Study on the ground settlement during reclamation of Xiamen airport

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Abstract. The settlement of soft soil foundation is a critical problem for the airport construction in coastal area. In order to study the long-term settlement characteristics of soft soil foundation of a Chinese reclamation airport (Xiamen Airport), this paper analyzed the monitoring settlement development of different regions in two runways to be built. The relationship between the total settlement from January 11, 2019 to May 22, 2020 and the thickness of soft soil was studied for guiding the settlement prediction of subsequent construction. The results showed that the development law of foundation settlement with different preloading durations under the same thickness of soft soil is different. As the preloading duration increases, the total settlement in the same period becomes smaller. Besides, the total settlement of Runway 2 increases approximately linearly with the thickness of soft soil (silt soil). However, the total settlement of Runway 1 under different thickness of soft soil is similar, which probably indicates primary consolidation has basically completed in this region. The research results in this paper is useful to understanding the settlement characteristics of Xiamen Airport, and can be used to analyse the settlement characteristics of other similar reclamation airports.

1. Introduction

With the rapid development of airport construction in China, the settlement of reclamation soil foundation of airports has been a limiting problem for the construction schedule due to the existence of saturated soft soil with high void ratio on the seafloor. The settlement process of soft soil like silt layer under the external loads of structures is complicated and hard to be predicted in practice [1-2]. Excessive settlement of soft soil may often lead to engineering accidents and is harmful to the operation of airports, for example the famous case of Kansai International Airport in Japan [3], where the settlement of the foundation far exceeds the expectations of geotechnical experts. The total settlement of soft soil layer under external loads can be divided into instantaneous settlement, primary consolidation settlement, and secondary consolidation settlement. The instantaneous settlement can be completed once the loads are applied, therefore, it has little effect on thesequent settlement after the structures or runway of airport are constructed. Many researchers have studied the soil consolidation based on the classical soil mechanics [4-6]. In fact, what may have an impact on the project is the primary consolidation settlement and the secondary consolidation settlement, which will take a long period to complete.
The fitting method of measured settlement curve for studying and predicting the consolidation settlement of soft soil is practical and reliable in actual engineering. Many studies have been carried out based on the measured settlement of foundation. Sridharan et al. [7] pointed out that the ratio of consolidation degree to the time factor has linearity relationship with the time factor when the consolidation degree is between 60% and 90%. Wei Rulong [8] thought the compression curve of soft clay is more like the elliptic shape. Asaoka [9] proposed a process according to the settlement observation data obtained from a certain time to predict the total settlement and settlement speed, which was also called a new practical calculation method. It can determine the vertical drainage consolidation coefficient and the final settlement. Besides, the Poisson curve, which is derived from the population mathematics [10], can be considered to fit the S-shaped curve for settlement prediction [11]. The general gray model [12] is another advanced prediction method to study the settlement characteristics of soil, the core basis of which is the gray theory. All the fitting methods above are based on a number of accurate measured settlement of soil. The measured data can not only be used to study the settlement characteristics of foundation, but also determine the accuracy of settlement prediction to a certain extent. Therefore, the study of characteristics of measured settlement curves is useful and meaningful, which will be the focus of this paper.

Based on the measured settlement curve of a reclamation airport under construction in Xiamen of China, this paper analyzed the consolidation settlement characteristics of this special area and studied the shape of the settlement curve under different thicknesses of soft soil and external loads. In this airport, the offshore area is filled with sea sand to form a land area for airport construction, and the foundation treatment is carried out by the preloading method with drainage plate in the foundation. The current reclamation area covers a large area, which is mainly divided into phase I and phase II as shown in Figure 1. According to the geological exploration data, different preloading schemes are adopted for the foundation in different functional areas and thickness of soft soil. In the loading process, monitoring points were set up to monitor the foundation settlement, and the monitoring was stopped after the surface settlement reached the basic stability (i.e., two successive monitoring settlements were less than 2mm). Before unloading, the settlement of the full field needs to be reviewed, and therefore, some important areas have recently been monitored again. The loading time on the foundation has reached 2-3 years. The measured settlement curve studied in this paper is derived from the second settlement monitoring, that is, the subsequent settlement characteristics after the first settlement monitoring is considered to have been stable. This project has a wide construction scope and a long construction time, so the measured data of foundation settlement is of great help to the study of soft soil foundation settlement of reclamation airport. The research work in this paper is conducive to understanding the settlement characteristics of soft soil foundation, and can be used to analyze the settlement characteristics of this airport or other similar reclamation airports, so as to provide a basis for the subsequent formulation of corresponding foundation treatment methods.

2. Project overview
The airport under construction in this paper is located in the east of Xiamen Island, near to the southeast sea of Xiang'an District. The land reclamation for the airport construction is designed to be carried out in three phases, and the reclamation material is sea sand, which is mined from the deep sea far from the mainland. The reclamation location in each phase is shown in Figure 1. The currently reclamation are called the first phase and the second phase, and the third phase of reclamation has not yet been carried out. The first phase reclamation project includes a total area of about 3 square kilometers and has been filled since 2010; the second phase reclamation project has a total area of about 7.58 square kilometers, and the land reclamation has been carried out since 2015, and the hydraulic reclamation work has been basically completed.

According to the geological exploration data, the soil layers in the soil foundation of the present project are distributed from the soil surface as plain fill soil, silt, silty clay, medium sand, residual sandy clay, fully weathered granite, and gravel-like strongly weathered granite, etc. The silt layer has the greatest impact on the consolidation and settlement of the airport foundation. The thickness
distribution of the silt layer varies greatly within the entire field, and the thickness is generally between 0.4-25.1 meters. The relative physical properties and compressibility of silt soil are shown in Table 1 and Table 2, respectively.

![Figure 1. Reclamation area in the airport.](image)

**Table 1.** The physical property indexes of silt soil in the foundation.

| Physical index       | Water content (%) | Density (kg/m³) | Dry density (kg/m³) | Natural void ratio | Saturation (%) | Liquid limit (%) | Plastic limit (%) | Plasticity index |
|----------------------|-------------------|-----------------|---------------------|--------------------|---------------|-----------------|-------------------|------------------|
| Average value        | 60.1              | 1.6             | 1.01                | 1.68               | 96            | 49.7            | 27.0              | 22.71            |
| Standard deviation   | 8.75              | 0.08            | 0.11                | 0.23               | 2.93          | 3.69            | 1.99              | 2.59             |
| Variation coefficient| 0.145             | 0.047           | 0.113               | 0.139              | 0.031         | 0.074           | 0.074             | 0.114            |

**Table 2.** The compressibility indexes of silt soil in the foundation.

| Compressibility index | $a_{1-2}$ / (MPa$^{-1}$) | $P_c$ / kPa | $C_c$ | $C_v$ / (cm$^2$/sec) | $E_{a,0.05-1}$ / MPa | $E_{a,1-2}$ / MPa | $E_{a,2-4}$ / MPa | $E_{a,4-8}$ / MPa |
|-----------------------|--------------------------|-------------|-------|----------------------|----------------------|--------------------|--------------------|-------------------|
| Average value         | 1.46                     | 56.23       | 0.50  | 0.35                 | 1.23                 | 1.92               | 3.30               | 5.55              |
| Standard deviation    | 0.30                     | 16.41       | 0.06  | 0.18                 | 0.44                 | 0.50               | 0.74               | 1.34              |
| Variation coefficient | 0.207                    | 0.292       | 0.126 | 0.113                | 0.357                | 0.26               | 0.225              | 0.241             |

Note: $a_{1-2}$: Compression coefficient; $P_c$: Compression coefficient; $C_c$: Compression index; $C_v$: Consolidation coefficient under confining pressure of 100 kPa; $E_{a,0.05-1}$, $E_{a,1-2}$, $E_{a,2-4}$ and $E_{a,4-8}$: Compression modulus under the stress range of 0.005-1 MPa, 1-2 MPa, 2-4 MPa and 4-8 MPa, respectively.

Because of the high compressibility and low strength of the silt soil, it is prone to large settlement and uneven settlement in the foundation of the airport. Therefore, in the process of reclamation, it was designed to use the drainage plate inserted in the foundation for preloading treatment. The thickness of the reclamation soil in the first phase reclamation region is about 4.5m, and the filled soil is relatively uniform. However, due to the large difference in the thickness of silt soil, regional importance and seabed height, the thickness of the reclamation sand in the second phase reclamation region varies greatly, and the maximum thickness of the filled sand can reach about 11m.

### 3. Settlement monitoring scheme

In order to study the impact of the additional loads caused from the reclamation sand on the settlement of the foundation, the settlement of the entire field was monitored during the land reclamation and preloading treatment. The leveling measurement method was adopted for monitoring the settlement,
which was divided into two stages in different periods. The first stage of settlement monitoring occurs from the beginning of the preloading with sea sand for about one and a half year, and then the monitoring was stopped when the absolute settlement of two adjacent times is less than 2mm. At this moment, it was considered that the settlement development was basically stable, and the main consolidation settlement of the slit soil was basically completed. The second stage of settlement monitoring occurred after the preloading process was completed for more than 2 years. And the settlement monitoring currently of the reclaimed area in the site belongs to the second stage. The soil settlement during the second stage can be considered to be caused from mainly secondary consolidation process. The study on the settlement characteristics in this period is conducive to understand the long-term settlement of the soil, and it is very helpful to the operation of the airport after the projected is completed.

Due to the large number of settlement measurement points in the field, this paper mainly selects representative measurement points with different silt thicknesses in the second phase of reclamation area for analysis limited to the length of the paper. The monitoring position and relative parameters of each measuring point in the runways are shown in Figure 2.

4. Analysis of monitoring results

Because of the uneven thickness distribution of soft soil, the distribution of monitoring points located in the runway is also uneven. On Runway 1, the area under the thickness of soft soil greater than 10m is located at about 1/3 of the east side of the runway as shown in Figure 2. On Runway 2, the area under the thickness of soft soil greater than 10m is located at about 1/4 of the east side of the runway as shown in Figure 2. The number of monitoring points are SW10 and SW1, which are located in the second-phase reclamation area. The measured settlement curve of each point from January 11, 2019 to May 22, 2020 (497 days) is shown in Figure 3.

It can be seen that the total settlement of 497 days was 24-26mm in Runway 2. And the settlement curves of the two monitoring points are similar, which means the settlement development are authentic. However, the total settlement in Runway 1 was only 4-6mm, far less than that of Runway 2, the reason of which is that the preloading duration in Runway 1 is much longer than that of Runway 2.

Figure 2. The monitoring position in the runway.

Figure 3. The settlement curve of ground surface under soft soil of thickness greater than 10m in the runway (The black line and red line in the figure are the settlement curve of Runway 1 and Runway 2, respectively).
The area where the thickness of soft soil ranges from 3 to 10 m in Runway 1 is mainly distributed in the middle of the runway, accounting for about 1/2 of the total area of the runway. The Runway 2 has a small distribution range, with two monitoring points P2-3 and P2-26. The measured settlement curve of each point is shown in Figure 4 and Figure 5. It can be seen that the total settlement of Runway 2 is 16-19mm. The settlement curves of the two measuring points are basically the same, and the settlement is slightly less than that in the region of the soft soil thickness of 6-10m (17-26mm), which indicates the correlation between the settlement and thickness of the soft soil. The total settlement of Runway 1 is also small (2-9mm), which verifies that the settlement of Runway 1 has been stable.

**Figure 4.** The settlement curve of ground surface under soft soil of thickness 6-10m in the runway.

**Figure 5.** The settlement curve of ground surface under soft soil of thickness 3-6m in the runway.

**Figure 6.** The settlement curve of ground surface under soft soil of thickness less than 3m in the runway.
Within the current reclamation area, the region where the thickness of soft soil in the runway is less than 3m is mainly distributed on Runway 2, with an area of more than 1/2 of the total runway area. There are no corresponding monitoring points on Runway 1. The measured settlement curve of each measuring point is shown in Figure 6. It can be seen that the total settlement of the area is 9-15mm. The settlement development of each measuring point is consistent, and the settlement is slightly less than the area with soft soil thickness of 3-6m (16-19mm), which also conforms to the correlation between settlement and soft soil thickness.

To sum up, the settlement of the region where the thickness of soft soil is over 10m, 6-10m, 3-6m and less than 3m in Runway 2 is 24-26mm, 17-26mm, 16-19 and 9-15mm, respectively. The correlation between the thickness of soft soil and the settlement is shown in Figure 7. As the thickness of soft soil increases, the settlement in Runway 2 increases almost linearly. However, the settlement development in Runway 1 under different thicknesses soft soil is similar as shown in Figure 8, and the settlement amount is small, generally within 10mm. To some extent, this indicates that the settlement of the Runway 1 has been basically stable due to the long loading duration. Therefore, the displacement of soil ground is related to both soft soil thickness and preloading duration.

5. Conclusions
The settlement development during preloading reclamation under different kinds of thickness of soft soil were studied in the runway of the offshore airport under construction in the city of Xiamen, China. The key results are summarized as follows.

- The development law of foundation settlement with different preloading durations under the same thickness of soft soil is also different. As the preloading duration increases, the total settlement in the same period gets smaller.
- Approximate linear correlation between the thickness of soft soil and the settlement in a certain period was discovered, which is helpful to predict the sequent settlement development.
- The settlement development in Runway 2 under different thicknesses of soft soil is different. And as the thickness of soft soil increases, the total settlement increases almost linearly.
The settlement development in Runway 1 under different thicknesses soft soil is similar. And the settlement amount is small, generally less than 10mm. It indicates that the settlement of the Runway 1 has been stable due to the long loading duration.

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