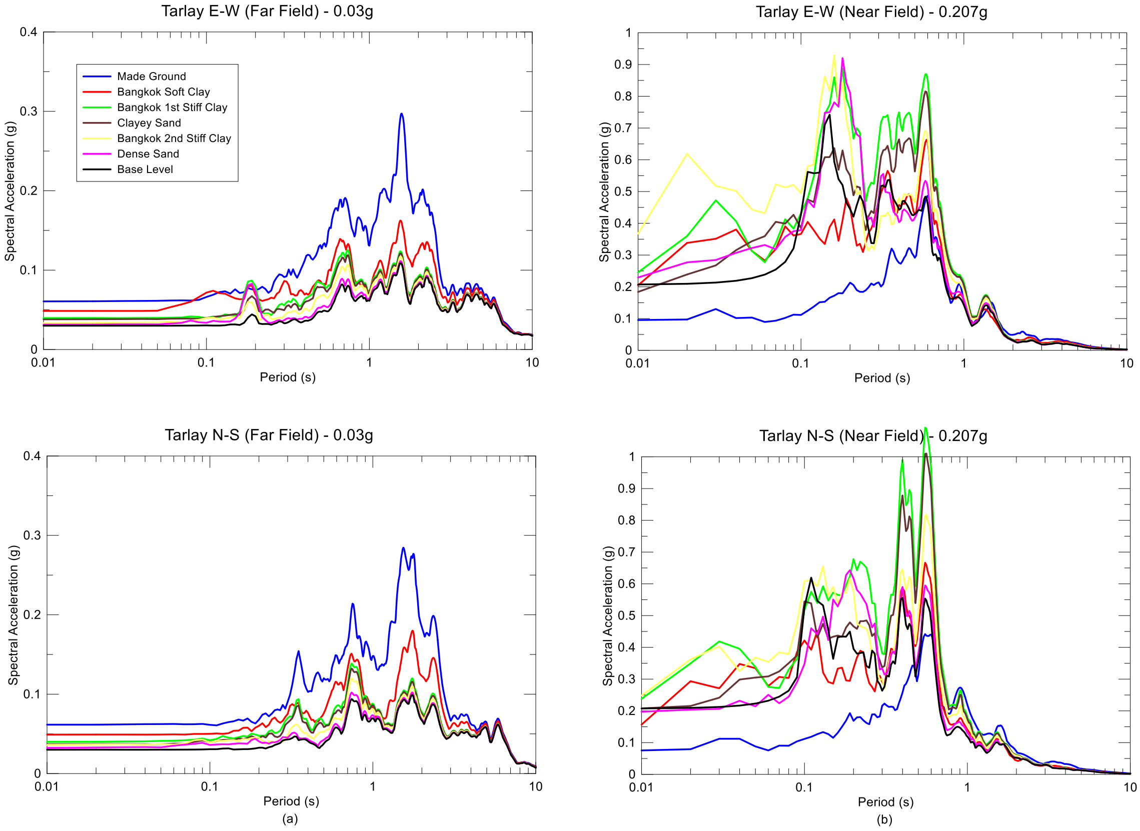


Figure 6. Profiles of maximum horizontal acceleration |a_x| and maximum vertical acceleration |a_y| along soil depth at (a-b) free-field and (c-d) tunnel vertical during Tarlay far-field and near-field earthquake.

Due to the upward propagation of the horizontal wave into the soil deposit which includes the tunnel structure, parasitic vertical accelerations a_y are also generated during the simulations, particularly below and above the tunnel, as shown in Figure 6. This is more evident in the case of the near-field earthquake, for which the maximum |a_y| reaches a value of 0.04g at surface along the free-field vertical (Figure 6b) and around 0.25g below the tunnel (Figure 6d).

Despite its lower acceleration, the far-field earthquake generates bigger horizontal displacement in the soil compared to the near-field results, due to its long duration. As a consequence, the maximum horizontal displacement at the top of the Bangkok soft clay in free-field conditions is 260 mm compared to only 85 mm induced by the near-field earthquake, and 167 mm at the tunnel crown compared to 56 mm. While the induced vertical displacements along the free-field vertical are similarly small for both far-field and near-field, the amplified accelerations at the tunnel crown and invert generated by the near-field ground motion are higher than the far-field ones, pushing the tunnel up by 275 mm with a resulting heave at the ground surface of about 257 mm. Such amount of heave can cause great concern to any structure or utilities located above the tunnel.



(a) (b)

Figure 7. Response spectra recorded at mid-depth of each soil strata for the E-W and NS components of the Tarlay earthquake (a) far-field and (b) near-field.

6.2. Soil shear strains and destructuration

The evolution with time of the soil shear strains around the tunnel and the corresponding time histories of the RMW parameter r, representing the degree of destructuration, recorded during the two seismic motions are presented in Figure 8 as a function of the angle θ (defined positive in the anti-clockwise direction). The higher development of shear strains in the soft clay corresponds to the higher degree of destructuration during the dynamic action, as similarly observed in previous works (Cabangon et al., 2019). In particular, the Bangkok soft clay reaches a fully destructured state (i.e., $r \approx 1$) at the end of both seismic events. The largest shear strains are predicted at the benches/side walls of the tunnel, with a maximum value of 38% for Tarlay far-field, occurring around the springline (i.e., $\theta = 90°$ and $270°$). On the other hand, the smallest shear strains induced around the tunnel occur at the crown ($\theta = 180°$), with a maximum value of 0.56%, and at the invert ($\theta = 0°$), with a value of max 0.44%. This is consistent with the degree of destructuration at the corresponding locations, as a full structure degradation can be observed in the soil at the benches/sidewalls, while only partial destructuration occurs at the crown and invert (Figure 8b and Figure 8d).

Given the higher frequency content of the near-field earthquake and the lower induced horizontal displacements, the shear strains induced in the soil around the tunnel, shown in Figure 8, are much smaller than those generated by its far-field counterpart. In this case, a maximum shear strain of 26% is recorded around the knees ($\theta = 45°$, $315°$) and shoulders ($\theta = 135°$, $225°$) of the tunnel, while its value at the crown is only 0.14%. The figure also shows how a full structure degradation can be observed in the soil around the tunnel knees and shoulders, while only partial destructuration occurs at the crown (Figure 8f and Figure 8h).

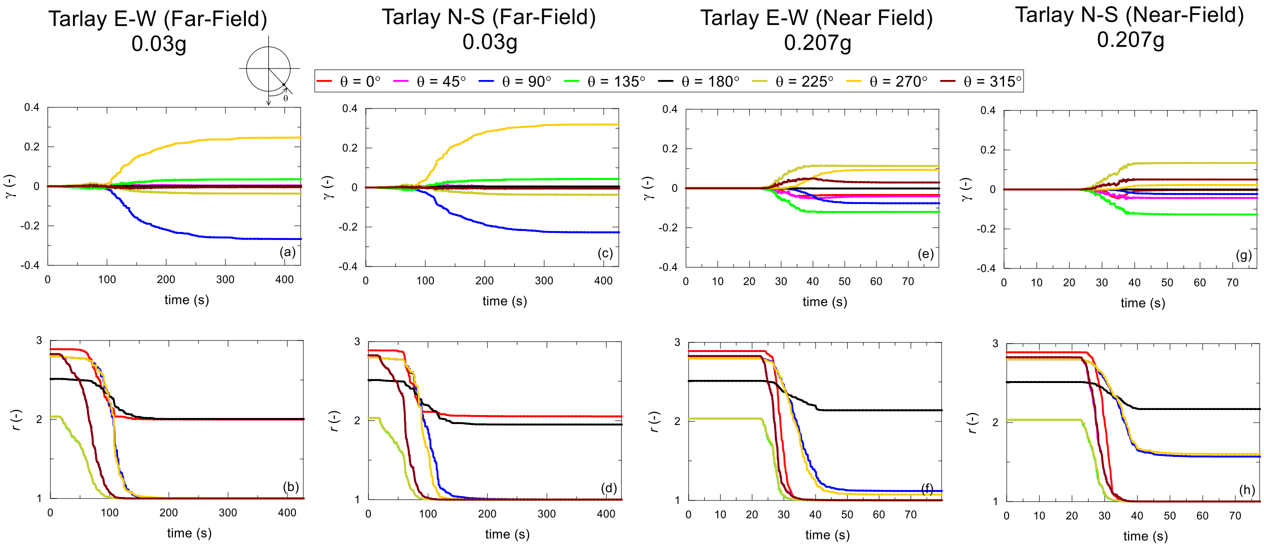


Figure 8. Time histories of shear strain and RMW soil parameter r around the tunnel during the Tarlay earthquake (a-b) E-W and (c-d) N-S far-field; (e-f) E-W and (g-h) N-S near-field.

6.3. Tunnel lining forces

Figure 9 shows the distribution of hoop force *N*, bending moment *M* and shear force *V* after the seismic events as a function of the angle *θ*. The standard convention of structural analysis (i.e., compression negative) is adopted here when presenting the results in terms of lining forces. The envelopes of maximum and minimum values of *N*, *M* and *V* during the earthquake events are also shown in the same figure with dashed lines. For both input motions, the use of an elasto-plastic model allows to predict permanent increments of hoop force (*ΔN*), bending moment (*ΔM*) and shear force (*ΔV*) at the end of the events due to the accumulation of plastic deformations in the soil deposit during the earthquakes, as already observed by other researchers (e.g., Amorosi and Boldini, 2009). The maximum lining forces predicted during the far-field event are slightly higher than the ones generated by the near-field, as illustrated in the figure. This can be attributed to the higher shear strains induced by the far-field Tarlay earthquake around the tunnel compared to the shear strains induced by the near-field motion. The results clearly demonstrate that far-field, long-period, long-duration earthquakes can be as damaging as strong, near-field, short-duration events, despite having less intensity, and, therefore, should be considered when designing shallow tunnels in soft clay deposits.

7. Conclusions

The goal of this paper is two-fold: firstly, it aims to assess the vulnerability of shallow tunnels in soft clays against far-field, long-duration, long-period earthquakes and, secondly, to emphasise how these ground motions can be as important and destructive as near-field, short-duration earthquakes. The paper describes a set of non-linear FE analyses for the simulation of the transverse behaviour of a shallow circular tunnel in the Bangkok clay deposit subjected to strong earthquake actions. The soil cyclic behaviour has been simulated through advanced elasto-plastic constitutive models. Far-field, long-duration input motions, recorded in Bangkok, scaled up to the peak acceleration recommended by the latest PSHA, have been applied at the base of the 2D FE model. For comparison purposes, their near-field, short-duration counterparts, recorded near the earthquake epicentre, have also been applied at bedrock. The principal findings of the analysis are:

- The soil structure degradation does not particularly affect the wave propagation in the deposit but leads to higher shear strain levels in the soil due to its softer behaviour.
- Strong earthquake loading, both far-field and near-field, can induce sufficient stiffness degradation in the soil associated with strain-softening processes, which, in turn, facilitate the transmission of higher loads to the tunnel lining.
- Strong far-field, long-duration, long-period earthquakes, despite having lower intensity, are characterised by a lower frequency content and can generate bigger displacement fields than near-field motions. In fact, when imposed on shallow tunnels within thick layers of soft clays with a fundamental long period, these ground motions can generate large soil displacements around the tunnel, resulting to

higher soil shear strains, and, consequently, induce bigger forces in the tunnel lining which can be as large and damaging as those generated by near-field earthquakes.

All the findings highlight the high vulnerability of shallow tunnels built in structured soft soils under strong far-field earthquakes, which has never been explored in the past, thus emphasising the need to consider the effects of such input motions in the tunnel design.

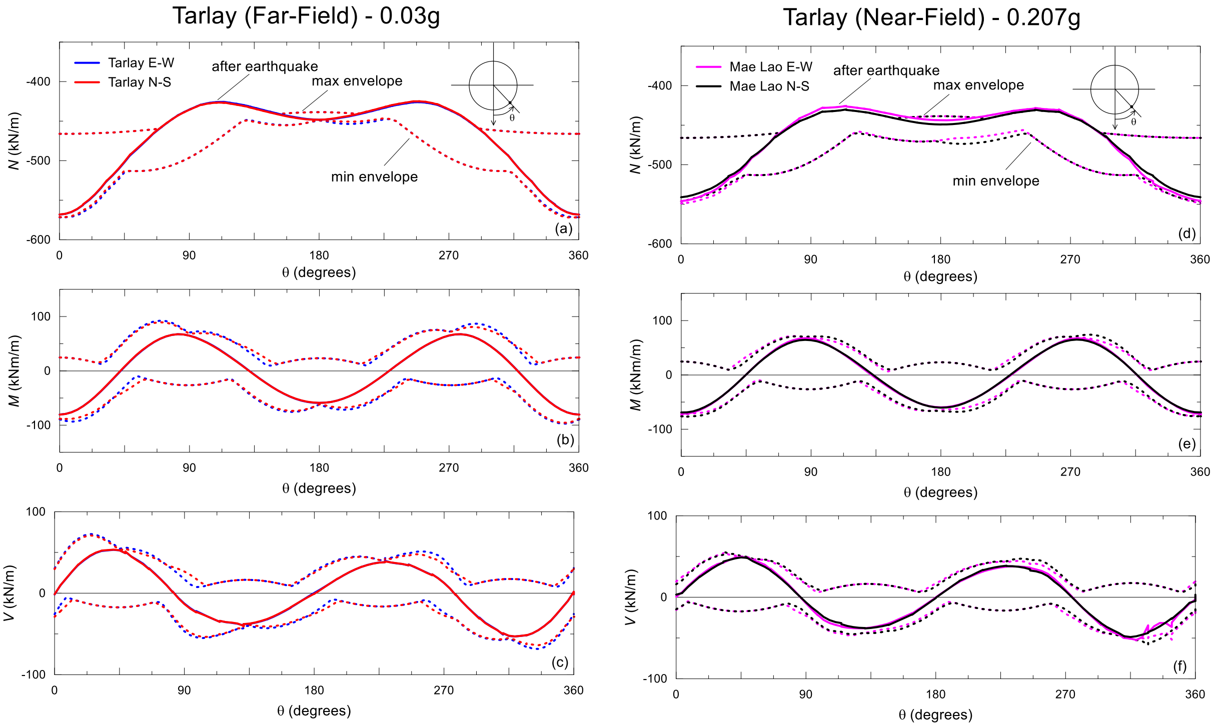


Figure 9. Distribution of maximum and minimum hoop force N, transverse bending moment M and transverse shear force V for (a-c) far-field and (d-f) near-field events.

8. References

Amorosi, A. & Boldini, D. (2009). Numerical modelling of the transverse dynamic behaviour of circular tunnels in clayey soils. *Soil Dynamics and Earthquake Engineering,* 29**,** 1059-1072.

Arias, A. (1970). Measure of Earthquake Intensity. Massachusetts Inst. of Tech., Cambridge. Univ. of Chile, Santiago de Chile.

Ashford, S. A., Jakrapiyanun, W. & Lukkunaprasit, P. (2000). Amplification of earthquake ground motions in Bangkok. Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Brinkgreve, R. B. J. & Broere, W. (2021). PLAXIS 2D Reference Manual. *In:* Bentley (ed.) *Delft, Netherlands.*

Cabangon, L. T., Elia, G. & Rouainia, M. (2019). Modelling the transverse behaviour of circular tunnels in structured clayey soils during earthquakes. *Acta Geotechnica,* 14**,** 163-178.

Cabangon, L.T., Elia, G., Rouainia, M., Keawsawasvong, S., Ornthammarath, T. (2023). Seismic vulnerability of shallow tunnels subjected to far-field long-period ground motions. *Soil Dynamics and Earthquake Engineering* (in print).

Chheng, C. & Likitlersuang, S. (2018). Underground excavation behaviour in Bangkok using three-dimensional finite element method. *Computers and Geotechnics,* 95**,** 68-81.

Chintanapakdee, C., Naguit, M. & Charoenyuth, M. (2008). Suitable attenuation model for Thailand. 14th World Conference on Earthquake Engineering, Beijing, China. 1-8.

Elia, G. & Rouainia, M. (2012). Seismic Performance of Earth Embankment Using Simple and Advanced Numerical Approaches. *Journal of Geotechnical and Geoenvironmental Engineering,* 139**,** 1115-1129.

Elia, G. & Rouainia, M. (2014). Performance evaluation of a shallow foundation built on structured clays under seismic loading. *Bulletin of Earthquake Engineering,* 12**,** 1537-1561.

Elia, G. & Rouainia, M. (2016). Investigating the cyclic behaviour of clays using a kinematic hardening soil model. *Soil Dynamics and Earthquake Engineering,* 88**,** 399-411.

Hashash, Y. M. A., Hook, J. J., Schmidt, B. & I-Chiang Yao, J. (2001). Seismic design and analysis of underground structures. *Tunnelling and Underground Space Technology,* 16**,** 247-293.

Hattori, S. (1980). Seismic Risk Map in the Asian Countries (Maximum Acceleration and Maximum Particle Velocity)-China, India, Pakistan, Burma, Thailand, Philippines, Indonesia and Others. International Conference on Engineering for Protection from Natural Disasters, Asian Institute of Technology, Bangkok, Thailand. 491-504.

Koketsu, K. & Miyake, H. (2008). A seismological overview of long-period ground motion. *Journal of Seismology,* 12**,** 133-143.

Kuhlemeyer, R. L. & Lysmer, J. (1973). Finite Element Method Accuracy for Wave Propagation Problems. *Journal of the Soil Mechanics and Foundations Division,* 99**,** 421-427.

Likitlersuang, S., Chheng, C., Surarak, C. & Balasubramaniam, A. (2018). Strength and stiffness parameters of Bangkok clays for finite element analysis. *Geotech. Eng,* 49**,** 150-156.

Likitlersuang, S., Surarak, C., Suwansawat, S., Wanatowski, D., Oh, E. & Balasubramaniam, A. (2014). Simplified finite-element modelling for tunnelling-induced settlements. *Geotechnical Research,* 1**,** 133-152.

Likitlersuang, S., Surarak, C., Wanatowski, D. & Balasubramaniam, A. (2013a). Analysis Of Ground Movements Induced By MRT Construction: A Case Study Of Bangkok MRT Blue Line Project. *18th Southeast Asian Geotechnical Conference (18SEAGC) & Inaugural AGSSEA Conference (1AGSSEA).* Singapore.

Likitlersuang, S., Surarak, C., Wanatowski, D., Oh, E. & Balasubramaniam, A. (2013b). Finite element analysis of a deep excavation: A case study from the Bangkok MRT. *Soils and Foundations,* 53**,** 756-773.

Ornthammarath, T., Warnitchai, P., Worakanchana, K., Zaman, S., Sigbjörnsson, R. & Lai, C. G. (2011). Probabilistic seismic hazard assessment for Thailand. *Bulletin of Earthquake Engineering,* 9**,** 367-394.

Ove Arup & Partners International Ltd (1998a). MRTA ISP - North Contract: Interpretative Geotechnical Report. ION (ITD, Obayashi, Nishimatsu) Joint Venture.

Ove Arup & Partners International Ltd (1998b). MRTA ISP - North: Bored Tunnels - Precast Concrete Lining - Design Drawings. ION (ITD, Obayashi, Nishimatsu) Joint Venture.

Pailoplee, S. & Charusiri, P. (2016). Seismic hazards in Thailand: a compilation and updated probabilistic analysis. *Earth, Planets and Space,* 68**,** 98.

Pisitsopon, P., Jirajaran, T., Keawsawasvong, S. & Likitlersuang, S. (2018). Simulation of Bangkok MRT Tunnels subjected to strong earthquake *The Thirty-First KKHTCNN Symposium on Civil Engineering.* Kyoto, Japan.

Poovarodom, N. & Jirasakjamroonsri, A. (2016). Seismic Site Effects of Soil Amplifications in Bangkok. *Science & Technology Asia,* 21**,** 59-69.

Poovarodom, N., Jirasakjamroonsri, A. & Warnitchai, P. (2017). Development of new design spectral accelerations for Bangkok considering deep basin effects. 16th World Conference on Earthquake Engineering, Santiago, Chile.

Rouainia, M. & Muir-Wood, D. (2000). A kinematic hardening constitutive model for natural clays with loss of structure. *Géotechnique,* 50**,** 153-164.

Rouainia, M. & Muir Wood, D. (2001). Implicit numerical integration for a kinematic hardening soil plasticity model. *International Journal for Numerical and Analytical Methods in Geomechanics,* 25**,** 1305-1325.

Shibuya, S., Tamrakar, S. & Theramast, N. (2001). Geotechnical site characterization on engineering properties of Bangkok Clay. *Geotechnical Engineering, Journal of the Southeast Asian Geotechnical Society,* 32**,** 139-152.

Stroud, M. (1988). The Standard Penetration Test-Its Application and Interpretation-Penetration in UK. Proc. of Geotechnology Conference organized by ICE, Birmingham.

Subedi, B., Kiyono, J., Furukawa, A., Ono, Y., Ornthammarath, T., Kitaoka, T., Charatpangoon, B. & Latcharote, P. (2021). Estimation of Ground Profiles Based on Microtremor Survey in the Bangkok Basin. *Frontiers in Built Environment,* 7.

Surarak, C. (2011). *Geotechnical aspects of the Bangkok MRT blue line project.* PhD Thesis, Griffith University.

Tavakoli, H., Gilani, H. & Abdollahzadeh, G. (2012). Comparative evaluation of seismic parameters for near-fault and far-fault earthquakes. The 15th World Conference on Earthquake Engineering, Lisbon. 24-28.

Viggiani, G. & Atkinson, J. H. (1995). Stiffness of fine-grained soil at very small strains. *Géotechnique,* 45**,** 249-265.

Vucetic, M. & Dobry, R. (1991). Effect of Soil Plasticity on Cyclic Response. *Journal of Geotechnical Engineering,* 117**,** 89-107.

Warnitchai, P., Sangarayakul, C. & Ashford, S. A. (2000). Seismic hazard in Bangkok due to long-distance earthquakes. Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand.

Yanuviriyakul, A. (2009). *A study of response behavior of soft bangkok clay from earthquakes.* Master Thesis, Kasetsart University.

Zhao, J., Sheng, D., Rouainia, M. & Sloan, S. W. (2005). Explicit stress integration of complex soil models. *International Journal for Numerical and Analytical Methods in Geomechanics,* 29**,** 1209-1229.

Zienkiewicz, O. C., Chan, A. H. C., Pastor, M., Schrefler, B. A. & Shiomi, T. (1999). Computational Geomechanics with special reference to Earthquake Engineering.