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The Application of Deep Mixing Method for a River Wall and Finite Element Simulation

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Abstract – This paper presents an application of using deep cement mixing method to construct a river wall. The geotechnical characteristics, construction sequence and its behaviours were presented in this paper. The behaviours of river wall were simulated by 3-dimensional finite element by using Midas GTS NX software. The different type of constitutive models of cement admixed clay were used in the analysis. The stress-strain simulation of stress path triaxial test for cement admixed clay was conducted using SoilTest feature in GTS NX software. The Mohr Coulomb model showed the best performance to predict the deformation characteristics of cement admixed Pasak Clay among UBCSand Model and Hardening Soil Model. The predicted stiffness from stress response develops overestimated the stiffness of cement mixed clay when having low mean stress. The three-dimensional finite element analysis can predict the overall behaviours of river wall improved with cement. The best model for cement admixed clay was Mohr Coulomb Model.

Keywords**:** Constitutive Model, Cement Admixed Clay, Finite Element

1. Introduction

The ground improvement of soft ground by mixed with cement is very popular and effective method [3][2][1][7]. The stiffness as well as strength of soft ground can be improved by hydration and pozzolanic reaction between soil and cement [13]. The cement admixed clay (CA) is widely used in geotechnical projects, which are embankment [3], retaining structure [12] and foundation [8]. The stiffness increment of improved ground can reduce the unsatisfactory deformation of the project. The use of CA with retaining structure is very challenge for geotechnical engineers. The stress increment of this application is compression unloading stress condition, which lateral stress decreased, and vertical stress is constant. Not only the challenge of increasing the state of stress, but also the development of tensile stress in CA is also a very serious problem. The excessive tensile stress will create a crack in CA and create failure.

A finite element analysis was used to simulate and design CA improve ground in many projects with different types of constitutive model. The simulation of both axial and lateral of deep mixing of CA (DMC) has been done by 3-dimensinal finite element analysis by Voottipruex et al. [12]. The constitutive model of cement CA was elasto-plastic with Mohr Coulomb as yield function (MCM). The constitutive model parameters were back calculated from field testing results, which cause different in parameter for each certain condition. For embankment simulation, the MCM with strain softening was used as a constitutive model for CA for simulating the behaviours of embankment by Yapage et al. [8]. The consolidation analysis successfully simulated the embankment settlement. The behaviour of CA improved slope was analysis with finite element by Jamsawang et al. [10]. The model for CA was MCM. The factor of safety was also analyzed by finite element analysis. The behaviour of retaining structure was also simulated by finite element analysis by Jamsawang et al. [11]. The elastoplastic model with both kinematic and isotropic hardening, which is Hardening Soil Model (HSM), was used to model the behaviors of CA. The model parameters were obtained by curve fitting from element test by undrained triaxial and oedometer tests. From overall literature, the finite element analysis of deep mixing method (DMM) was used elasto-plastic model with and without hardening feature to simulate the behaviours of CA. The question might arise whether these constitutive models are suitable for simulation with other stress paths like compression unloading. The gap of research was the simulation of CA with different stress paths with the aforementioned constitutive model. The limitations and evaluation of constitutive models need to be studied.

This paper presents the behaviours of using deep mixing method (DMM) to improve the stability and serviceability of a river wall. The main objective of this wall is for dredging propose to enlarge a water channel of river. The construction sequence and its behaviour are discussed in this paper. Moreover, the 3-dimensional finite element analysis was used to simulate the wall behaviour. The evaluation of constitutive models with different stress path is discussed. The comparison of the stress response envelop of test results and model prediction is presented. Then, the simulation of river wall with DMM was done by using GTX NX software.

Overall, the contributions of this work can be listed as follows:

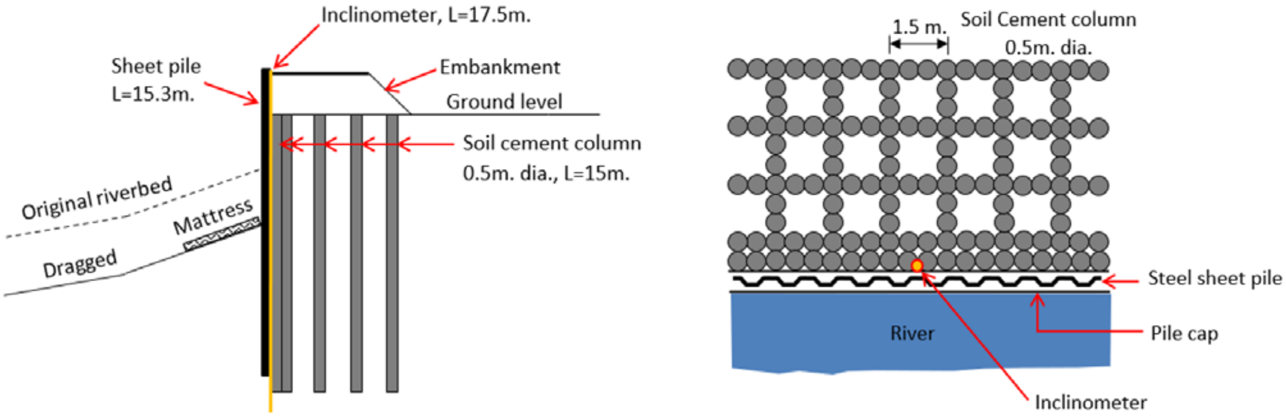
1) The effectiveness of different types of constitutive model for CA was assessed with a stress path triaxial test, which has compression loading and unloading. The stiffness predictions of different constitutive model were accessed by their response envelop.

2) The construction procedure and behaviours of river wall improved with CA were presented.

3) The numerical technique and procedure for simulate an application of CA as retaining structure was proposed. This might be an initial guideline to a simulation and design of using CA in a river wall.

2. Project information

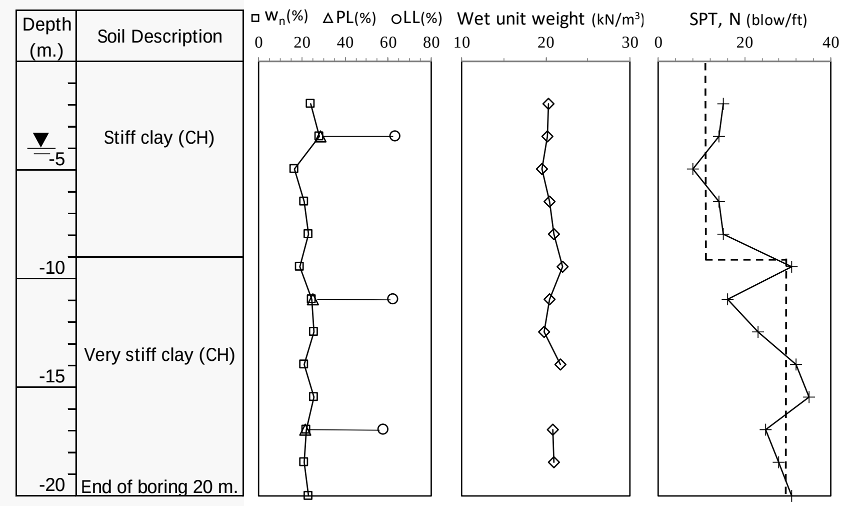
Pasak River is a major river in central Thailand for water transport. It locates 100 kilometers northern part of Bangkok. Due to the shallow current channel, the riverbed needs to be dredged to increase the river channel. The stability of the river bank had to be improved by a soil cement column as shown in Fig. 1. The front of the wall was sheet pile to improve the stiffness and erosion resistance of the system. The arrangement of cement column was honeycomb pattern to increase its moment of inertia of improved area and cost effectiveness. During the construction stage, soil at front wall was excavated for more space of water transportation on the river. Stress state of cement admixed clay reduced in lateral direction called ‘compression unloading’. The stress increase is not only compression unloading, but some part also has different stress increase status such as compression loading. The inclinometer was installed in the DMM near the sheet pile at the front face of the wall.



a) Typical Section b) Typical Plan

Fig. 1: The typical cross section of deep mixing of cement admixed clay improved river bank

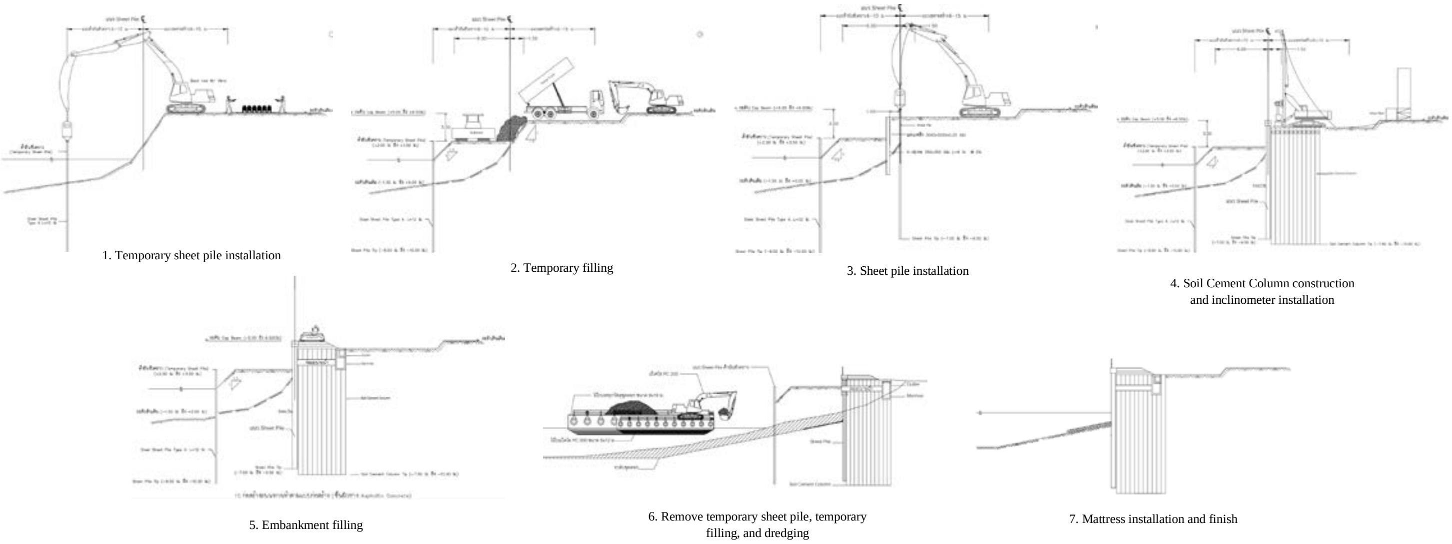
The soil profile of this project consists of stiff clay and very stiff clay from a depth of 20 meters as shown in Fig. 2. The standard penetration value (SPT-N) tends to slightly increase with depth. The water content of soil was relatively uniform through the investigation borehole. The ground water level is similar to water in the river 5 m from the ground surface. The initial water content of soil is near its plastic limit cause have a high strength and stiffness. The soil type is high plasticity clay due to its high liquid limit, which is more than 50%. Mixing cement with clay is difficult because of its high plasticity, when the total soil water content is between the liquid and the plastic limit. The deep mixing with high pressure was first selected to ensure the bonding destroy before adding cement for mixing. However, the high pressure of jet caused the movement of sheet pile wall. The low pressure with mechanical mixing was used at the DMM near the sheet pile wall.



Notes

SPT : Standard penetration test, w_n : Natural water content, PL : Plastic limit, LL : Liquid limit

Fig. 2: Soil profile


1. Temporary sheet pile installation

2. Temporary filling

3. Sheet pile installation

4. Soil Cement Column construction and inclinometer installation

5. Embankment filling

6. Remove temporary sheet pile, temporary filling, and dredging

7. Mattress installation and finish

Fig. 3: The construction sequence river wall

The construction sequence begins with installing a temporary sheet pile in front of the proposed wall in the river, as shown in Fig. 3. Then, the permanent sheet pile was installed for use as a wall face. The DMM was then constructed behind the sheet pile wall. Some part of DMM was blocking to build a drainage of groundwater to a front wall. After the strength of DMM increased to an expected value, the embankment was built on DMM with a sidewalk for the cycling track. Finally, the soil in front of the pile of sheets was removed by the excavator on a river boat.

3. Constitutive model evaluation

Before performing full finite element simulation, we calibrate the constitutive model parameters for CA with different model, which are elasto-plastic with Mohr Coulomb as yield function (MCM), hardening soil model (HSM) and UBC-Sand Model (UBSM) [4][9]. The MC model has one fix yield function without hardening feature. When the stress state reaches the yield criteria, the dilatancy characteristic, which are contraction and dilation, is control by a dilatancy angle, ψ. This simulation assumed to be zero dilatancy caused no changing of excess water pressure after yield. The MCM and UBSM have 2 hardening yield functions, which can move according to changing deviatoric and volumetric strains. The dilatancy characteristics of UBSM was controlled by the different between mobilized friction and constant volume friction angle. The model parameter for each model was curve fitting from the test result as shown in Table 1. The model parameters of MCM were in similar ranged with the previous research [12]. The elastic modulus of this study was a bit higher than the previous due to a higher cement content.

Table 1: Constitutive model parameters of cement admixed clay

Name	Cement Admixed Clay (CA)		
	CA-MCM	CA-HSM	CA-UBSM
Material	Isotropic	Isotropic	Isotropic
Model Type	Mohr-Coulomb	Hardening Soil	UBC sand
Property	3D-Solid	3D-Solid	3D-Solid
Poisson's Ratio, ν	0.3	0.3	0.178
Wet Unit Weight (kN/m^3)	13.74	13.74	13.74
Drainage Condition	Undrained	Undrained	Undrained
Skempton's B coefficient	1.0	1.0	1.0
Effective Cohesion, c (kPa)	196.33	250	180
Effective Friction Angle, $\varnothing$ (degree)	13.47	13.47	-
Dilatancy Angle, ψ (degree)	0	0	0
Elastic modulus, E (kPa)	100,000	-	100,000
Secant Stiffness, E_{50}^{ref} (kPa)	-	100,000	-
Tangential Stiffness, E_{oed}^{ref} (kPa)	-	100,000	-
Unloading and Reloading Stiffness, E_{ur}^{ref} (kPa)	-	300,000	-
Failure Ratio, R_f	-	0.97	0.97
Reference Pressure, P_{ref}	-	100	100
Power of Stress Level Dependency	-	0.1	-
Initial Void Ratio, e_0	0.5	0.5	0.67
Over Consolidation Ratio, OCR	-	8	-
Lateral Earth Pressure Coefficient, K_0	0.6	0.6	0.6
Peak Friction Angle, $\varnothing_p$ (degree)	-	-	17
Constant Volume Friction Angle, $\varnothing_{cv}$ (degree)	-	-	12
Plastic Shear Modulus Number, $K_{g,p}$	-	-	400
Plastic Shear Modulus Exponent, n_p	-	-	0.5
Elastic Shear Modulus	-	-	Power Law 210/0.5

The results from constitutive model simulation are shown in Fig. 4. We perform the stress strain simulation by using "Soil Test" subroutine in GTS NX program. The program feature could help calibrate the model parameters before conducting full finite element analysis. The stress-strain increment was set to be an undrained triaxial compression test, which increasing vertical strain with constant lateral stress. The set of parameters was biased to match the q-es relationships more than predicting excess pore water pressure to minimize the prediction error. UBSM perform the best performance with other models for simulation of q and es. It can simulate the nonlinear behaviours of test results after q being more than 400 kPa. MCM and HSM were over-predicting the value of q. For the q-p stress path prediction, MCM shows the best prediction compared to another model. The excess pore water pressure initially positive and then not significantly change after it reaches the yield condition. The UBSM and HSM overpredicted the excess pore water pressure that having the value of mean stress being lower than the actual test results.

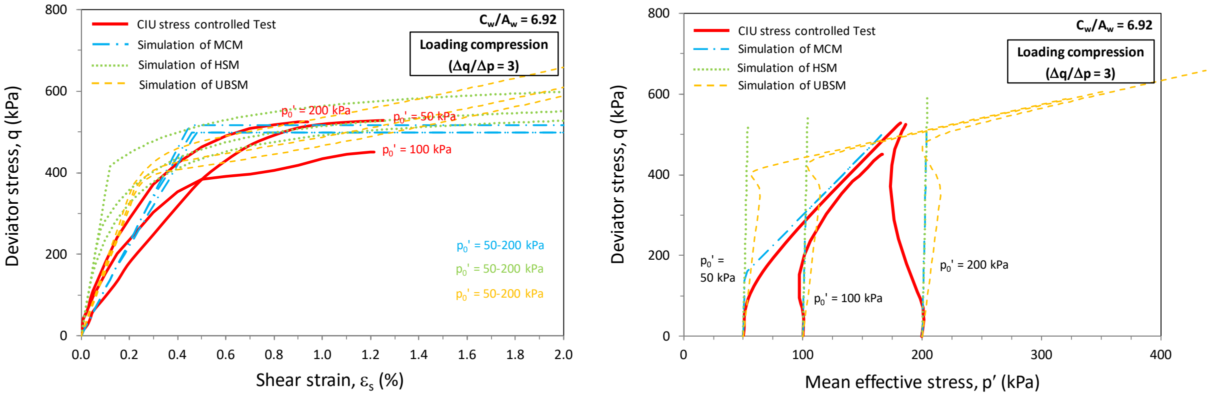


Fig.4: Stress-strain and stress paths of CIU test results and constitutive model simulations

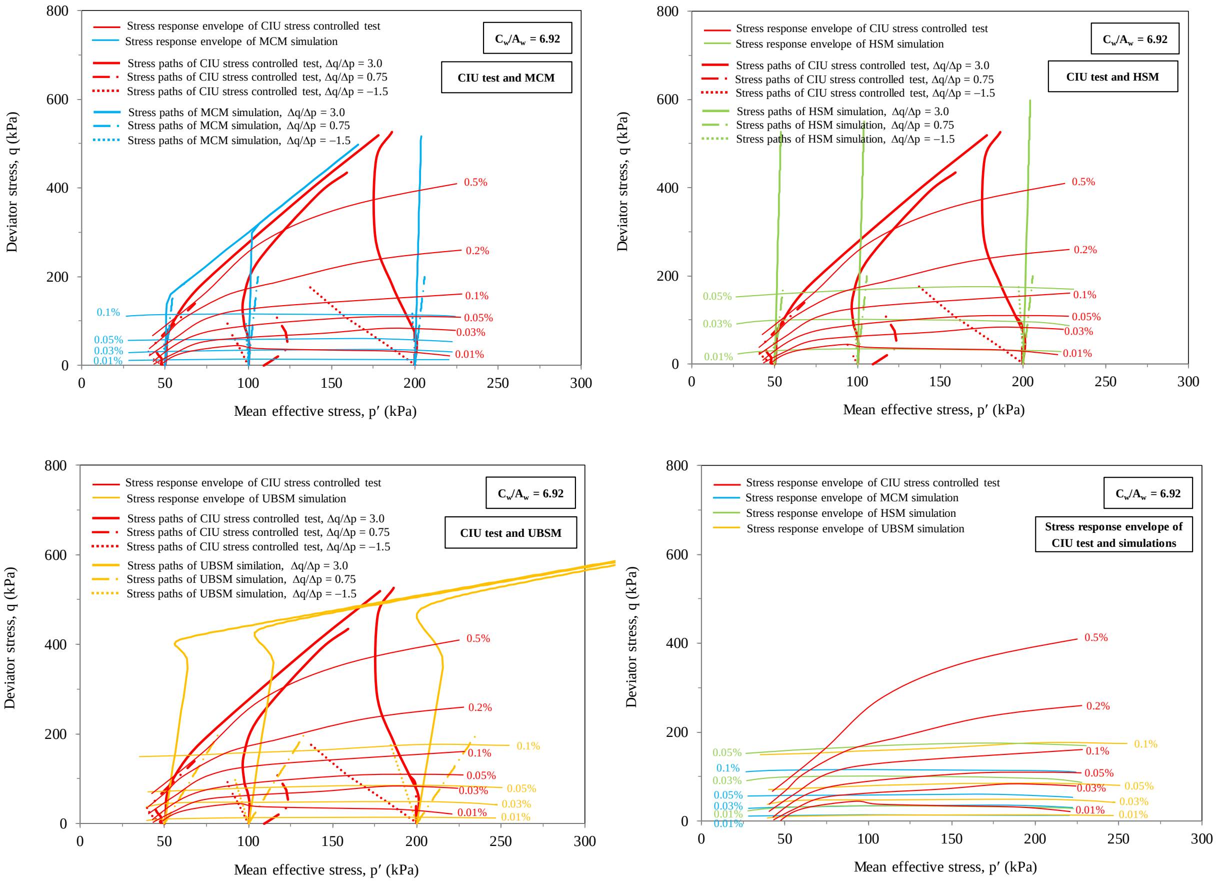


Fig. 5: Stress response envelope of CIU test results and simulation with MCM, HSM and UBSM

The performance of each constitutive model with a different stress path was present by its stress response envelope as shown in Fig. 5. The stress response envelope is the response of stress by certain magnitude of strain [4][9]. The higher stress level of the model showed the higher stiffness. The model performance is compared with the test results obtained from the triaxial stress path of CA by Makararotrit et al. [15]. The stiffness of CA predicted by MCM is higher than that of test results when mean stress was lower than 70 kPa for considering strain level at 0.1%. The predicted stiffness at high mean was overall higher than the test results. The performance of UBSM was higher than HSM. Overall, predicted stiffness overestimated test results when having low mean stress or compression unloading stress condition. The effective constitutive model for CA is required to predict for overall stress state and stress path. The model parameters of each model were based on back calculation or curve fitting the results. The bias of the parameters might occur. Systematic optimization by using particle swarm [5] optimization or genetic algorithm [14] might be required to reduce the error of the prediction.

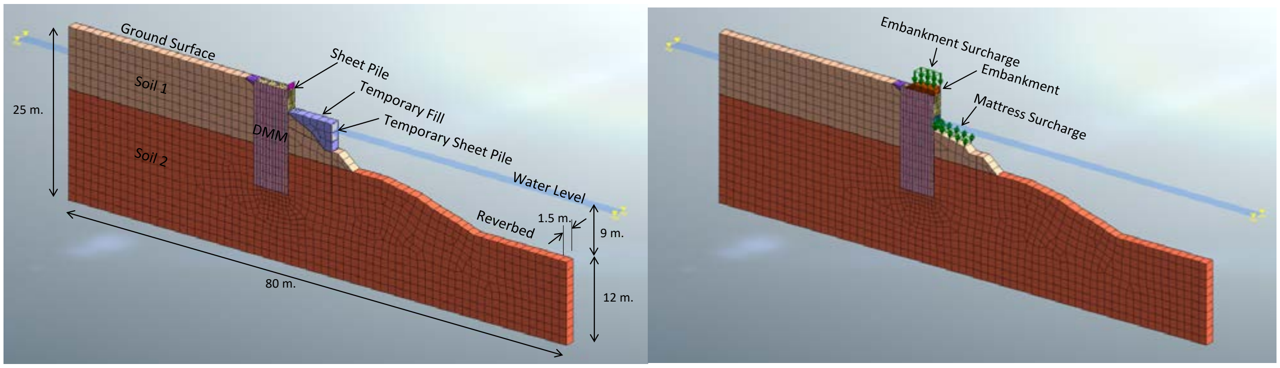
4. Finite element simulation

The behaviors of DMM river wall were simulated with 3-dimensional finite element analysis. The program Midas GTS NX was used for simulation. We simplified the 1.5 meters width of wall for analysis. The finite mesh for this study is shown in Fig. 6. The element type of the analysis was 20 node hexahedrons [6]. Mesh of an analysis composed of 11,059 elements and 58,518 nodes. The boundary condition was set to be fixed at the bottom of mesh and having a vertical degree of freedom at every side of the mesh. The effect of boundary condition was checked by enlarge mesh size to have no effect on the analysis result. The water level was set to be constant during the time of construction and monitoring. The water level at the site was not changed due to the water management of a dam on the water upstream. The river wall simulation was divided into 4 stages that consisted of 1. Initial stage 2. Embankment filling and 20 kPa surcharge on the embankment 3. Temporary filling and temporary sheet pile were removed 4. Dredging and 5. Mattress installation.

Table 2: Constitutive model parameters

Name	Soil 1	Soil 2	Fill	Embankment	Temporary Fill
Description	Stiff clay	Very stiff clay	Compacted clay	Base and subbase	Compacted clay
Material	Isotropic	Isotropic	Isotropic	Isotropic	Isotropic
Model Type	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Property	3D-Solid	3D-Solid	3D-Solid	3D-Solid	3D-Solid
Poisson's Ratio, ν	0.3	0.3	0.3	0.3	0.3
Wet Unit Weight (kN/m^3)	20	21	17	21	17
Drainage Condition	Undrained	Undrained	Undrained	Undrained	Undrained
Effective Cohesion, c (kPa)	35	200	40	20	40
Effective Friction Angle, $\varnothing$ (degree)	5	10	10	36	10
Elastic modulus, E (kPa)	6,000	20,000	9,000	20,000	9,000
Dilatancy Angle, ψ (degree)	0	0	0	0	0
Initial Void Ratio, e_0	0.5	0.5	0.5	0.5	0.5
Lateral Earth Pressure Coefficient, K_0	0.6	0.6	0.6	0.6	0.6

The comparison between finite element analysis and field measurement of wall movement is shown in Fig. 8. The wall was moved to the river direction due to unloading by dredging. The largest movement occurred about 80 mm at the top of the wall. The lateral movement decreased with depth and no movement 15 meters from the ground surface. The MCM showed the best performance to predict the lateral wall movement. The prediction obtained from HSM and UBSM underpredicted the wall movement from 0 to 7 from the ground surface. The wall prediction results performance could be explained by the stress response envelop in Fig. 5. The performance of constitutive model to predict triaxial test results is good with high confining stress ($p > 70$ kPa). The results conform to the finite element prediction that the forecast was agreed with monitoring results when mean stress was more than 70 kPa or depth being more than 6 m. The stiffness of the MCM model was the lowest one and lower than that of UBSM and HSM.



a) Initial stage

b) Final stage

Fig. 6: 3-dimensional finite element mesh

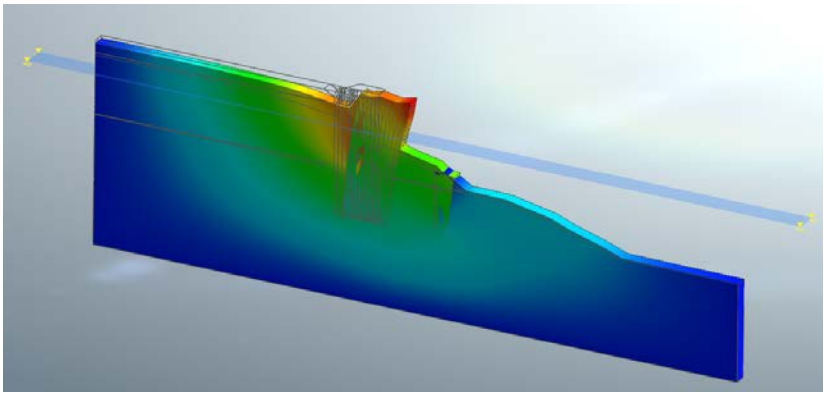


Fig. 7: Deformation of river wall from finite element analysis

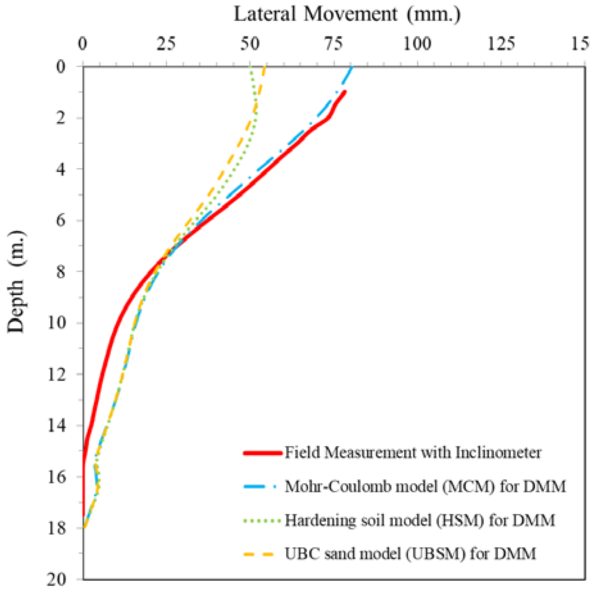


Fig. 8: Comparison between field monitoring and finite element simulation

5. Conclusion

The behaviours of river wall improved with cement admixed clay as well as finite element simulation was presents. The conclusion can be made as follow:

1. MCM dementated the best performance to capture the stress-strain relationship of CA from the triaxial test compared to UBCM and HSM. UBSM and HSM overpredicted the pore water pressure from triaxial tests.
2. According to the response envelope, the predicted stiffness tends to overestimate the test results. MCM showed the best performance among UBSM and HSM.
3. A three-dimensional finite analysis was successfully used to predict the river wall movement. The prediction underestimated the field measurement with low mean stress.
4. The best constitutive model for DMM in finite element analysis was MCM. When using HSM and UBCM for CA, the result of finite element underpredicted the field measure.

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