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NUMERICAL ANALYSIS OF SOIL SETTLEMENT PREDICTION AND ITS APPLICATION IN LARGE-SCALE MARINE RECLAMATION ARTIFICIAL ISLAND PROJECT

Jie Zhao*
Lingyun Bao
Guixuan Wang
Civil Engineering Technology Research and Development Center, Dalian University, China
* corresponding author

ABSTRACT

In an artificial island construction project based on the large-scale marine reclamation land, the soil settlement is a key to affect the late safe operation of the whole field. To analyze the factors of the soil settlement in a marine reclamation project, the SEM method in the soil micro-structural analysis method is used to test and study six soil samples such as the representative silt, mucky silty clay, silty clay and clay in the area. The structural characteristics that affect the soil settlement are obtained by observing the SEM charts at different depths. By combining numerical calculation method of Terzaghi's one-dimensional and Biot's two-dimensional consolidation theory, the one-dimensional and two-dimensional creep models are established and the numerical calculation results of two consolidation theories are compared in order to predict the maximum settlement of the soils 100 years after completion. The analysis results indicate that the micro-structural characteristics are the essential factor to affect the settlement in this area. Based on numerical analysis of one-dimensional and two-dimensional settlement, the settlement law and trend obtained by two numerical analysis method is similar. The analysis of this paper can provide reference and guidance to the project related to the marine reclamation land.

Keywords: Microstructure; Consolidation; Creep; Artificial island; Settlement

INTRODUCTION

With rapid economic development in the coastal areas, the demand for land resources is increasing. To alleviate this problem, the marine land reclamation has gradually become one of the main measures to fully utilize the ocean resources and ensure economic development. The structural distortion, strength change and soil settlement of the soil structure under the comprehensive environment and load become a main focus of the rock engineering field [1-2].

In the 1920s, Terzaghi, a predecessor of soil mechanics, pointed out that the microstructure should be considered when evaluating the geological property of the clay soil and rock work. This started a new research field in the soil microstructure [3]. The academician Shen Zhujiang pointed out that the structural research of soils is a frontier subject in today's research on soil mechanics and the key issue of the soil mechanics in the 21st century is to develop and establish the soil structure model and corresponding analysis theory [4]. Bai and Smart [5] defined a set of directional indicators, which studied the orientation of clay particles in the process of consolidated-undrained shear according to the analysis of the electron microscope photos. Kong Lingwei and others [6-9] conducted experimental research on soils in different marine areas, analyzed the micromechanism of its special work property from the mineral composition to gap structure, and deepened understanding of the basic property of the ocean soil. The microstructure of sand was studied with the guide of fractal theory. Based on the analysis of the microstructure of the sandy soil, Moore C.A and Donaldson C.F [10] concluded that the particle shape of sandy soil has fractal characteristics, which indicates that the quantitative study of soil microstructure has entered a new stage.

Domestic and foreign scholars have conducted plentiful research on the soil settlement of the ocean work [11-13]. At Bay Farm Island in San Francisco Bay and Kansai International Airport in Japan, accurate predictions of settlement magnitudes require accurate evaluations of clay compressibility and preconsolidation pressure. Duncan, J developed an improved model of clay compressibility that includes the effects of strain rate [14]. Cheng Xiang and Tongling Zhou [15, 16] studied consolidation settlement of the bank protection structure of the artificial island by using the creep model for numerical simulation, analyzed sensitivity of key parameters, and summarized the response law of the settlement results. Mamoru Mimura [17] studied consolidation settlement of the No .1 runway of the Guangxi International Airport. The actual monitoring values are roughly consistent with the finite numerical calculation results of consolidation settlement after completion. Mesri,G[18] analyzed the soil consolidation settlement of the Guangxi International Airport in Japan. Zhao Jie [19] measured the settlement law by using the dual-frequency GPS and high-precision level gage, based on Terzaghi one-dimensional and Biot two-dimensional consolidation theory.

This paper studies the soil settlement of the large-scale marine reclamation artificial island project based on the above mentioned research work. Terzaghi's one-dimensional and Biot's two-dimensional consolidation theories are used in numerical calculation. The parameters in the engineering report can meet the calculation, whose result is accurate and costing less time. This is a widely used calculation method in actual engineering both domestically and abroad. The SEM method is used for microstructure analysis. With macro numerical calculation and microstructure analysis, the settlement influence law of the whole artificial island is analyzed, so it can provide reference to the design of similar marine reclamation projects.

BASIC PRINCIPLE

SCANNING ELECTRON MICROSCOPE (SEM)

Now this method is one of the most popular methods to study the soil microstructure, which features deep visual field, high zoom time and direct research on sample surface. The SEM scans the surface of treated samples with a focused beam of electrons and generates various signals. These signals will change with fluctuation of the surface form of samples. After these signals are detected, zoomed out and processed, they will be transferred to the display system and produce the scanning electronic image of the analyzed area of the samples.

PRINCIPLE OF ONE-DIMENSIONAL CONSOLIDATION SETTLEMENT ANALYSIS

The foundation consolidation settlement includes instantaneous settlement, main consolidation settlement and secondary consolidation settlement. The main consolidation settlement of the foundation is computed by using e-p curve method based on hierarchical summation method [20]. The calculation equation under the load is described as follows:

$$S_c = \sum_{i=1}^{n} \frac{e_{0i} - e_{1i}}{1 + e_{0i}} \Delta h_i \quad (1)$$

In this equation, S_c is the main consolidation settlement, m and n are the layer number of the foundation in foundation settlement; e_{0i} is the stable void ratio at the middle point of ith layer under action of the self-weight stress when the next-level load is not imposed; e_{1i} is the stable void ratio at the middle point of ith layer under action of the self-weight stress and additional stress when the load is imposed; Δh_i is the layer thickness m in calculation of ith layer and should be 0.5~1.0m. 0.5m is used in calculation of this work. When the natural stratum boundary occurs in calculation of layer range, it is used as the boundary layer.

PRINCIPLE OF TWO-DIMENSIONAL CONSOLIDATION SETTLEMENT ANALYSIS

The soft soil consolidation creep model (SSC) is mainly used in the numerical simulation of the two-dimensional consolidation settlement to simulate the foundation consolidation settlement and secondary consolidation settlement in the whole area. The SSC is a 3D creep model extended from the one-dimensional creepage model, which is proposed by Neher&Vermeer [21] based on the standard 24h load consolidation test. The main parameters include natural weight γ, saturated weight γsat, horizontal permeability Kh, vertical permeability Kv, cohesion, internal friction angle φ and dilatancy angle ψ.

Buisman first proposes the creep equation under the effective stress:

$$\varepsilon = \varepsilon_c - C_B \log\left[\frac{t_c + t'}{t_c}\right] \quad (2)$$

Later Butterfield proposes a new equation:

$$\varepsilon = \varepsilon_c - C \ln\left[\frac{\tau_c + t'}{\tau_c}\right] \quad (3)$$

In this equation, εc is the total strain when the main consolidation is completed; tc is the completion time of main consolidation; after tc in the equation (2) is replaced with τc in the equation (3), we can get effective creep time t'=t-tc. Based on achievements of other scholars on the creep model, εc can be described as follows:

$$\varepsilon_c = \varepsilon_c^e + \varepsilon_c^c = -A\ln\left[\frac{\sigma'}{\sigma_0'}\right] - B\ln\left[\frac{\sigma_{pc}}{\sigma_{p0}}\right]$$

$$\varepsilon_c = \varepsilon^e + \varepsilon^c = -A\ln\left[\frac{\sigma'}{\sigma_0'}\right] - B\ln\left[\frac{\sigma_{pc}}{\sigma_{p0}}\right] - C\ln\left[\frac{\tau_c + t'}{\tau_c}\right]$$

In this equation, σ_0' is the initial effective stress prior to loading, σ' is the effective stress of the final load; σ_{p0} and σ_{pc} are the pre-pressing consolidation stress and final consolidation stress prior to loading; σp is the pre-pressing consolidation pressure. To compute the derivative for the time and make $\frac{\tau}{\tau_c} = \left[\frac{\sigma'}{\sigma_p}\right]^{\frac{B}{C}}$, the final creep equation is described as follows:

$$\dot{\varepsilon} = \dot{\varepsilon}^e + \dot{\varepsilon}^c = -A\frac{\dot{\sigma}'}{\sigma'} - \frac{C}{\tau}\left[\frac{\sigma'}{\sigma_p}\right]^{\frac{B}{C}}$$

In the formula, $A = \frac{C_r}{(1+e_0)\ln 10}$; $B = \frac{C_c C_r}{(1+e_0)\ln 10}$; $C = \frac{C_\alpha}{(1+e_o)\ln 10}$

WORK OVERVIEW

The total area of the artificial island project based on the marine reclamation land is about 21 km^2 at Linkong Industrial Park, Dalian. This work is 6621.1m long and 3328.3m wide. The stratum is composed of marine facies, marine and land crossing facies and land facies. The coverage layer is 50–80m thick. The settlement layer of marine facies, which includes the silt, mucky silty clay, silty soil and a mixture of silt and sand, is under the fluid plastic and soft plastic state. And in some these areas, there is plenty of fine sand. The settlement layer of marine and land crossing facies, which includes the clay and silty clay, is under the plastic-hard plastic state. The settlement layer of land facies, which includes clay and silty clay, is under the hard plastic state. The bed rock layer mainly consists of strong weathered rock.

OVERVIEW OF THE MICROSTRUCTURE ANALYSIS METHOD

SAMPLE PREPARATION METHOD OF SOIL

The vacuum freezing drying method is used to collect the microstructure samples. This method keeps samples dry without deformation and is widely used by foreign and domestic scholars. It is a very effective sampling technology. The vacuum freezing drying method requires sophisticated devices and complicated operation, but it creates small disturbance to soil samples and better reflects the original state of the soil structure.

SOIL SAMPLE ANALYSIS

The SEM method is used for the microstructure analysis of the soil. SEM of 20kv and 10000 magnification times is used. Representative six soil samples such as silt, mucky silty clay, silty clay under three different depths, and clays are tested and studied at the field (the depth of the soil sample is shown in Table 8). Some SEM photos with different magnification times are used to systematically study the relation between the microstructure features and macro mechanical property of soils in this work. These photos also reflect the essential factors of the microstructure that influence deformation and strength of the soil.

Tab. 1. Depth of soil sample of microstructure analysis

SN	Name of soil sample	Sample depth
1	silt	3.0 m -3.5m
2	mucky silty clay	9.0 m -9.5m
3	silty clay	29.1 m -29.3 m
4	silty clay	33.1 m -33.3 m
5	silty clay	47.1 m -47.3 m
6	clay	17.1 m -17.3 m

CALCULATION PARAMETERS AND MODELS OF ONE-DIMENSIONAL CONSOLIDATION SETTLEMENT

Based on the engineering investigation report of the rock soil, about 500 geological bores are deployed at the whole field (details are shown in Figure 1). One-dimensional settlement analysis model is established based on the bore column charts in the investigation report. (For the calculation model, refer to the Figure 2.) Based on the plane distribution diagram of the load at the field, the obtained one-dimensional numerical analysis model of the soil can accurately reflect the soil settlement distribution at different positions of the field, so the settlement law of the whole field can be obtained.

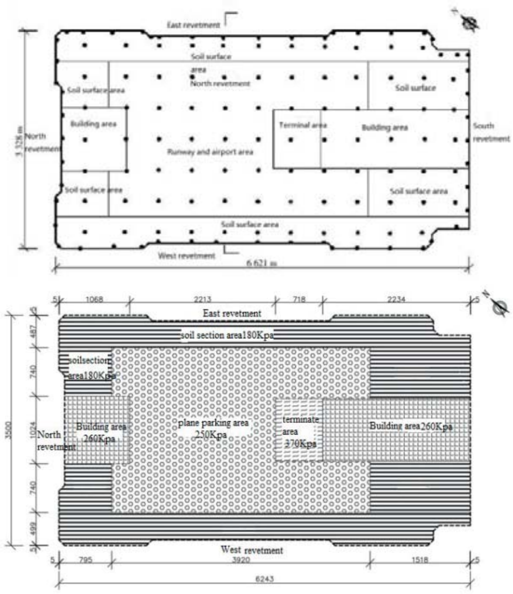


Fig. 1. Plane distribution of the regional and the main layout

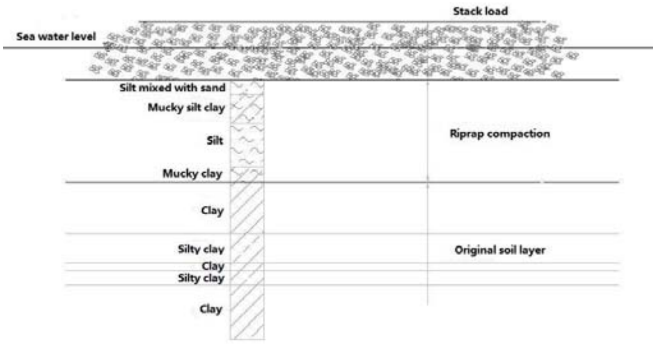


Fig. 2. The calculation model of one-dimensional consolidation settlement

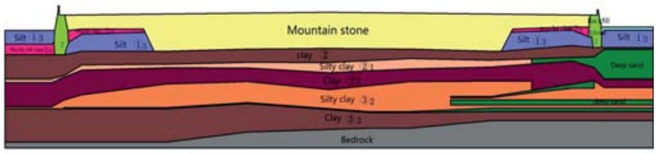


Fig. 3. Structure profile of artificial island

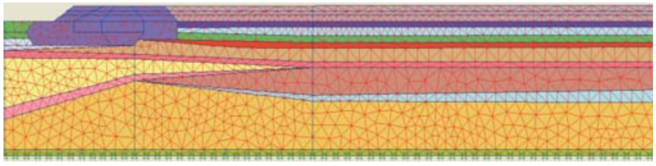


Fig. 4. The settlement analysis model of two-dimensional

When there is not enough data on physical and mechanical property of some bores, the average physical and mechanical parameters of the rock soil in different areas can be used. Table 2 shows the average physical and mechanical property of the soils in the land backfilling area.

Tab. 2. Physical-mechanical property of partial soil in one-dimensional settlement analysis

Name of soil	Water content %	Natural density	Vertical consolidation factor	Horizontal consolidation coefficient	Second consolidation coefficient	Compressibility modulus
Powder soil	28.1	1910	0.01000	10.0000	0.0005	12.10
Mucky silty Clay	42.2	1760	0.00129	0.00169	0.0350	2.900
Silt	63.7	1600	0.00025	0.00025	0.050	1.510
Silty clay	25.1	1960	0.00180	0.00238	0.002	6.040
Clay	28.7	1910	0.00239	0.00175	0.003	6.900

CALCULATION PARAMETERS AND MODEL OF TWO-DIMENSIONAL CONSOLIDATION SETTLEMENT CALCULATION PARAMETERS

The finite element analysis software PLXIS of the rock engineering specialty is used in calculation. One section of this work is used as the example (Figure 3) in this paper for numerical analysis. The figure shows the structural section of the artificial island. The two-dimensional settlement analysis model is established. The 2-order six-node triangle unit is used in numerical calculation. The maximum length of the model is 80m. Its width is 3500m. 20670 units and 21633 nodes are divided in the finite element model. Figure 4 shows one part of the calculation model. The soils are diversified in the work. This paper lists partial typical calculation parameters of the soils in calculation (Table 3). The SSC model is used for clay soils such as silt, mucky silty clay, clay and silty clay.

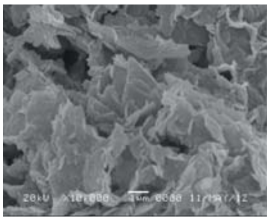
Tab. 3. Soil mechanical parameters of two dimensional settlement analysis

Soil name	Block stone	Strong-weathered rock	Silt	Clay	Silty clay
Constitutive model of soil body	M-C	M-C	SSC	SSC	SSC
Saturation density	2000	2050	1660	1900	1960
void ratio			1.64	0.91	0.78
Cohesion	0.0	50.0	13.1	38.8	41.8
internal friction angle	38.0	38.0	12.4	13.7	17.6
Permeability coefficient	8.0	8.0	0.00025	0.00023	0.00019
Modified compression index			0.105	0.052	0.046
Modified expansion index			0.021	0.0105	0.0092
Modified creep index			0.0042	0.0021	0.0019
Poisson ratio	0.33	0.30			
rigidity	150	1000			

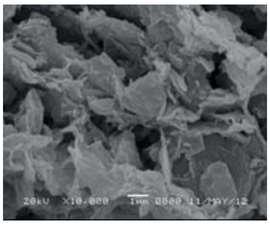
RESULT ANALYSIS

MICROSTRUCTURE RESULT ANALYSIS OF SOIL

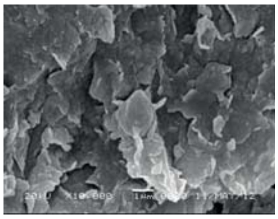
Figure 5 shows the SEM photo of six soil samples with 10000 magnification times under different depths.



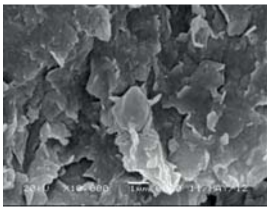
SEM diagram of silt at 3.0-3.5m depth



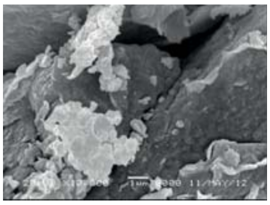
SEM diagram of mucky silty clay at 9.0-9.5m depth



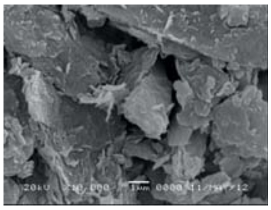
SEM diagram of clay at 17.1-17.3m depth



SEM diagram of silty clay at 29.1 -29.3 m depth



SEM diagram of silty clay at 33.1-33.3m depth



SEM diagram of silty clay at 47.1 m -47.3 m depth

Fig. 5. SEM photos of soils at different depths

From the above figure, we can see that:

On the whole, the silt at 3.0-3.5 m depths will be gray and black. From photos of the high-electron microscope, the framework of the soil sample is made of flocculating constituents and the clay connects the flocculating constituent. The sample mainly consists of intergranular pores. It indicates that this silt has low strength and its compressibility, fluidity and sensitivity are relatively high.

The mucky silty clay samples at 9.0-9.5 m depths will be black and there are some ruptures at the middle. From the photos of the high-electron microscope, the framework of the soil sample is flocculating link structure. The sample mainly consists of intergranular pores. This soil sample has low strength, but the strength is higher than that of the silt. Its compressibility, fluidity and sensitivity are relatively low.

The silty clay samples at 17.1-17.3m depths will be light brown. The soil samples are layered and include some sands. After assessment, the soil with sands has greater strength. From the photos of high-electron microscope, the framework of the soil sample is aggregate particles or powder particles and certain gap is distributed between particles.

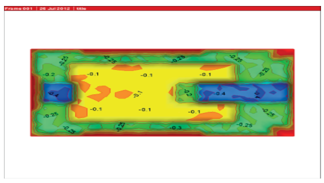
On the whole, the silty clay samples at 29.1 m -29.3 m depths will be sand yellow. After assessment, this soil sample is much rougher than previous soil samples and has higher hardness. From the photos of the high-electron microscope, the soil sample is cascaded to form the clay "domain".

From the photos of the high-electron microscope, the silty clay at 33.1-33.3m depths is the same as the silty clay sample at 29.1 m -29.3 m and is sand yellow on the whole, but the color is light yellow. After assessment, this soil sample has the top roughness and hardness among all soil samples.

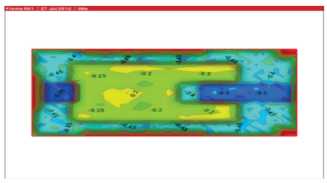
On the whole, the clay at 47.1 m -47.3 m depth is stone gray. From the photos of the high-electron microscope, the framework of this soil sample is the clay sheets formed by the aggregate particles or powder particles. The clay sheets will contact each other in a face-to-face manner and the pore is small, so it belongs to the low-compressibility land facies settlement soil.

ANALYSIS RESULTS OF ONE-DIMENSIONAL SETTLEMENT

Figure 6 gives the whole settlement distribution after the whole field has operated for 2a, 5a, 10a, 20a, 50a and 100a (refer to the Figure 6). The figure shows that the settlement of the soil section area and building construction area is remarkable and higher than that in other areas. Compared with that, the settlement at the runway and plane parking area is relatively small. With evolvement of consolidation, the maximal settlement will reach 1.502m in the soil section area after completion for 100a. The maximal settlement will reach 1.752m in the building area, 1.648m in the terminal area, 1.150m in the runway and plane parking area and 0.912m in the bank protection area.

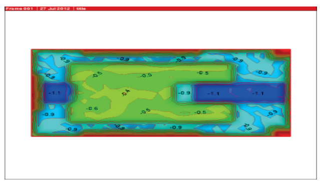


2 years

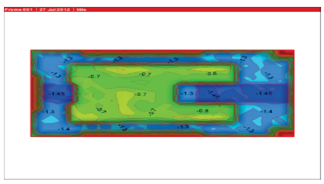


5 years

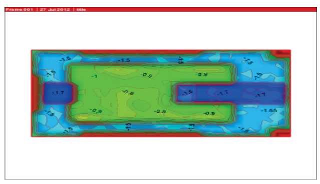
10 years



20 years



50 years



100 years

Fig. 6. The map of settlement distribution after work

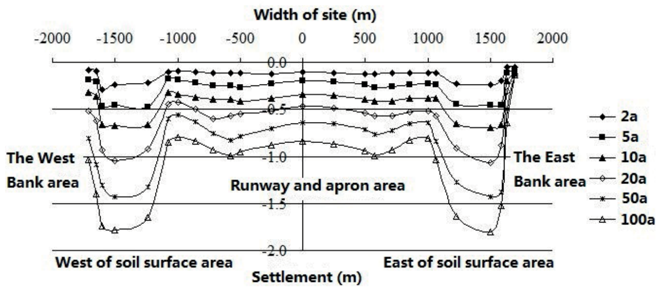


Fig. 7. The map of settlement distribution of section after work.

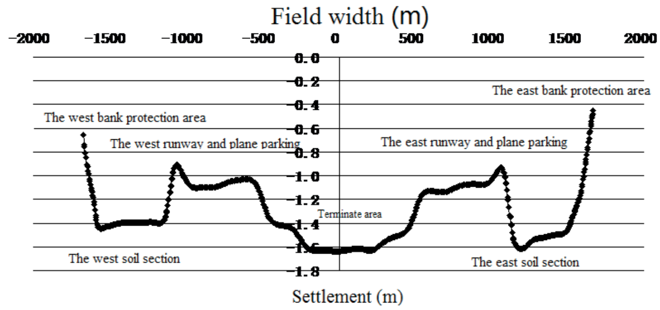


Fig. 8. Trend of cross section settlement after work

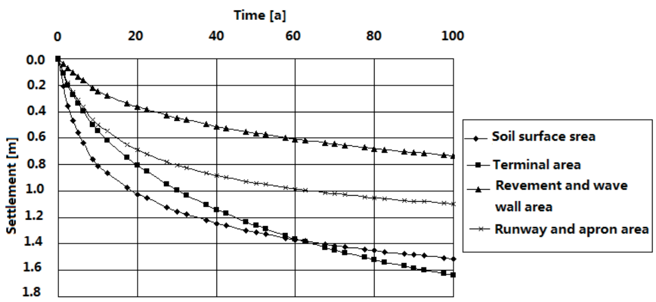
Figure 7 shows that the settlement differences are significant in different areas at one section. The settlement in the bank protection, runway and plane parking area is relatively small. The settlement is high in terminal areas, building areas and soil section areas. The settlement will increase significantly with time.

ANALYSIS RESULTS OF TWO-DIMENSIONAL SETTLEMENT

The two-dimensional calculation and analysis results are shown in Table 4 and Figure 8. It indicates the law of the residual settlement in different benchmark periods after completion. The results are described as follows: the maximal settlement is 1.098m in the runway and plane parking area, 0.737m in the bank protection area, 1.517m in the soil section area and 1.098m in the terminal area 100 years after its completion.

Tab. 4. Calculation of residual settlement of sections in different benchmark period

Section position	Settlement of different datum period /m					
	2a	5a	10a	20a	50a	100a
Soil section area	0.356	0.559	0.814	1.021	1.315	1.517
Bank protection and wave wall area	0.074	0.134	0.249	0.365	0.564	0.737
Runway and plane parking area	0.185	0.311	0.503	0.691	0.941	1.098
Terminal area	0.201	0.339	0.547	0.806	1.260	1.642



COMPARATIVE ANALYSIS OF ONE-DIMENSIONAL AND TWO-DIMENSIONAL SETTLEMENT VALUES

Based on numerical analysis of one-dimensional and two-dimensional settlement data, the settlement law and trend from two numerical analysis methods are roughly similar. The maximal settlement is about 0.6-0.8m in the bank protection and wave wall area is about 0.6-0.8m. The maximal settlement is about 1.1-1.2m in the runway and plane parking area, the maximal settlement is about 1.4-1.7m in the soil section area. The maximal settlement is about 1.6-1.7m in the terminate area. And the maximal settlement is about 1.8m in the building area 100 years after completion.

CONCLUSIONS

Based on microstructure analysis on the soil, the gap mainly includes the inter-particle gap and some holes existing in the silt and mucky silty clay, so the soil has high compressibility and low strength. The silty clay has higher compressibility and strength at three different depths. The silt and mucky silty clay has bigger influences on the settlement results and the silty clay has smaller influence on the settlement results in the settlement prediction and analysis at the whole field.

Based on numerical analysis on one-dimensional and two-dimensional settlement, two numerical analysis methods have roughly consistent settlement law and trend. If the complex model is used to calculate the settlement, the parameters are easy to be dispersed in the calculation process, which leads to an increase of computation time and inaccurate result. It is only suitable for academic research. So the sedimentation numerical analysis method of one-dimensional and two-dimensional is more applicable to the engineering practice.

Settlement of the whole field is mainly caused by the soil gap and inter-particle gap. The runway and plane parking are mainly composed of the clay and silty clay. The aggregate or powder particles composing the framework of the soil and particles keeps certain gap among particles, so the settlement is relatively small. The soil section area is covered by silt and mucky silty clay with certain thickness and features low strength and higher compressibility, fluidity and sensitivity, so it leads to bigger settlement. The terminal area and building area include plentiful deep sands, silt and a small number of mucky silty clay, composing a very loose and soft framework, so the settlement is maximal in these two areas.

The microstructure analysis method for soils can be extensively used in the field of rock soil engineering. It is very significant to combine the macro mechanical shape with microstructural deformation and study their inherent association. Research on this field is insufficient in China, so this field is worthy of further studies.

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CONTACT WITH THE AUTHORS

Jie Zhao

Civil Engineering Technology Research
and Development Center
Dalian University
Dalian 116622
China