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THE IMPACT OF SOIL CONSTITUTIVE MODEL SELECTION ON GROUND SURFACE SETTLEMENT ANALYSIS

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ABSTRACT: Choosing the appropriate constitutive model to analyze the ground surface settlement is essential. This study aims to predict ground surface settlement depending on groundwater level change in Bangkok, Thailand, by comparing two constitutive soil models. These are the Mohr-Coulomb model (MCM) and the Hardening Soil model (HSM). Simulations were conducted using PLAXIS 3D Version 2024 2.0 to analyze ground surface settlement trends. The results indicate that both constitutive models show a similar settlement trend during groundwater drawdown. During groundwater recovery and stable, HSM shows good agreement with measured data, which continues to settle with time. The ground surface settlement by HSM is 0.2 mm/yr. While MCM shows a rebound of ground surface elevation by the ground surface settlement rate is 0.05 mm/yr. Therefore, HSM can capture the ground surface settlement behavior of soil soil during groundwater fluctuation, which requires advanced parameters to analyze. MCM is suitable for preliminary analysis of simple issues or models that require only simple parameters and take less time to analyze.

Keywords: Hardening Soil model, Mohr-Coulomb model, Surface settlement, Groundwater level

1. INTRODUCTION

Ground surface settlement is a critical issue in many regions, such as Shanghai in China [1], Tokyo in Japan [2], and Bangkok in Thailand [3]. Because the cities were located on soft soil deposits. It is a primary factor of ground surface settlement. The other factors from natural disasters (e.g., earthquakes or storms) and human activities (e.g., construction loading, live loads, or overgroundwater pumping) contribute significantly to ground surface settlement. This led to many problems, including structural instability, building cracks, and differential bridge settlements.

Thailand, Bangkok, and urban areas are located on the Chao Phraya River Basin. This basin occurred from soil deposited between clay and sand over a long time. Due to this area being the capital of Thailand and an industrial area, the use of irrigation has rapidly increased. It tends to the ground surface settlement because people use water from groundwater pumped from the aquifer layer. Groundwater was pumped from many aquifer layers by the investigation of the Department of Groundwater Resources (DGR). The aquifer systems using Well Logging Techniques and Driller’s logs [4]. This investigation found eight major aquifers below the ground surface, such as the Bangkok Aquifer, the Phra Pradaeng Aquifer, the Nakhon Luang Aquifer, the Nonthaburi Aquifer, the Samkohk Aquifer, the Phata Thai Aquifer, the Thonburi Aquifer, and the Pak Nam Aquifer.

The groundwater levels of Bangkok and urban areas have been recorded since 1978. The data also reported that the groundwater level directly relates to water usage. Most groundwater levels decreased due to groundwater pumping. The DGR clarifies that ground surface settlement relates to the groundwater level. After that, the groundwater level was controlled. It affected the groundwater level recovery from 1997, as shown in Fig.1. Changing the groundwater levels has a recovery trend, especially in the zones of Bang Kapi and Min Buri. To follow the changing groundwater level, Fig.2 shows that the groundwater level of the Min Buri zone is quite stable after year of 2012. Groundwater level of the Phra Pradaeng aquifer is approximately 25 meters below the ground surface. Moreover, other provinces around Bangkok also have fluctuations in groundwater level. Groundwater level changing rate represents the details in Table 1. Data from the site investigation showed that Bangkok and urban areas have a small change in groundwater level in the range of 2018 to 2022.

According to the groundwater level situation from the past until the present, the groundwater level changed due to groundwater pumping, which is the main cause of land subsidence in Bangkok. Following the recorded data, the zoning of Hua Mak, the ground surface settlement increases by 10 cm/yr. while the groundwater decreased from 1978 to 1985. The ground surface settlement decreased to 1.3 cm/yr. in 2005, after using controlled groundwater pumping in 1997. The zoning of Min Buri was invested in the ground surface settlement increased about 3.4 cm/yr.

while the groundwater decreases to 0.65 cm/yr. from 1998 to 1999. Overall, DGR reported that the ground surface settlement has a decreasing trend due to groundwater pumping. After 1997, many zones revealed that groundwater level recovery was due to the law of controlled groundwater. It affected the groundwater recovery. The DGR report published that Bangkok and provinces around Bangkok have the ground surface settlement of about 1-2 cm/yr. from 2006 to 2012, after that, less than 1 cm/yr. from 2012 to 2018. The period from 2018 to 2019 found that the ground surface settlement had two behaviors. Some areas continued to settle at a rate of 0-1 cm/yr, while others exhibited recovery at a rate of 0-2 cm/yr. Both the ground surface settlement rates are distributed around the central area of Thailand, such as Bangkok, Nonthaburi, Pathumtani, Nakhonpathom, Ayutthaya, Samut Prakan, Samut Sakhon, and Samut Songkhram.

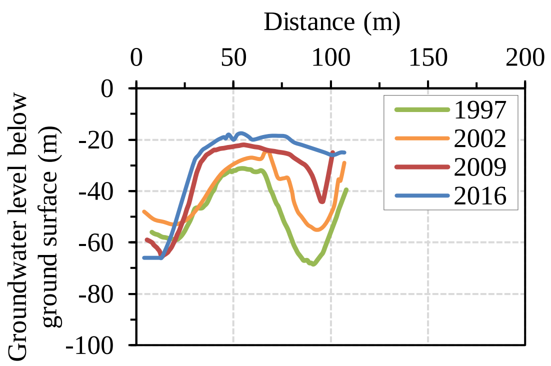

Fig. 1 Characteristic of the groundwater level changes

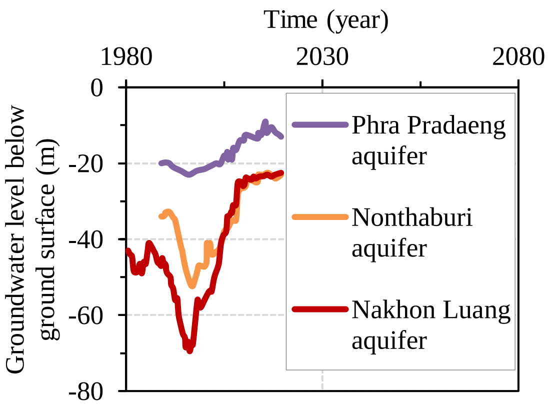

Fig. 2 Groundwater level changes of Min Buri

Therefore, the prediction of ground surface settlement is very important to know. Because it will help people who live in the soft clay area understand and stay safe. However, predicting ground surface settlement is a complex process. The prediction results depend not only on the variability of soil layers, deposited soil characteristics, land use, and soil parameters, but also on choosing the optimal analytical method. Many researchers often use numerical modeling techniques to simulate ground surface settlement. The constitutive models are mentioned with the accuracy results. According to the reliable prediction of the famous constitutive model for excavation and tunneling. The study analyzed tunneling-induced deformations and compared results from the Mohr-Coulomb Model (MCM), Hardening Soil Model (HSM), and Hardening Soil Small-Strain Model (HSSM) with measured data. The results indicated that HSM closely matched observed settlements, while MCM overestimated soil stiffness and led to unrealistic uplift predictions of retaining walls. As a result, previous studies have advised against using the MCM for soft clay soils due to its limitations in accurately capturing soil behavior [5]. Other previous research also analyzes the ground surface settlement by using the PLAXIS 3D by using the HSM for stiff clay. The results showed that the ground surface settlement was related to the field observation and also related to the ground surface settlement result of the centrifuge test [6,7]. On the other hand, many software programs were used to predict the ground surface settlement for the Bangkok area, such as the ABAQUS program. The researcher analyzed the ground surface settlement by considering the Modified Cam Clay (MCC). This is an advanced constitutive model because the analysis must consider the unsaturated soil parameters, such as the lambda (λ), and Kappa (κ). The associated input parameters of MCC required more than the MCM and HSM. The ground surface settlement results by MCC represented that the little ground surface rebound [8].

Table 1. Groundwater level in Bangkok and urban Thailand

Province /GWL.	2018	2022	Groundwater level rate (m/yr)
Bangkok	13.5	13.3	+0.04
Nakornpathom	15.9	16.6	-0.14
Pathum Thani	8	7.5	+0.1
Ayutthaya	6.7	6.2	-0.1
Ayutthaya (NakornLuang)	13.4	16	-0.52
Samut Prakan	14.6	14.7	-0.02

However, despite its limitations, the MCM remains widely used due to its simplicity and minimal input parameter requirements. Associated input parameters are easy to find because they are the general soil properties.

Therefore, this study focuses on comparing the MCM and HSM to analyze and predict the ground surface settlement during groundwater level changes in Bangkok, Thailand. The study uses the PLAXIS 3D Version 2024 2.0 and compares the results with the field observations. The results are presented and discussed the appropriate constitutive model for the prediction of the ground surface settlement. And, also recommend between the MCM and HSM.

2. RESEARCH SIGNIFICANCE

The assessment of ground settlement can be performed using hand calculations or a

A Finite Element Analysis program, such as PLAXIS. However, simplified methods may produce inaccurate results in complex soil conditions influenced by groundwater fluctuations. This study compares ground settlement predictions using the MCM and the HSM to evaluate their suitability for ground surface prediction of Bangkok clay under varying groundwater levels. The results highlight the limitations of each model and identify key parameters affecting settlement behavior, enabling engineers to select appropriate models for more accurate predictions consistent with field observations.

3. CONSTITUTIVE MODELS

The Finite Element Method (FEM) is widely used in geotechnical engineering for analyzing and predicting soil behavior. Selecting an appropriate constitutive model is crucial. Figure 3 presents the material behavior of 5 constitutive models, such as the Mohr-Coulomb model (MCM), Modified Cam Clay model (MCCM), Cap model, Hardening Soil model (HSM), and Hardening Small Strain model (HSSM). The MCM represents the linear elastic perfectly plastic behavior. It is a different model from the other models, which have the non-linear behavior derived from the hyperbolic model. In truth, the soil characteristic has a non-linear behavior because the stress is still increasing, which is related to the increasing strain.

Even though the MCM has a linear elastic perfectly plastic behavior, it is widely used due to its simplicity to study the general behavior of soil. It requires only five input parameters: two elastic parameters, Young's modulus (E) and Poisson's ratio (ν), and three plastic parameters, friction angle (ϕ), cohesion value (c), and dilatancy value (ψ). These parameters can be readily obtained from field tests, laboratory tests (e.g., basic soil properties test, oedometer test, triaxial test), and correlation values from the previous research.

Another well-known constitutive model is the HSM, which was developed in 1999 [9,10]. The model is derived from the hyperbolic model. It can adapt to analyze all types of soil. The model is quite complex because this is a non-linear model. The associated parameters consist of two terms. In terms of the resistance parameters, there are the friction angle (ϕ), the cohesion value (c), and the dilatancy value (ψ). In terms of the soil stiffness parameters, the stiffness of the secant modulus at 50% stress (E_{50}), the oedometer modulus from the slope of the stress-strain curve of the oedometer test (E_{oed}), and the unloading-reloading modulus (E_{ur}) [11].

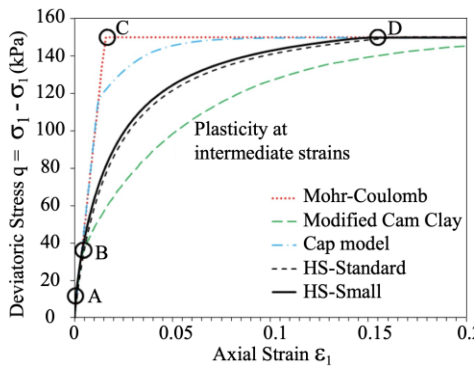

Fig. 3 Comparison of the soil behavior in each model

4. SITED DESCRIPTION

Due to the central Bangkok area has many monitoring stations for investigating the ground surface settlement. Two boreholes are located at Kasetsart University and the Finance School, as shown in Fig.4. The settlement measured data is used to verify with analysis results.

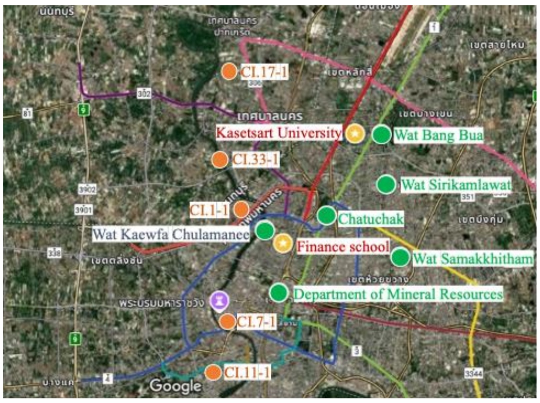

Fig. 4 Location of the Bored holes and GWL. Stations

Moreover, this study has obtained groundwater level data from 6 stations consist of Chatuchak Station (CTC), Wat Bang Bua Station (WBB), Wat Sirikamlawat Station (WSRKMLW), Wat Samakkhitham Station (WSMKT), the Department of Mineral Resources Station (DMR), and Wat Kaewfa Chulamanee Station (WKCLMN). The location of observation stations is shown in Fig.4. Figure 5 shows the trends of groundwater level fluctuation between 1986 and 2023 across all stations in the Phra Pradaeng Aquifer. It found that the groundwater level trend has three characteristics. First, groundwater drawdown occurred between 1986 and 1997 due to excessive groundwater pumping. Second, the groundwater level recovered continuously at all stations after pumping was prohibited. Finally, the groundwater level remained stable until 2023. The characteristics of groundwater are also presented in Table 2 [12].

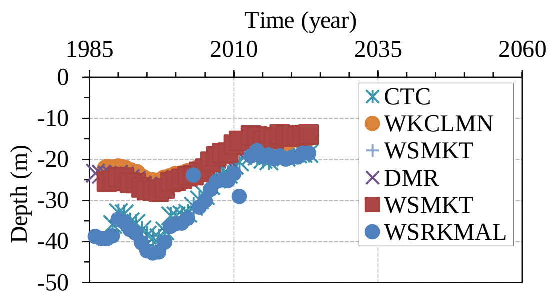

Fig. 5 Groundwater level change in the study area

Table 2. Groundwater level changes in each location

Location	Min. GWL. (m)	GWL.		Rate of GWL. (m/yr)
		2556	2566	
CTC	39.58	18.57	19.3	0.073
WBB	28.45	12.87	12.76	-0.011
WSRKMLW	43.22	19.24	18.62	-0.062
WSMKT	27.9	14.47	14	-0.047
DMR	27.1	-	-	-
WKCLMN	25.99	14.77	14.44	-0.033

5. METHOD STATEMENT

Ground surface settlement depends on various factors, including soil characteristics, time, and external influences such as land use history and live loads. The ground surface settlement typically occurs in clay due to the presence of water and air between soil particles. When overburden pressure increases from additional external loads on the ground surface, even the self-weight of soil, water, and air is expelled from the soil, called the "Consolidation process". Terzaghi's theory separates the consolidation settlement into three stages such as the immediate settlement, the primary consolidation settlement, and the secondary consolidation settlement (Creep) [13]. Soil consolidation is described based on Terzaghi's theory [13]. Equation (1) represents the soil parameters that affect the ground surface settlement, such as the past and present effective stress, overburden pressure, and especially pore water pressure in the soil. The pore water pressure is in terms of an effective stress, as in Eq. (2). Changes in groundwater levels directly impact the pore water pressure characteristic of soil. Equation (1) is one part of the consolidation stage called primary consolidation settlement. This is a significant settlement stage because most of the soft soil settlement occurs during this stage, which takes a very long time. Although Terzaghi's theory provides a fundamental framework, the actual settlement behavior is complex and influenced by factors such as external load, soil characteristics, and stress-strain development. Hence, researchers apply the Finite Element Method (FEM) to estimate the complex ground surface settlement issues. PLAXIS 3D is conducted to analyze the ground surface settlement of Bangkok during groundwater fluctuation. This software offers significant benefits for this research. This study contains multiple boreholes and observation data, which PLAXIS 2D is unable to analyze according to these conditions. The model condition for this study is not a plane strain or axisymmetric condition as in PLAXIS 2D. PLAXIS3D can capture complex geometry, data, and allow pore pressure change due to groundwater fluctuation in 3D conditions. However, accurate predictions depend on selecting an appropriate constitutive model, input data, and consolidation time increment [11]. This study will compare the MC and HSMs to determine the most reliable ground surface settlement prediction method for the soft Bangkok clay during groundwater fluctuation.

$$S_c = \frac{C_s H}{1+e_0} log \frac{\sigma'_c}{\sigma'_o} + \frac{C_c H}{1+e_0} \log \left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_c}\right) \quad (1)$$

$$\sigma = \sigma' + \Delta U \quad (2)$$

This study aims to predict ground surface settlement in the central Bangkok area. The soil properties depend on the type of soil deposit and the thickness of the soft clay layer. The study area focuses on six groundwater level monitoring stations and two Boreholes to create the soil profile in FEM software. The two Boreholes are located near the groundwater level monitoring stations. Therefore, this study adopts soil data from Kasetsart University and the Finance School boreholes, provided by the Department of Public Works and the Town & Country Planning [14].

Each soil Boring log is interpreted to be the soil profile for creating the 3D model in the PLAXIS 3D Version 2024 2.0, as shown in Fig.6. The dimension of the 3D model is 70x70x70 m. The soil layers consist of soft clay, dense sand, and stiff clay, respectively. The soil parameters of each soil layer are input following the constitutive soil model of the MCM and the HSM. Both models have the same general parameters, such as the saturation unit weight, unsaturation unit weight, cohesion value, friction angle, and dilatancy value, as shown in Tables 3 and 4. Each basic parameter is calibrated from Kasetsart University and the Finance School boring logs. HSM require more associated input parameters, Young's modulus (E), the soil stiffness parameters, the stiffness of the secant modulus at 50% stress (E_{50}), the oedometer modulus from the slope of the stress-strain curve of the oedometer test (E_{oed}), and the unloading-reloading modulus (E_{ur}), Poisson's ratio (ν) are obtained from the previous research, which have a site nearby this study area [15]. All parameters are calculated from the basic soil properties testing, the oedometer test, and the triaxial test. Permeability values in each axis are assumed to be the same value by using the classification type is User-defined by Van Genuchten. For Bangkok clay, the permeability values are in the same range, which is equal to $8.64x10^{-3}$ m/day in this study. The OCR values are only required in the HSM, while MCM sets the OCR equal to 1 at the beginning. The soil properties of soft Bangkok clay at the Suvarnabhumi airport site. The OCR values are equal to 7 at the surface and decrease to 1 at 4 m depth. An average OCR of soil deeper than 4 m is about 1 [16]. Moreover, the soil properties of Bangkok clay at MRT Sutthisan station. The OCR value is 2.7 at 3.5 m depth, and deeper than 4.5 m till 13.7 m. is 1.1-1.6 (average about 1.29). The soil properties data of the Chao Phraya River Basin. The OCR of the central Chao Phraya River basin is about 1.874 for soft clay, 1.517 for medium stiff clay, 1.2 for stiff clay, and 0.718 for very stiff clay [17]. Therefore, this study prefers to define the OCR values equal to 1.874 for soft clay and 1.517 for stiff clay. Both values also relate to the soil properties of the soil boring log of this study. After that, the groundwater level is defined to determine the groundwater level change in the model. According to Biot's theory of consolidation, the model considers using fully coupled deformation analysis. It is implemented to calculate deformation and groundwater flow with time-dependent boundary conditions in partially saturated and saturated soils [18].

According to the recorded data, this study separates the analysis to be three stages, which relate to the groundwater changing periods. The first stage is the groundwater drawdown that occurred from 1989 until the minimum groundwater level in 1997. The water level begins to flow at -22 m to -28 m below the ground surface. The second stage, the groundwater levels recovered continuously from 1997 until 2013. Then, the water level increases to at -10 m below the ground surface. During 2013 to 2023, the groundwater level is stable at -10 m. Hence, the groundwater level in the last stage also remains stable at -10 m until 2043. The PLAXIS 3D model mesh resolution is medium. Then, create and analyze the model related to time. The stage of construction determines the groundwater level fluctuation period and the consolidation steps. Model convergence is checked after the calculation, and all phases are in green color or convergence.

Table 3. Input parameters in the MCM

Parameters/Type	Soft clay	Stiff clay
γ_{sat} (kN/m^3)	13	15
γ_{unsat} (kN/m^3)	19	20
E (kN/m^2)	800	9500
ν	0.2	0.2
C'_{ref} (kN/m^2)	1	32.8
Φ' (degree)	23.6	26.3

Table 4. Input parameters in the HSM

Parameters/Type	Soft clay	Stiff clay
γ_{sat} (kN/m^3)	13	15
γ_{unsat} (kN/m^3)	19	20
E_{50}^{ref} (kN/m^2)	800	9500
E_{oed}^{ref} (kN/m^2)	850	12000
E_{ur}^{ref} (kN/m^2)	8000	30000
ν	0.2	0.2
C'_{ref} (kN/m^2)	1	32.8
Φ' (degree)	23.6	26.30
ψ (degree)	0	0
k_x, k_x, k_x (m/day)	$8.64x10^{-3}$	$8.64x10^{-3}$
OCR	1.874	1.517

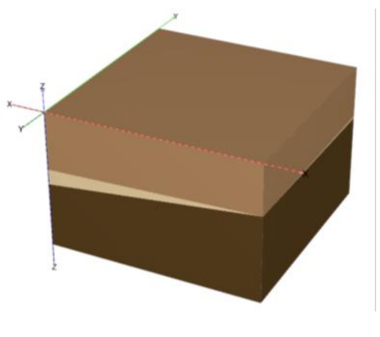

Fig.6 3D model of FEM

6. RESULTS AND DISCUSSION

The ground surface settlement results during groundwater fluctuation using the MCM and the HSM are compared and align with monitoring results in the field. The soil strength is an important factor to explain settlement behavior during groundwater level fluctuation in each period since the groundwater decreases, rises up and stable. Figures 7-8 reveal the pore water pressure changes in each stage from MCM and HSM, respectively. The pore water pressure at the beginning period from MCM is higher than HSM at the same groundwater level. This is different affected by the associated input parameters and constitutive soil model. The HSM required the specific soil parameters, which are the soil modulus and OCR. The soft and stiff Bangkok clay have OCR values more than 1, while the OCR value in MCM is set as default equal to 1. The pore water pressure is one of the key factors in terms of vertical effective stress. According to decreasing and increasing of groundwater level, vertical effective stress also increases and decreases, respectively. The vertical effective stress from HSM is higher than MCM, as shown in Fig.9. Figures 10-12 also reconfirm that the vertical effective stress values from HSM are more than MCM in every stage, even when groundwater is stable in the last stage. Additionally, the OCR values from MCM and HSM increase in the first stage due to most of the settlements occurring at this stage, as shown in Figs.13-14. The OCR values of both models have the same trend. In the stiff clay, the OCR values are quite stable even during groundwater fluctuation because the ground surface settlement in stiff clay is smaller than soft clay above. In the soft clay, the OCR values increase greatly near the ground surface and gradually decrease with depth until the bottom of the soft clay. The overall OCR values from HSM are higher than MCM because required input parameter of HSM. MCM is a simplified soil model that has constant stiffness and no memory of past pressure. The OCR values from MCM cannot represent the behavior of the soil. HSM has stress-dependent stiffness, the hardening behavior, and automatically tracks the past pressure. OCR values from HSM are more realistic than MCM.

The key factors of ground surface settlement analysis are the pore water pressure, the vertical effective stress, and OCR. The ground surface settlement results from MCM give the ground surface settlement rate in stages of the groundwater drawdown, groundwater recovery, and stable groundwater level are equal to 0.80, -0.05, and -0.005 cm/yr, respectively. The overall trend of the MCM has a rebound in the prediction period. The MCM trend is opposite to the HSM trend, as shown in Fig.15. The HSM represents the ground surface settlement trend in each stage equal to 0.85, -0.01, and 0.02 cm/yr, respectively. Both models analyze high settlement rates during groundwater drawdown, but long-term behavior is different. Moreover, both results are compared with the measurement data as shown in Fig.15 and Table 5 [16]. Following the measurement at the site, the HSM has a similar trend, but settlement values are different because each site has a variation in the groundwater level, external load or vertical stress, and soil properties etc. In the Hardening Soil Model (HSM), settlement continues to occur over time at a very small rate, reflecting ongoing consolidation and plastic deformation processes. In contrast, the Mohr-Coulomb Model (MCM) predicts a slight rebound of the ground surface, indicating an elastic unloading behavior with minimal residual settlement. The settlement analysis results from HSM are more accurate and realistic than MCM due to stress-dependent stiffness, hardening behavior, and automatically track the past pressure change with time.

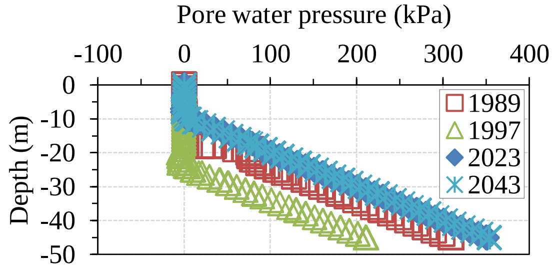

Fig. 7 Pore water pressure of the MC

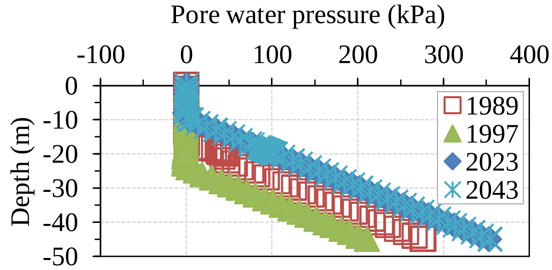

Fig. 8 Pore water pressure of the HSM

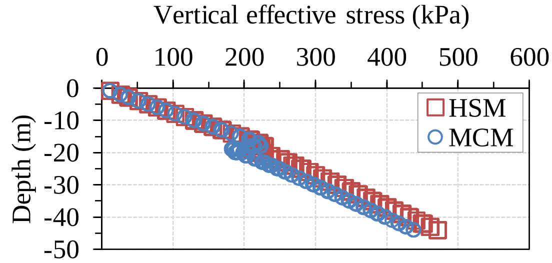

Fig. 9 Vertical effective stress in 1989

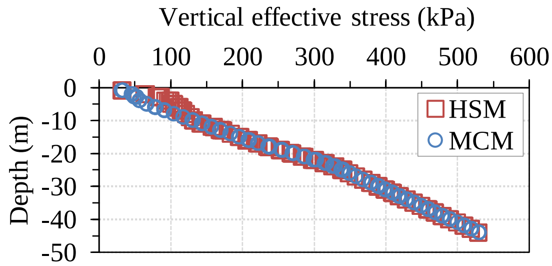

Fig. 10 Vertical effective stress in 1997

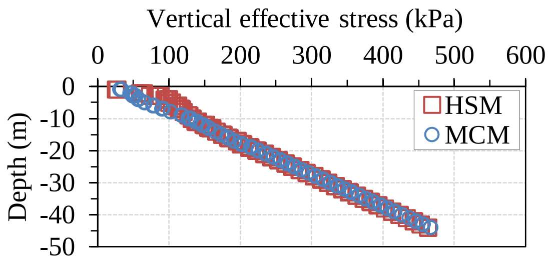

Fig. 11 Vertical effective stress in 2023

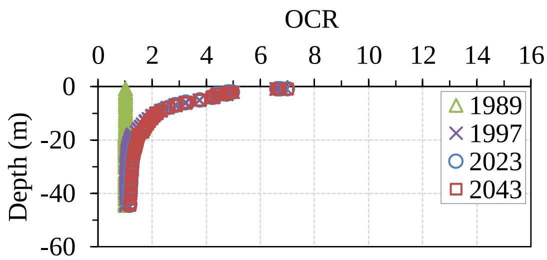

Fig. 13 OCR changing by using MCM

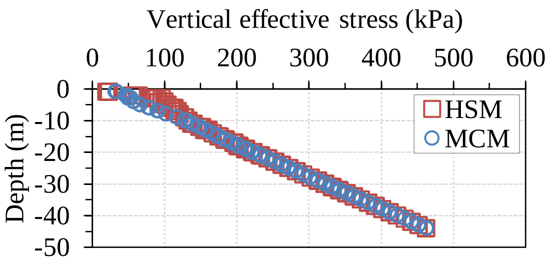

Fig. 12 Vertical effective stress in 2043

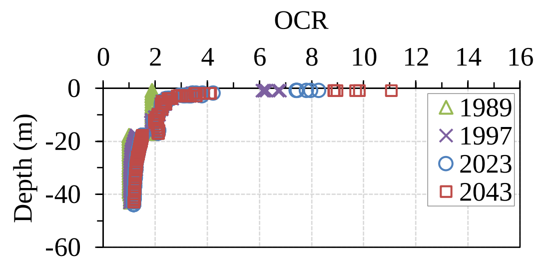

Fig. 14 OCR changing by using HSM

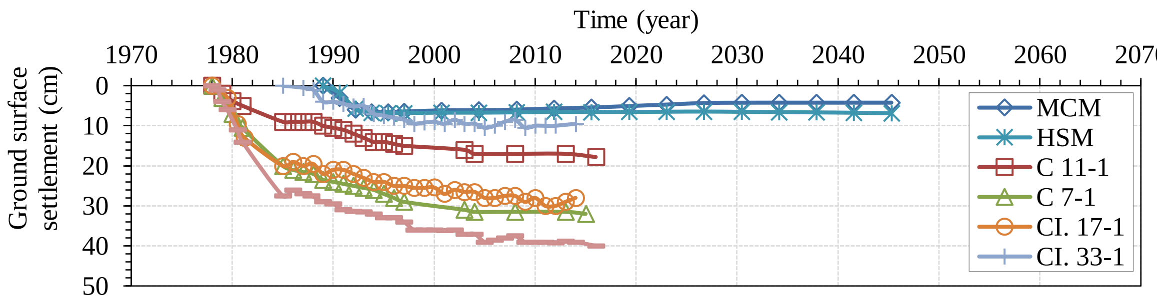

Fig. 15 Comparison of ground surface settlement

Table 5. Comparison of ground surface settlement

Description/GWL changing	Ground surface settlement (cm/yr)		
	Drawdown	Recovery	Prediction
CI. 7-1	1.53	0.17	-
CI. 11-1	0.79	0.15	-
CI. 34-1	0.84	0.05	-
CI. 17-1	1.32	0.18	-
CI. 33-1	0.71	0.06	-
CI. 1-1	1.79	0.32	-
MCM	0.80	-0.05	-0.005
HSM	0.85	-0.01	0.02

7. CONCLUSION

The selection of the constitutive model significantly influences the accuracy of settlement analysis, especially for soft clay during groundwater level fluctuation. MCM has simple bi-linear behavior and constant elastic parameters, which are only suitable for the basic behavior of soil. MCM is not concerned about stress history (OCR), plastic hardening, and changes in pre-consolidation pressures lead to inaccurate settlement analysis for complex model conditions such as groundwater fluctuation. Hence, MCM reveals the unrealistic behavior, such as ground surface rebound during groundwater level recovery. Whereas HSM can simulate realistic behavior. HSM considers hardening mechanisms and stress history, which allows HSM to simulate continuous settlement during groundwater drawdown and recovery. Not only the settlement simulation, but HSM can capture hardening or stiffened response during groundwater fluctuation with time.

The settlement results obtained from HSM show the same trend with measured data in groundwater drawdown, rebound, and stable conditions. The settlement results from MCM also have the same trend during groundwater drawdown. However, during groundwater recovery and stable conditions, MCM shows rebound behavior, which is contrary to both HSM and measured data. However, the ground surface settlement results analysis is different from the measured data because the groundwater level at each monitoring station varies and may have additional external loads. Therefore, both MCM and HSM can be adopted to analyze the settlement of soft soil, depending on the requirement of accuracy and complexity of the model. HSM can simulate more accurately long-term settlement of soft soil during groundwater fluctuation. However, MCM can be used as a preliminary settlement assessment for a simple model that requires fewer parameters than HSM.

However, for further prediction of the ground surface settlement, other phenomena may impact ground surface settlement, such as flooding, seismic events, depending on the site requirement. Sensitivity analysis of key parameters should also be performed for each phenomenon.

8. ACKNOWLEDGMENTS

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