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NUMERICAL MODELLING OF RAILWAY EMBANKMENTS FOR HIGH-SPEED TRAIN CONSTRUCTED ON SOFT SOIL

Suched Likitlersuang [1,2], Phitsanu Pholkainuwatra [3],
Thanakorn Chompoorat [4], and Suraparb Keawsawasvong [5*]

ABSTRACT

Recently, several mass rapid transit projects have been launched to improve the logistics of trade in Thailand. The railway construction projects linked from Bangkok will be a challenging task for civil engineers since they are located on soft ground conditions. Consequently, an understanding of geomaterial properties and subsoil conditions is important in the design phase. This paper presents a numerical study of railway embankment behaviour when constructed on soft soil. Simplified finite-element modelling was performed to predict stability and deformation characteristics of railway embankments under high-speed design requirements. The construction materials, including ballasts and subgrade soils were selected and tested to characterise their engineering properties. It was found that existing railway embankment conditions exhibit a large degree of movement under a high-speed train load. The study recommends improvements of subgrade conditions, using methods such as cement stabilisation to enhance stability and reduce settlement of the railway embankments.

Key words: Embankment, soft soil, finite-element modelling, high-speed train.

1. INTRODUCTION

Recently, the government of Thailand has begun planning to develop effective standardised and extensive inland transportation networks accessible to passengers and businesses. To this end, the Office of Transport and Traffic Policy and Planning (OTP) and the Thai Ministry of Transport have planned for several high-speed rail lines. The north-eastern line from Bangkok (BKK) to Saraburi (SRI) is a priority for economic reasons and is therefore being prepared for construction. This line of approximately 100 kilometres from BKK to SRI will pose significant geotechnical challenges, particularly for creating embankment stability on soft ground, as most of this route is located in flood plains and the delta of the Chao Phraya River, which consists of an extensive overlay of Bangkok soft marine clay. It is well-known that Bangkok clay is of low strength and is highly compressible material. Moreover, it is also undergoing piezometric drawdowns and land subsidence from several decades of extensive ground water pumping (Surarak *et al.* 2012; Likitlersuang *et al.* 2013a).

In Thailand, the construction of a railway embankment on soft clay has become a challenging task for geotechnical engineers. The large magnitude and rate of subsoil settlements occurring during and after construction need to be controlled. A precise prediction of settlement is also required for estimating the volume of fill material required during construction. After construction, the total and differential settlements are also serious issues in the railway construction. In particular, the requirements of a high-speed railway project are more serious than those of normal railway projects. During the past decade, some technical studies on the consolidation settlement of Bangkok soft clay have been published (Bergado *et al.* 2002; Voottipruex *et al.* 2014). The settlement was monitored from test embankments constructed on soft Bangkok clay. Consolidation settlements of 1.0 ~ 1.4 m were observed from 4-meter high test embankments in the Bangkok international airport project (Bergado *et al.* 2002).

This project aims to study the settlement behaviour of railway embankment constructed on soft ground conditions. A two-dimensional (2D) finite element method using PLAXIS is employed to simulate the railway embankment conditions. The construction materials, including ballasts and subgrades, were selected and tested to determine the material parameters. The subsoil conditions were modelled based on a set of parameters drawn from previous studies (Likitlersuang *et al.* 2013a; Likitlersuang *et al.* 2014; Chheng and Likitlersuang 2018; Likitlersuang *et al.* 2018). The finite element simulations cover the conditions of the existing conventional railway and the high-speed railway in Thailand. The results are reported for both short and long term behaviour of the railway embankment. Furthermore, ground improvement of subgrade material and foundation is recommended to reach the requirements of a high-speed railway.

1.1 Existing Condition of the State Railway of Thailand

The State Railway of Thailand (SRT) is responsible for railway engineering and operation works for more than 4,000 km of railway, which consists of five main routes covering a service area comprising 47 provinces of Thailand, as shown in Fig. 1. Most of the railway lines of the SRT are made up of a single ballasted track system, generally with a formation 5.20 m wide for metre gauge track (1.00 m). The side slope of the track generally

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[1] Professor, Geotechnical Research Unit, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand.
[2] Transportation Institute, Chulalongkorn University, Bangkok Thailand.
[3] Civil Engineer, State Railway of Thailand, Bangkok, Thailand.
[4] Associate Professor, Department of Civil Engineering, School of Engineering, University of Phayao, Phayao, Thailand.
[5*] Ph.D. student (corresponding author), Geotechnical Research Unit, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand (e-mail: suraparb@hotmail.com).

uses the ratio of 1:1.5 to 1:2. A 25 cm thick ballast layer is normally provided below the sleepers to transfer the load to the subgrade. The ballast material most often used is igneous rock. Moreover, 60% of the existing tracks have been used for over 30 years (OTP 2011). The SRT railway structure consists of multiple components that serve in load distribution of the traffic of passing trains. The main component of the superstructure includes rails, sleepers, and fastening system. The substructure consists of ballast and subgrade, as well as natural ground as shown in Fig. 2. SRT (2013) has recommended gradations, rock types, and other properties of aggregate used for ballast as summarised in Tables 1 and 2. SRT (1994) guidelines say that the liquid limit of subgrade material should not be more than 50%.

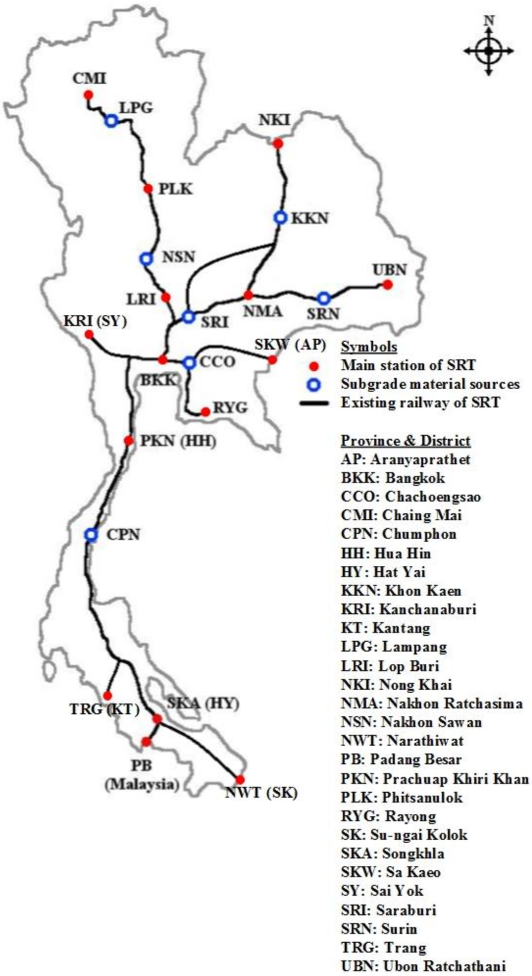
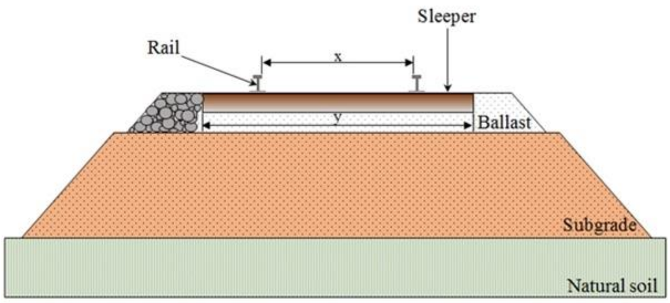


Fig. 1 SRT railway routes and subgrade materials sources



x = 1,000 mm for MG and 1,435 mm for SG
y = 2,000 mm for MG and 2,600 mm for SG
MG: Metre gauge; SG: Standard gauge

Fig. 2 Main component of track structure

Table 1 Recommended ballast gradation (SRT 2013)

Standard sieve designation (mm)	Percent passing (%)
64.0	100
50.8	80 ~ 100
38.1	25 ~ 70
25.4	0 ~ 20
19.0	0 ~ 5

Table 2 Recommended ballast properties (SRT 1994)

Properties	Value
Rock type	Granite, Basalt, Rhyolite, Andesite, Quartzite and Dacite
Los Angles abrasion test	Max. 25% (ASTM C535)
Flakiness index	Max. 30% (BS 812-105:1 and BS 812-105:2)
Elongation index	

1.2 High-Speed Rail

High-speed rail (HSR) is a new type of transportation rails that is significantly faster than conventional rail (typically enabling speeds of more than 200 km/hr). The installation of an HSR system consists of upgrading track, using better designed rolling stock, adopting a superior form of traction, and using modern systems and techniques in various operations of railway systems. HSR commonly operates on a standard gauge track (1.435 m) and continuously welded rail. According to European legislation (IRSC 2008), the minimum speed of HSR is 250 km/hr for specially built high-speed railway, and is 200 km/hr for routes upgraded from normal rail.

1.3 Numerical Modelling of Embankments

In the past decade, numerical simulations to predict highway and railway embankment settlements have been studied by many researchers. For example, Esmaeili *et al.* (2013) studied the performance of high railway embankment reinforced by micro piles using both physical and numerical modelling. The 3D finite elements were selected to simulate the stability of embankments under micro pile reinforcement. The results demonstrate that the use of reinforcement can increase the safety factor of an embankment by around 30% and reduce the settlement of the embankment crest by approximately 35%. Moreover, Sanchez *et al.* (2014) studied the behaviour of railway constructed on shrink-swell soils using finite element simulations.

2. RAILWAY EMBANKMENT MODELLING

The main purpose of this study is the investigation of the behaviour of HSR embankment; numerical models were used to study deformations in a ballasted-HSR track constructed on soft clay. Figures 3 and 4 present the geometry of the single track (ST)

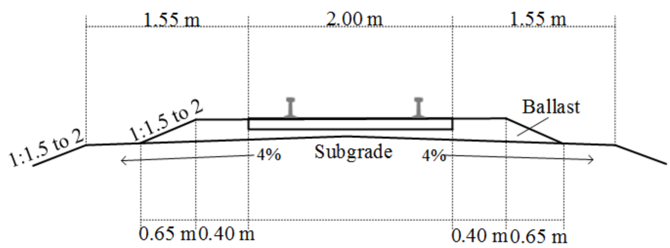


Fig. 3 Typical railway section for Metre gauge of single track (SRT 1982).

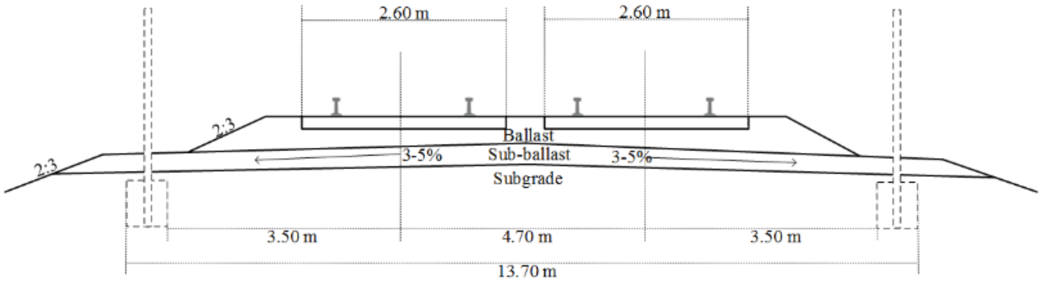


Fig. 4 Typical railway section for standard gauge of double track (after Profillidis 2014)

and double track (DT) embankment, respectively. The railway embankment structure consists of a ballast layer and a subgrade layer with a specified grain size distribution. The ballast layer mainly consists of granular material in the range of medium to coarse gravel sized particles (10 ~ 60 mm) and a small percentage of cobber sized aggregates. The subgrade layer beneath the ballast layer should be cohesionless material and compacted as a load-bearing layer. The top 30 ~ 60 cm of the subgrade layer shall be free from organic material and be suitable for supporting and distributing the loads to the stratum – the so called blanket layer, or sub-ballast (Selig and Waters 1994; RDSO 2003). The subgrade should also have moisture resistance to reduce the possibility of failure due to a change in water conditions. The geometry of ST and DT follows the railway structure of SRT (1982) and the HSR of German Railways (Profillidis 2014; FIP 1987).

2.1 Ballasts

The main purpose of ballast layer is to distribute the stress to the subgrade soil. This layer was modelled and placed on the top of the subgrade layer. The thickness of the ballast placed on the top was 0.25 m and 0.30 m, designed to support the load of ST with metre gauge track for conventional rail, and the load of DT with standard gauge track for HSR, respectively. In addition, a 0.3 m thick sub-ballast layer for DT was placed between the ballast and the subgrade to prevent contamination of ballast by subgrade material. The engineering properties and strength parameters of ballast were obtained from the experimental tests of index properties and a series of large direct shear tests. The results can be used to interpret the shear strength parameters based on the Mohr-Coulomb (MC) model as illustrated in Figure 5. Table 3

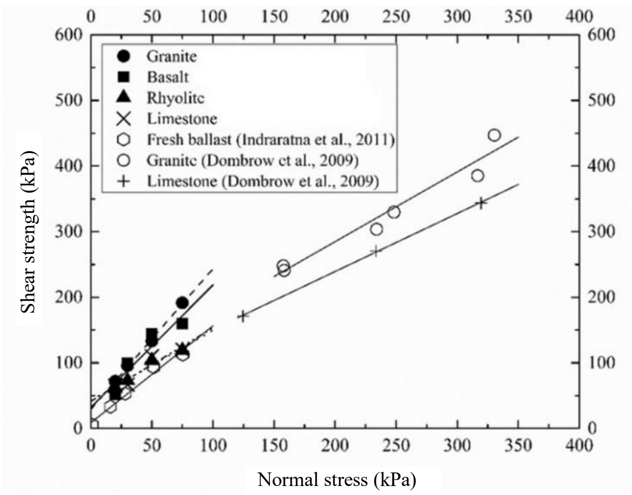


Fig. 5 Large direct shear test results of ballast samples

Table 3 The results of the ballast properties tests (SRT 2013)

Properties	Unit	Location of ballast sources			
		SRI	BRM	SRI	SRI
Rock type	–	Granite	Basalt	Rhyolite	Limestone
G_s	–	2.63	2.67	2.69	2.70
C_u	–	1.76	1.75	1.71	1.76
D_{50}	–	42.7	41.9	49.7	41.9
γ_b	kN/m^3	14.925	15.023	14.778	14.818
E.I.	%	26.52	23.50	18.87	21.84
F.I.	%	16.12	13.70	9.54	14.56
LAA	%	19.24	18.31	22.35	29.39
W.A.	%	0.42	0.53	0.77	0.40

Noted: G_s = specific gravity; C_u = coefficient of uniformity; D_{50} = mean particle size; γ_b = bulk unit weight; E.I. = elongation index; F.I. = flakiness index; LAA = Los Angles abrasion; W.A. = water absorption; SRI = Saraburi; BRM = Buriram.

summarise the properties of ballast typically used by SRT. Table 4 shows the MC model parameters (c, ϕ) of the ballasts interpreted from the large direct shear tests, compared with the results from other studies (Dombrow *et al.* 2009; Indraratna *et al.* 2011).

2.2 Subgrade Soils

The subgrade, which is the layer beneath the ballast or sub-ballast underlying the track system, plays a role in the platform of track structure. The performance of railway subgrade is governed by two characteristics *i.e.*, strength and deformation (Selig and Lutenegger 1991). The strength of subgrade can be simply indicated by the undrained shear strength of subgrade soil. The deformation of subgrade refers to two processes *i.e.*, elastic and plastic deformations (McHenry and Rose 2012). In this study, seven subgrade material sources from different locations, as listed in Table 5, were selected. These subgrade soils represent the

Table 4 Friction angle and cohesion intercept of ballasts from large direct shear test (SRT 2013)

Rock type	Cohesion intercept, c (kPa)	Friction angle, ϕ (°)
Granite	31.4	65.4
Basalt	31.9	61.9
Rhyolite	42.8	46.9
Limestone	41.4	48.2
Fresh ballast*	8.6	55.9
Clean granite#	69.8	46.7
Clean limestone#	61.4	41.5

Remarks: #Dombrow *et al.* (2009); *Indraratna *et al.* (2011)

Table 5 Results of the subgrade properties tests (SRT 2013)

Properties	Unit	Location of subgrade sources						
		SRI	NSN	LPG	CCO	SRN	KKN	CPN
G_s	–	2.67	2.63	2.58	2.50	2.53	2.64	2.73
Passing No.10	%	38.4	82.9	93.5	84.2	99.2	98.0	41.7
Passing No.40	%	28.7	68.8	75.8	69.3	97.0	93.9	28.5
Passing No.200	%	14.5	50.9	65.4	62.1	84.8	75.5	14.1
LL	%	19.6	64.3	55.1	55.1	32.9	33.4	21.7
PL	%	13.3	21.9	35.2	40.9	20.7	22.5	16.9
OMC	%	7.4	15.7	23.0	24.0	18.0	17.0	7.0
$\gamma_{d,\max}$	kN/m^3	20.78	17.74	18.03	17.25	17.64	18.42	20.78
Soaked CBR	%	32.7	4.7	8.9	7.2	2.4	2.1	54.7
Unsoaked CBR	%	33.4	9.8	12.3	11.2	3.3	3.1	56.0
Swelling	%	0.8	6.1	3.8	2.9	1.2	1.3	0.5
UCS	kPa	347.6	227.3	216.5	247.3	27.7	39.5	87.6
USCS	–	SC-SM	CH	MH	MH	CL	CL	SC-SM
AASHTO Group	–	A-2-4	A-7-6	A-7-5	A-7-5	A-6	A-6	A-1-a

Noted: G_s = specific gravity; LL = liquid limit; PL = plastic limit; OMC = optimum moisture content; $\gamma_{d,\max}$ = maximum dry density; UCS = unconfined compressive strength; SRI = Saraburi; NSN = Nakhon Sawan; LPG = Lampang; CCO = Chachoengsao; SRN = Surin; KKN = Khon Kean; CPN = Chomphon.

materials used for the SRT routes as depicted in Fig. 1. The properties of subgrade soils were tested based on ASTM C535 (2011) and AASHTO M145-91 (2014), as summarised in Table 5.

2.3 Soft Soil Conditions

Bangkok is located on a thick soft layer of marine clay deposits formed during the Quaternary period. The soft clay layer is overlaid by a terrestrial deposit a few meters thick. The underlying layers alternate clay and sand, forming a broad sedimentary basin. Figure 6 presents a typical subsoil condition and its engineering properties identified by Likitlersuang *et al.* (2013b). The soft soil condition of Bangkok as shown in Fig. 7 is

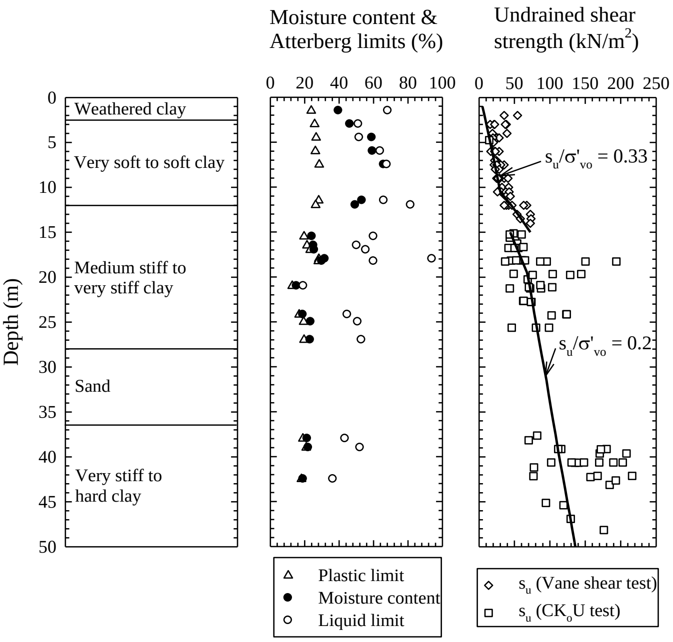
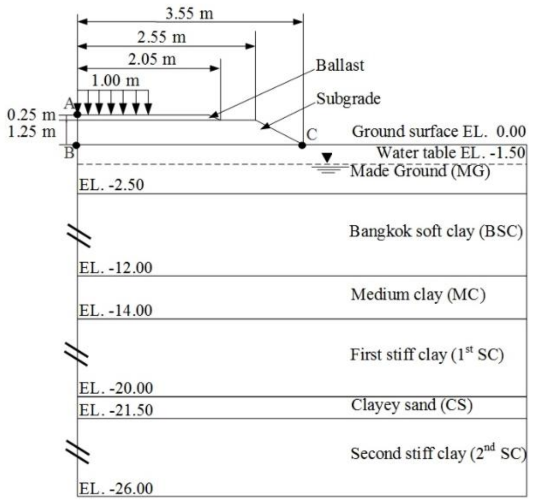
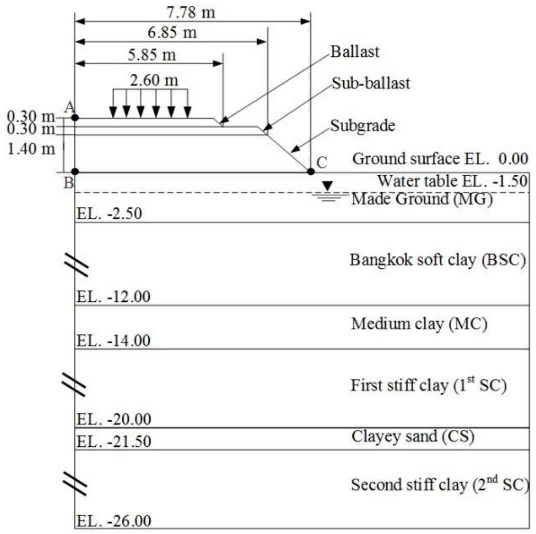


Fig. 6 Typical Bangkok subsoil condition (after Likitlersuang *et al.* 2013a)



(a) Single track structure under conventional train load



(b) Double track structure under high-speed rail load

Fig. 7 Simplified cross section of railway embankments

used in this study. The ground water level is located 1.5 m below the ground surface. The soil profile consists of 2.5 m of made ground (MG) underlain by a 9.5 m thick Bangkok soft clay layer (BSC). Below the BSC layer, there are 2.0 m of medium clay (MC), 6.0 m of first stiff clay (1^{st} SC), 1.5 m of clayey sand (CS), and second stiff clay (2^{nd} SC) layers, respectively. It is noted that the Bangkok soft clay layer exhibits low strength and high compressibility (Surarak *et al.* 2012; Likitlersuang *et al.* 2013a; Likitlersuang *et al.* 2013b; Likitlersuang *et al.* 2014; Chheng and Likitlersuang 2018; Likitlersuang *et al.* 2018).

2.4 Pseudo-Static Train Load

In this study, train loads applied to the model were simulated in a Pseudo-static condition. It is common practice to consider dynamic effects in terms of impact factor (*IF*). This method emphasises the effect of dynamic loading on railway structure, and a procedure has been developed to convert dynamic traffic conditions to a design static load. According to Sadeghi and Barati (2010), the *IF* of American Code (AREMA 2002) is slightly over-estimated for rail loads of speeds at higher than 80 km/hr. Therefore, it is safe to use the AREMA impact factor to simulate the load pressure. Two train models were considered in this study *i.e.*, the SRT conventional train (locomotive train) and the Chinese high-speed rail. The CSR Qishuyan-SDA3 model, which is currently used by the SRT, was selected to represent the conventional train, while the CRH3C model of Chinese Railways, which is an Electric Multiple Unit train (EMU) capable of service speed of 300 km/hr (Wang *et al.* 2014), was adopted as the high speed rail proxy.

In the pseudo-static approach, the design load (P) generated from train load is assumed to be a uniformly distributed load on the top of the ballast layer. A rail seat load (q_r) is a wheel load acting on each single rail, which is half of an axle load. The static rail seat load (q_r) of 10 kN/m and 6 kN/m is simulated for a 20 ton/axle of the SRT locomotive, and a 12 ton/axle of the HSR-EMU, respectively. The length of sleepers (L) which support the train loads are 2.0 m and 2.6 m for ST and DT, respectively. The speed of the train was taken into account using the impact factor (*IF*) referred to in AREMA (2002). The AREMA impact factor is a function with train speed (V) in km/hr and wheel diameter (D) in mm. In addition, the distribution factor (*DF*) is applied to estimate the distributed load carried by a single sleeper (AREMA 2002), which is a function of sleeper spacing (S) in mm. The pseudo-static load (P) is calculated using the following equations:

$$P = IF \times \frac{2q_r}{L} \times DF \tag{1}$$

$$IF = 1 + 5.21\left(\frac{V}{D}\right) \tag{2}$$

$$DF = \frac{(0.061 \times \mathrm{S}) + 13.37}{100} \tag{3}$$

All parameters for pseudo-static load calculation are summarised in Table 6. The calculation results for train loads are 74 kN/m/m for the locomotive train, and 62 kN/m/m for the high-speed train, respectively.

Table 6 Summary of parameters for train load calculation

Train parameters	Unit	CSR Qishuyan-SDA3[1]	CRH3C[2]
Axle load	t/axle	20	12
Wheel diameter	mm	1,067	920
Average speed	km/h	80	300
Track gauge	mm	1,000	1,435
Sleeper width	mm	2,000*	2,600*
Sleeper spacing	cm	60	60

Remarks: [1]SRT (2015); [2]Wang *et al*. (2014); *FIP (1987)

3. FINITE ELEMENT MODELLING

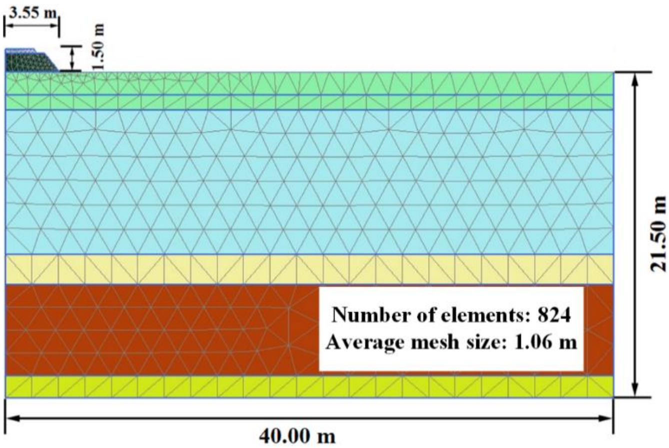
In this section, the 2D finite element modelling of railway embankments was performed using PLAXIS-2D software (Brinkgreve *et al.* 2012). The construction sequences were simulated following the SRT practical works. The embankment parameters were simplified into a 2D plan of strain and symmetry on the assumption that the transversal profile of the track is invariable in the longitudinal direction due to the long track and location in the middle of the embankment. Since Bangkok is a flat lowland area, the average elevation of the Bangkok area is 1.50 m above mean sea level (MSL) (Surarak *et al.* 2012) and the Chao Phraya River's highest recorded water level was 2.53 m above MSL (Saito 2014). In order to prevent flood caused by rainfall and high tide, the levels of embankment structures were modelled at 1.5 m and 2.0 m for ST and DT as shown in Figs. 7(a) and 7(b), respectively. The other dimensions of ST comprise base width of 7.12 m and crest width of 5.2 m. Meanwhile, the geometry of the DT cross section are 15.56 m width at the base and 13.70 m width at the crest. Due to symmetry, only half of the embankment was modelled as shown in Fig. 7. The railway embankment models consist of ballast, sub-ballast, subgrade and subsoil. Due to the strict requirements of the HSR track, the ground improvement at the subgrade soil level is applied to improve the performance of subgrade soil *i.e.*, increasing strength and stiffness (Selig and Lutenegger 1991). In Thailand, it is common to employ a cement treatment for pavement base or subbase. Therefore, the cement-treated soil technique was selected for subgrade soil improvement in this study. Table 7 summarises all analysis cases conducted in this study.

3.1 Mesh Discretisation

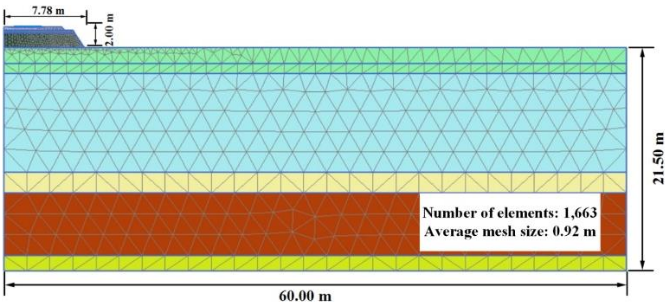
15-noded triangular elements are used to model the embankment and subsoil materials. Figures 8(a) and 8(b) present the finite element models and mesh generation for ST and DT, respectively. In Fig. 8(a), the ST problem consists of 824 elements with an average size of 1.06 m. The DT problem in Fig. 8(b)

Table 7 Analysis cases

Case No.	Type of load	Type of ballast	Subgrade material
1	SRT locomotive (Single track, ST)	Granite	Non-improved
2		Limestone	
3	HSR EMU (Double track, DT)	Granite	Non-improved
4		Limestone	
5		Granite	Soil-cement improved
6		Limestone	



(a) Single track structure under conventional train load



(b) Double track structure under high-speed rail load

Fig. 8 Finite element modelling

consists of 1,663 elements with an average size of 0.92 m. It is noted that the finer meshes were used for fill material layers. For example, the mesh sizes of the ballast layers are approximately 0.29 m and 0.16 m for single track and double track models, respectively.

3.2 Boundary Conditions

Prior to performing the analysis, a suitable boundary size must be identified. It is commonly known that too big a size will increase the computational time while too small a size will cause the boundary to affect the calculation results. In this study, the geometries of the boundary were carefully adjusted. It was found that 40 m and 60 m widths are suitable for the ST and DT models, respectively, and that 21.5 m depth of subsoil is good for both models. The boundary conditions of the mesh along both vertical sides were restrained from moving in the horizontal direction, while the movement in vertical direction was allowed. The horizontal and vertical fixed displacements were attached to the bottom of the boundary.

As recommended by Mestat *et al.* (2004) the numerical model for the embankment problem can be characterised by L/B and H/h ratios, where L and H are width and depth dimensions of the problem, respectively, and B and h are width and depth of embankment, respectively. It is recommended that L/B and H/h should be at least 3 and 4, respectively. As regards this study, the ratios used are $L/B = 11.3$ and 14.3 for ST and DT models, and $H/h = 7.7$ and 10.8 for ST and DT models, respectively.

3.3 Constitutive Models and Their Parameters

The constitutive models for embankment and subsoils are described in this section. The ballast material was represented by the Mohr-Coulomb model (MCM), which is particularly useful for modelling frictional materials. The characteristics of ballast on drained granular material can be reasonably modelled by MCM and drained analysis. The MCM strength parameters, cohesion (c') and friction angle (ϕ'), are determined from the results of large direct shear tests (Table 4). Due to limitations of the direct shear test, the results could not be used to define Young's modulus (E). Thus, a value of 110 MPa, recommended by Chinese railway tracks (Zeng 1997), was adopted for the typical Young's modulus of ballast. In this study, granite and limestone were selected, as they are most commonly used in this type of construction.

Saraburi (SRI) soil was selected for backfill material for the subgrade layer in the embankment. Since the SRI represents the subgrade material most commonly used in the central area of Thailand. The MCM can also be used to represent the subgrade material. The undrained shear strength (s_u), and secant modulus at 50% of strength (E^{50}) of the subgrade material were determined using the result of unconfined compressive strength (UCS) tests. For the soil-improvement case, the use of cement-treated soil is assumed for subgrade improvement. The input parameters are based on the standard of cement treated soil for subbase material recommended by Thailand's Department of Highways (DOH 1989). Table 8 summarises the parameters of ballast and backfill materials employed in the analyses.

Table 8 Summary of parameters of substructure materials used in finite element analysis

Parameter	Ballast		Sub-ballast	Subgrade	Soil-cement
	Granite	Limestone	Crushed rock	SRI	CTS
Model	MCM	MCM	MCM	MCM	MCM
Type of behavior	Drained	Drained	Undrained	Undrained	Undrained
γ_b (kN/m^3)	14.93	14.84	22.64**	22.34	20.80
E^{50} (MPa)	–	–	–	9.6	138#
E' (MPa)	110*	110*	350**	–	–
υ	0.3	0.3	0.3**	0.3	0.4#
c' (kPa)	31.4	41.4	–	–	–
s_u (kPa)	–	–	712**	173.8	345#
ϕ' (°)	65.4	48.2	0	0	0

Noted: SRI = Saraburi, CTS = Cement-treated soil, MCM = Mohr-Coulomb model, γ_b = bulk unit weight, E^{50} = secant modulus at 50% of strength, E' = drained modulus, υ = Poisson's ratio, c' = cohesion intercept, s_u = undrained shear strength, ϕ' = effective frictional angle.
Remarks: *Zeng (1997); **Sawangsuriya *et al*. (2008); #DOH DH-S 206/2532 (1989)

Because the expected routes of the high-speed railway will most likely run from Bangkok to other destinations, Bangkok subsoil conditions were selected for this study. The subsoil condition and constitutive parameters adopted here are based on comprehensive studies of Bangkok subsoils by Surarak *et al.* (2012); Likitlersuang *et al.* (2013a); Likitlersuang *et al.* (2013b); Likitlersuang *et al.* (2014); Chheng and Likitlersuang, (2018); and Likitlersuang *et al.* (2018). The subsoils were divided in to five layers and their constitutive behaviours were represented by the Hardening Soil Model (HSM). The HSM parameters for subsoils used in the analyses are summarised in Table 9. For short-term analysis, the undrained method A (Brinkgreve *et al.* 2012), governed by effective stresses, is used in conjunction with the hardening soil model. Therefore, the values for effective strength and stiffness are required in this study. Skempton's parameters A and B are calculated based on elasticity theory, *i.e.*, A = 1/3 and $B = 1/\left(1+(nK'/K_w)\right)$. PLAXIS automatically adds the stiffness of water (K_w) when an undrained material type is chosen. n and K' are the porosity and the effective bulk modulus of soil. For long-term analysis, a coupled consolidation analysis based on Biot's theory (Brinkgreve *et al.* 2012) is used in this study. The consolidation analysis requires the input of anisotropy permeability coefficients (k_x and k_y) as summarised in Table 10.

3.4 Staged Construction

The staged embankment construction was simulated according to the general practice of SRT. The first and second steps were identified as the construction of the subgrade embankment and ballast layer on the soft soils, respectively. These two steps involve undrained analyses. The third step is the consolidation analysis, simulating a 60-day consolidation during the post-construction period, prior to train operation. The fourth and fifth steps simulated train loading under both the short and long term conditions. In addition, for Cases 5 and 6, soil-cement improvement was applied for the subgrade layer. During the analyses, displacements of ballast and subgrade layers, settlement of ground surface, and excess pore water pressure were observed.

4. RESULTS AND DISCUSSION

In this section, the results of analyses are presented and discussed. As listed in Table 7, the finite element analysis results indicate influences of using different ballasts and soil-cement improvement on the high-speed rail (HSR) design. The results were focused on both stability and deformations.

4.1 Stability of Embankments

The embankment stability analysis was conducted using the strength reduction approach (Brinkgreve *et al.* 2012). In this approach, the shear strength parameters of soil (*i.e.*, tan ϕ' and c') are successively reduced until failure of the embankment occurs. The factor of safety (FS) is used to define the value of the soil strength parameters at limit stage:

$$FS = \min\left\{\frac{\tan\phi'_{input}}{\tan\phi'_{reduced}}, \frac{c'_{input}}{c'_{reduced}}\right\} \tag{4}$$

where the parameters with the subscript 'input' refer to the input shear strength parameters, and parameters with the subscript 'reduced' refer to the reduced values at the limit stage. In this study, the undrained stability analyses subjected to train load were conducted for all cases. The FS values calculated from the stress reduction method are reported in Table 11. From Table 11, the FS values in the case of granite ballast are slightly higher than the case of limestone. However, the soil-cement subgrade can significantly increase the FS values. Figure 9 illustrates the shear strain contour at the limit state, which can imply the location of failure zones. Cases 1, 3 and 5, with granite ballast, were selected to present in Figs. 9(a), 9(b) and 9(c), respectively. Case 1 presents the failure zone of single track structure under conventional train load while Cases 3 and 5 show the failure zones of double track structures under high-speed train load. It can be seen that Cases 1 and 5 show a general shear failure pattern; on the other hand, Case 3 exhibit a local shear failure mechanism. The results also confirm that the soil-cement subgrade (Case 5) can improve the stability of double track structure. It is noted that Figs. 9(b) and 9(c) occur at different FS value. As shown in Table 8, the subgrade soil improved by soil-cement exhibit stiffer behaviour (higher in stiffness and strength) than SRI (non-improved) subgrade. As the result, the safety factor is higher in the case of the soil-cement improved subgrade.

Table 9 Summary of HSM parameters of Bangkok subsoil (after Likitlersuang *et al.* 2013b)

Layer	Soil type	Depth (m)	γ_b (kN/m^3)	c' (kPa)	ϕ' (°)	ψ (°)	E_{50}^{ref} (MPa)	E_{oed}^{ref} (MPa)	E_{ur}^{ref} (MPa)	ν_{ur}	m	K_0^{nc}	R_f	Type of behaviour
1	MG	0-2.5	18	1	25	0	45.6	45.6	136.8	0.2	1	0.58	0.9	Drained
2	BSC	2.5-12	16.5	1	23	0	0.8	0.85	8.0	0.2	1	0.7	0.9	Undrained
3	MC	12-14	17.5	10	25	0	1.65	1.65	5.4	0.2	1	0.6	0.9	Undrained
4	1stSC	14-20	19.5	25	26	0	8.5	9.0	30.0	0.2	1	0.5	0.9	Undrained
5	CS	20-21.5	19	1	27	0	38.0	38.0	115.0	0.2	0.5	0.55	0.9	Drained
6	2ndSC	21.5-26	20	25	26	0	8.5	9.0	30.0	0.2	1	0.5	0.9	Undrained

Noted: γ_b = bulk unit weight; c' = cohesion intercept; ϕ' = effective frictional angle; ψ = dilation angle; E_{50}^{ref} = reference stiffness modulus corresponding to the references stress; E_{oed}^{ref} = tangent stiffness for primary oedometer loading; E_{ur}^{ref} = unloading/reloading stiffness; ν_{ur} = Poisson's ratio for unloading-reloading; m = power for stress level dependency of stiffness; K_0^{nc} = K_0-value for normal consolidation; R_f = Failure ratio

Table 10 Permeability coefficients for consolidation analysis (after Likitlersuag *et al.* 2015)

Layer	Soil type	k_x (m/day)	k_y (m/day)
1	MG	8.64×10^{-2}	4.32×10^{-2}
2	BSC	4.32×10^{-4}	6.85×10^{-6}
3	MC	8.64×10^{-4}	2.05×10^{-6}
4	1st SC	8.64×10^{-4}	1.92×10^{-6}
5	CS	8.64×10^{-4}	1.92×10^{-6}
6	2nd SC	8.64×10^{-3}	9.59×10^{-7}

4.2 Short-Term Analysis

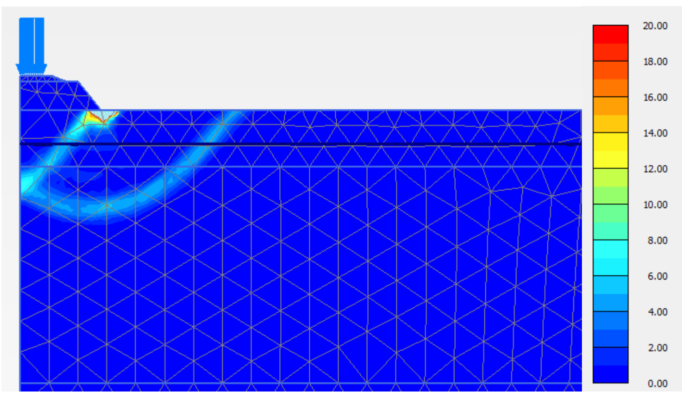
4.2.1 Surface Settlement

The analysis results of short term deformation were observed at ballast and ground surface settlement under train loading. Figures 10 and 11 present the surface settlements at short term for ST under conventional train load, and DT under HSR load, respectively. The maximum settlements along the centre of track at the ballast and ground surface (*i.e.*, points A and B, as depicted in Fig. 7) are reported in Table 11. The results show that short term deformations are not affected by the different strength parameters of ballasts. It is also shown that subgrade soil improvement can significantly reduce short term settlements. The maximum short term settlements at the centre of the track for the cement-treated subgrade was decreased to 8.5 cm, which is in the range of

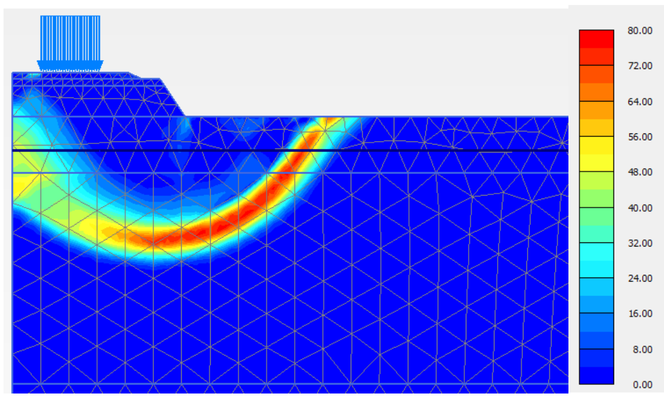
Table 11 Results of finite element analysis

Case No.	Structure	Ballast	Subgrade	FS*	Ballast surface settlement** (cm)		Ground surface settlement** (cm)	
					Short term	Long term	Short term	Long term
1	SRT locomotive (Single track, ST)	Granite	SRI	1.872	10.44	22.7	9.59	21.9
2		Limestone		1.869	10.44	22.7	9.58	21.9
3	HSR EMU (Double track, DT)	Granite	SRI	1.552	15.90	53.1	15.27	52.9
4		Limestone		1.547	15.99	53.5	15.38	53.3
5		Granite	Soil-cement improved	1.805	8.54	47.1	8.45	47.1
6		Limestone		1.802	8.55	47.3	8.50	47.2

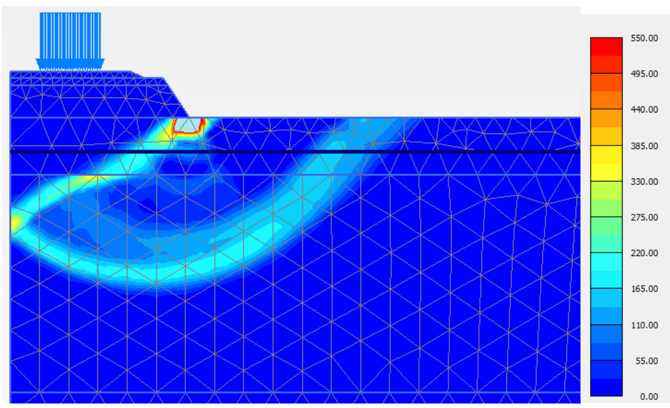
Remarks: *Factor of safety from stress reduction method; **Settlements at centre of the track



(a) Case 1: single track structure (ST), granite, SRI



(b) Case 3: double track structure (DT), granite, SRI



(c) Case 5: double track structure (DT), granite, soil-cement

Fig. 9 Distribution of shear strain subjected to train load

controlled settlement of 10 cm recommend by Chinese high-speed railway (Wang *et al.* 2014) (see Table 12). Figures 10 and 11 also show short term settlements of embankments at ballast and ground surface levels. These plots can illustrate the settlement patterns of railway embankments.

4.2.2 Excess Pore Water Pressure

The predicted excess pore water pressures along the centreline of the railway embankments are plotted in Fig. 12. The results show increases in excess pore water pressures due to the embankment fill and train loads. The maximum excess pore water pressure is presented in the soft clay layer at depths of 4.0 to 6.0 m. The cases of HSR with DT exhibit higher excess pore water pressure distributions than the cases of conventional train with ST, as expected.

Table 12 Controlled settlements of ballasted track high-speed railway in China (after Wang *et al.* 2014)

Description	Unit	Design speed (km/h)	
		250	300 to 350
Embankment zone	cm	10	5
Bridge embankment transitional zone	cm	5	3
Settlement rate	cm/year	3	2
Slope ratio	–	1/1,000	1/1,000

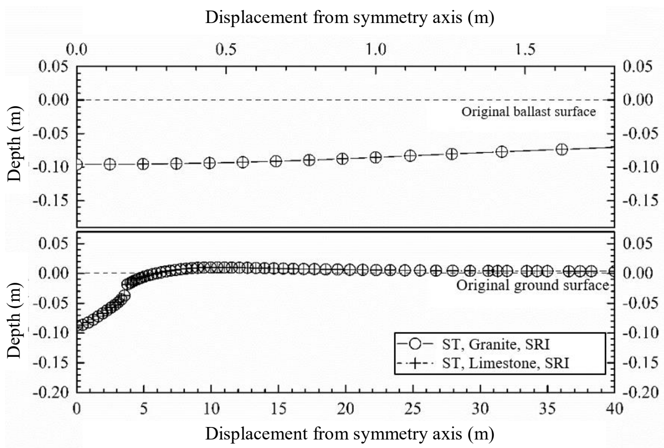


Fig. 10 Ballast and ground surface settlements of single track structure under conventional train load in short term

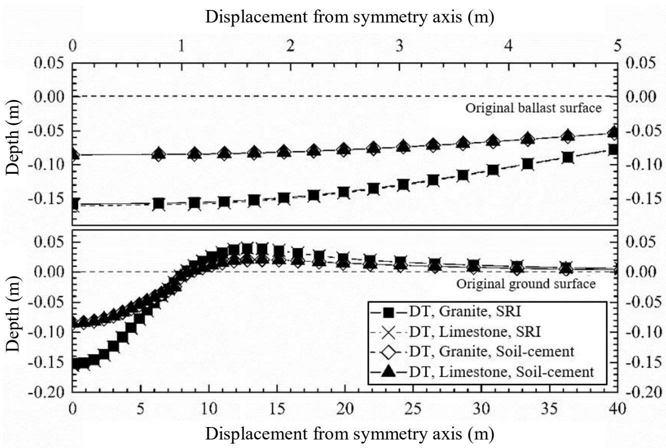


Fig. 11 Ballast and ground surface settlement of double track structure under high-speed rail load in short term

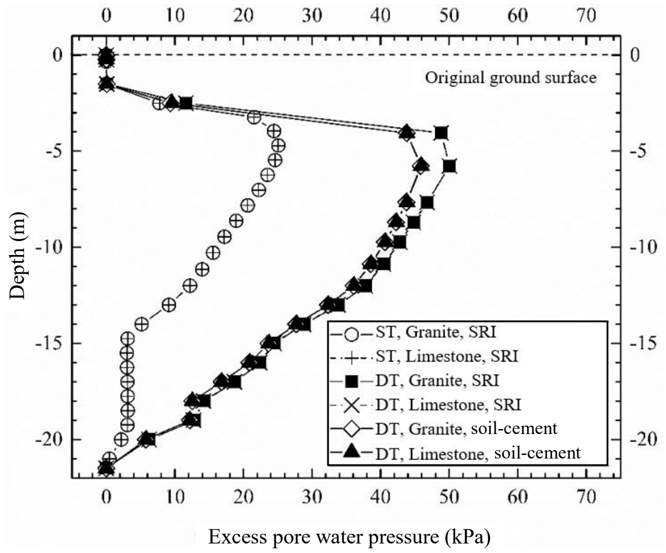


Fig. 12 Excess pore pressures in short term period at the centreline of embankment

4.2.3 Lateral Movement of Embankment

Lateral movements of soil underneath the toe of embankment (i.e., point C in Fig. 7) were observed, as plotted in Fig. 13. The results indicate that large lateral movements of subsoil occur in the soft soil layer up to 15 m below the ground surface. It can be seen that cement-treated subgrade can reduce the lateral movement by approximately half. This confirms that ground improvement is required to increase the stability of embankments.

4.3 Long-Term Analysis

Consolidation settlement of embankments was observed along the centreline of embankments at the ballast and ground surfaces (*i.e.*, point A and B as depicted in Fig. 7), as presented in Figs. 14 and 15, respectively. It can be seen that most of the consolidation settlement will occur in the first 5 years. The maximum settlements, after 99% consolidation, are reported in Table 11. The results show that the long-term settlement of

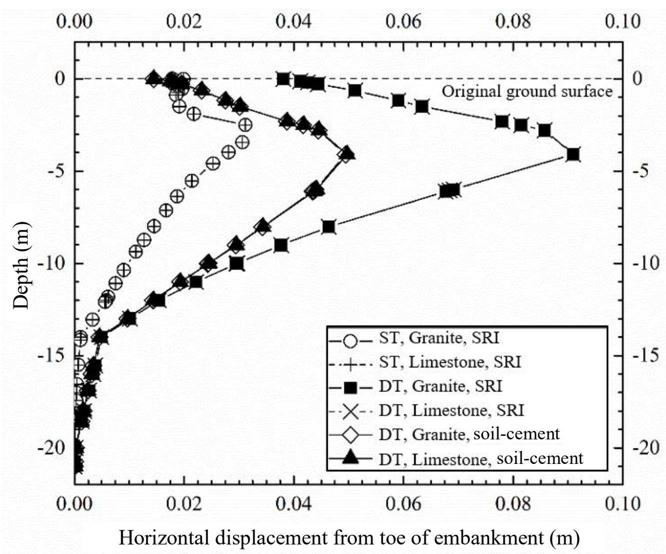


Fig. 13 Lateral movement of soil underneath the embankment toe at short term

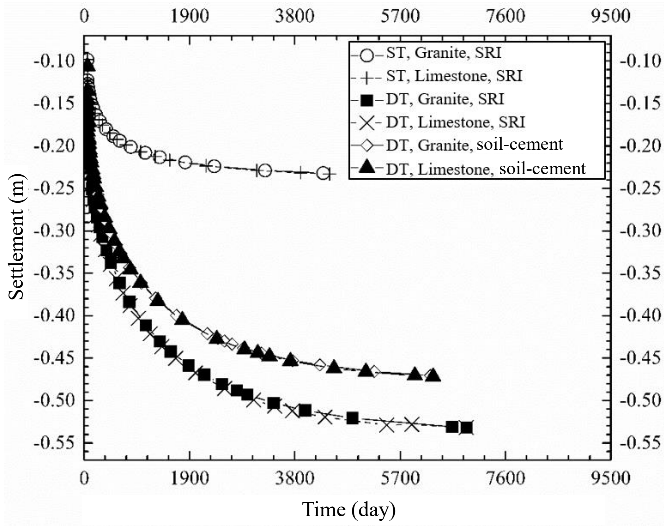


Fig. 14 Settlements versus time of ballast surface at centreline of the embankment

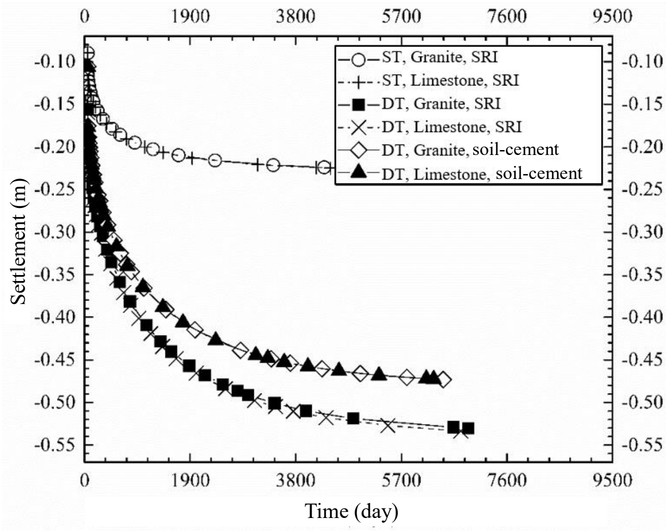


Fig. 15 Settlements versus time of ground surface at centreline of the embankment

embankments are over 20 cm and 50 cm for ST under conventional train load, and DT under HSR load, respectively. Even in the case of cement-treated subgrade, the long term settlement of the HSR embankment is still 47 cm. However, when comparing the results with the settlement rate of 3 cm/year recommended by the Chinese Railway in Table 12, the settlement should not exceed 15 cm in the first 5 years. Based on these results, it is highly recommended that the soft soil layer be improved using ground improvement techniques such as the deep-mixing method (cement column) or by employing driven piles.

5. SUMMARY AND RECOMMENDATIONS

The 2D finite element analyses were conducted for predicting the deformation behaviour of railway embankments constructed on soft soil under high-speed rail conditions. The analyses employed the pseudo-static train loading recommended by AREMA (2002). The case studies were based on a possible high-speed rail project of the State Railway of Thailand (SRT). The ballast and subgrade materials as well as subsoil conditions selected in this study are in line with information promulgated by the SRT. The ballasts and subgrade soils were tested to define the important input parameters for finite element analysis. Some key deformations resulting from the analyses were reported. The highlights of this study can be summarised as follows:

1. Specific technical information on a possible high-speed rail project of the State Railway of Thailand was gathered and reported on for the first time.
2. Ballasts and subgrade soils commonly used in railway construction in Thailand were selected and tested. The tested results can be used to define the parameters for finite element analysis.
3. The 2D finite element analysis for railway embankments was conducted based on the available technical information. The analysis results were focused on the stability and deformation characteristics of embankments, which is essential for the high-speed rail project.
4. Short term analysis was performed to evaluate the stability of embankments after construction. In addition, a long term analysis was conducted to determine expected consolidation settlement in the future. This can be used for routine maintenance and/or plans for upgrading tracks.
5. It is well-known that the thick Bangkok soft clay layer is a low strength and high compressible material. Most of the construction on Bangkok soft soil requires ground improvement. In this study, it was numerically proven that high-speed railway embankments in the Bangkok region require soil improvements. The cement-treated subgrade and, perhaps, deep-mixing methods are recommended for railway embankment construction on Bangkok soft soil.

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