Design and analysis of monitoring scheme for raft foundation of super high-rise building

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Abstract. Differential settlement of raft foundation for super high-rise buildings easily leads to adverse effects such as concrete cracking, deformation of pre-buried pipelines, and tilting of the building, but the current settlement theory and analysis methods are still difficult to simulate the change rule of actual foundation settlement. In this paper, in order to better consider the interaction effect of foundation soil, raft foundation and superstructure, a raft foundation monitoring scheme is established according to a super high-rise building project, and direct observation of on-site soil pressure, pore water pressure, internal force of the raft reinforcement and settlement of the raft is carried out. The monitoring data indicates that the soil pressure can show the stress unevenness of the foundation soil. The internal force of the raft reinforcement is closely related to the vertical load of superstructure, and has an exponential function relationship with the size of the settlement. The soil pressure, pore water pressure, and reinforcement stress can be measured by the automatic monitoring system in the whole process of the construction to ensure that there is no large force variation in the construction process. The settlement difference of raft foundation for the super high-rise structure in this paper is mainly affected by the early concrete creep, and its own gravity is the second influence factor.

Keywords: Super high-rise building; Raft Foundation; Foundation settlement; Monitoring scheme.

1 Introduction

Raft foundation can provide so strong punching and shearing resistance as to transfer internal force between the foundation soil and basement in super high-rise buildings[1], which coordinating the uneven settlement of the overall structure. The construction stage of the raft foundation is the weakest period of the ultra-deep basement structure located in dense urban areas. Upper fly ash content makes the raft foundation slow in strength development and presents four types of quality risks such as

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insufficient structural strength, insufficient structural stiffness, insufficient durability and leakage[2].

In order to ensure the construction quality of the overall structure, it is necessary to understand the force and deformation law of raft foundation and control the uneven settlement of super high-rise buildings. In this project, real-time structural health monitoring system is adopted to master the internal force of raft Foundation, which gives engineers decision-making functions for maintaining building structures.

At present, structural health monitoring systems are mainly used to assess the safety of super high-rise structures, such as the 632-meter Shanghai Tower[3], the 599.1-meter Ping An International Finance Centre[4] and the 600-meter Guangzhou New TV Tower[5]. However, there is a lack of examples of monitoring programs for raft foundations of super high-rise structures, and it is necessary to consider the technical difficulties in the complex environment of the basement, such as the high cost and difficult maintenance of the densely distributed traditional wired sensors, and the limitations of the network signal and power supply for the wireless sensors. In recent years, wireless smart sensor technologies have overcome these challenges. The UCLA/Rockwell Science Center team has developed a prototype wireless smart sensor called "AWAIRS I", which integrates the capabilities of seismic sensor, acoustic sensor and microprocessor computation[6]. Evans[7] introduced a low-cost wireless smart sensor formed by combining wireless network technology and MEMS sensors, and demonstrates its advantages by two cases. Gao et al.[8] proposed a distributed computing strategy for structural health monitoring applicable to dense distributed smart sensor networks. Yu et al.[9] designed a wireless acceleration sensor to measure civil engineering structure with low vibration frequency and small acceleration, and the sensor was integrated by chip ADXL202 based on MEMS technology. Some researches have shown that despite the advances of wireless smart sensor technology in academia, the execution of structural health monitoring technologies in the real world is still lagging behind[10]. This paper promotes the application and development of new technologies in complex basement environments by establishing a monitoring program for the raft foundation of a super high-rise building.

2 Project profile

The actual project is a 374-meter SRC column frame-core tube structure, including 59 floors of above ground tower, 5 floors of basement and 4 floors of podium. In order to understand the deformation of the raft foundation, settlement observation, reinforcement stress monitoring, soil pressure monitoring and pore water pressure monitoring of the raft foundation are carried out in the construction stage.

Figure 1 shows the elevation diagram of raft foundation bottom, the deepest relative elevation is -35.3m, the highest relative elevation is -28.1m, the thickness of the raft foundation is 3~4m, and the maximum height difference of the raft foundation is 10.7m. As shown in Figure 2, based on the geological examination information, the soil supporting layer is mainly composed of moderately weathered and slightly weathered foundations, and the maximum subgrade reaction is about 1100kPa, which is much smaller than the foundation bearing capacity, so that a raft foundation without piles is adopted for this building.

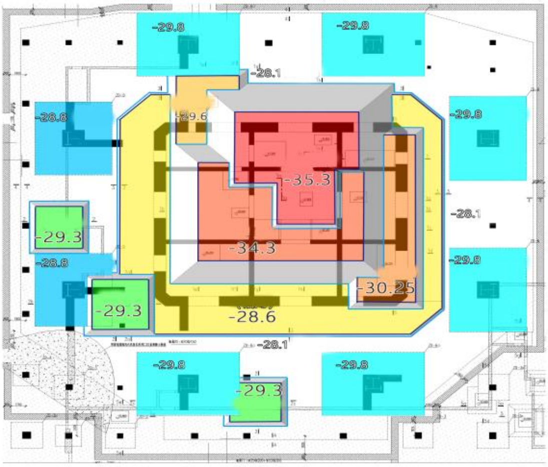


Fig. 1. The bottom relative elevation diagram of raft foundation on the tower section

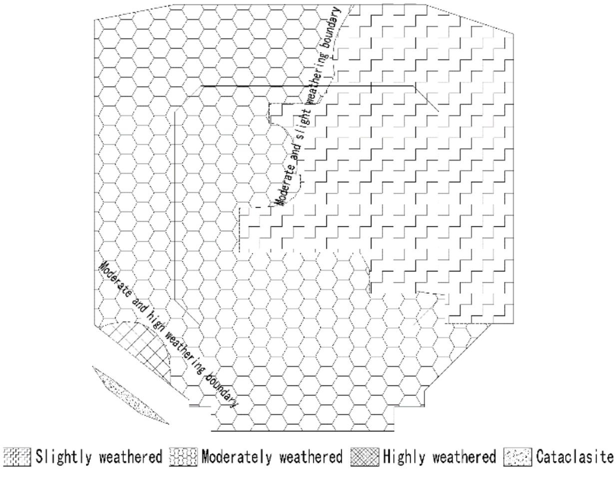


Fig. 2. Schematic diagram of natural foundation support layer on the tower section

3 Monitoring content

3.1 Observation of raft settlement

During the construction of the basement located under the tower, the other area around the tower is still not built. Therefore, it is convenient to measure the elevation of raft foundation by manual work directly through the peripheral area. When the peripheral area is under construction, scaffolds are set up, which leading to multiple passes of elevation. According to the Code for Deformation Measurement of Buildings JGJ8-2016[11], the settlement of the main structure is observed once every three floors. After the completion of the building, two consecutive half-yearly settlements of less than 2mm are taken as the condition for settlement stabilisation.

3.2 Observation of the reinforcement stress, soil pressure and pore water pressure of the raft reinforcement

The monitoring system, powered by batteries and solar panels, was installed for automated data acquisition after the final setting of the concrete for the raft foundation. Nonetheless, after the basement slab had been poured, the capacity to transmit data on the raft reinforcement stress, soil pressure and pore water pressure was limited by the space network signal. Therefore, a star topology local area network was established to implement the data transmission technique in the signal-absent basement environment, which results in that the aforementioned measurement data and settlement observation data can share a one-to-one mapping, and it is better to monitor the pattern of multiple influencing factors.

4 Design and implementation of health monitoring program

4.1 Layout of measuring points

The raft foundation is subjected mainly to the forces of the superstructure, the lower foundation soil and the water body. To identify the point of maximum internal forces, sensors and settlement observation points are set up.

4.1.1.Settlement of raft foundation.

The settlement difference of super high-rise buildings is used as a measure of the rationality for the design of the raft foundation, which is of great significance for judging the overall health of the structure. The raft foundation is designed as a rigid body to reduce the structural settlement difference, but there are many differences between the design and the reality, such as uneven foundations or large differences in the loads of the superstructure, etc., which can cause the building to have uneven settlement[12]. In order to truly reflect the settlement changes of the raft foundation, the settlement measurement points need to be uniformly distributed in the structural plane, and at the same time, measurement points should also be set up in the core tube and giant columns, as shown in Figure 3.

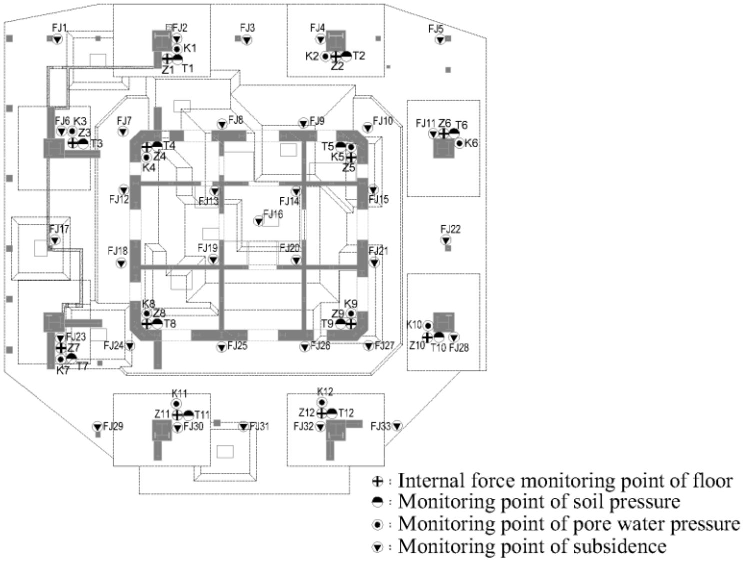


Fig. 3. Layout of monitoring points for raft foundation

4.1.2.The reinforcement stress, soil pressure and pore water pressure of the raft reinforcement.

Settlement is a parameter influenced by the combination of soil, foundation and superstructure. In most previous projects, these three factors aforementioned were often neglected, but monitoring them can effectively demonstrate their interdependent relationship, facilitating the quantification of variation rules[13,14]. The sensor arrangement adheres to the "dispersed and symmetrical" principle, which eliminates the monitoring blind zones caused by raft tilt, and to play a role of symmetrical data verification. In this project, there are 12 groups of measurement points. Each group of measurement points contains reinforcement strain sensors, soil pressure sensors and pore water pressure sensors. Two strain sensors are welded in the orthogonal direction of the reinforcement respectively, while soil pressure and pore water pressure sensors are buried in the corresponding positions. Schematic diagram of the buried measuring points is shown in Figure 3.

4.2 Project implementation

4.2.1.Installation of equipment on site.

(1) Installation of pre-embedded components for settlement observation

The details of the settlement observation member are illustrated in Figure 4. To prevent the inability to install or damage during construction, it is important that the pre-embedded components are installed and executed protection measures during the construction of the wall and column reinforcement.

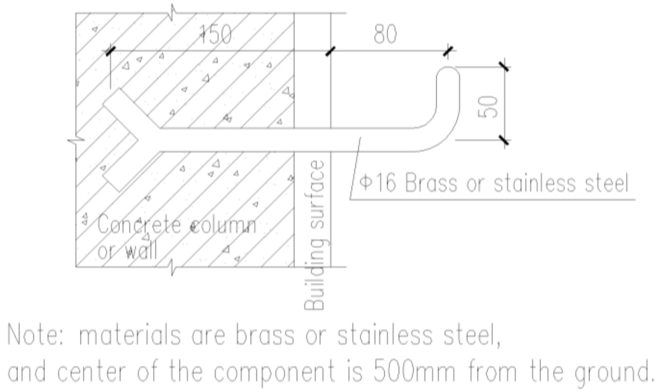


Fig. 4. The details of the settlement observation member

(2) Installation of reinforcement stress sensors

The strain sensors were welded to the reinforcements of the raft foundation that were subjected to greater stress, as shown in Figure 5.

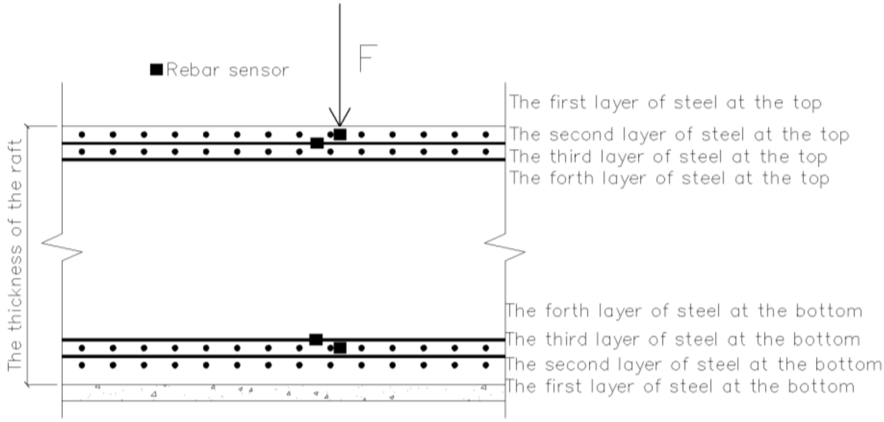


Fig. 5. Sketch of the reinforcement position of the raft

(3) Installation of soil pressure and pore water pressure sensors

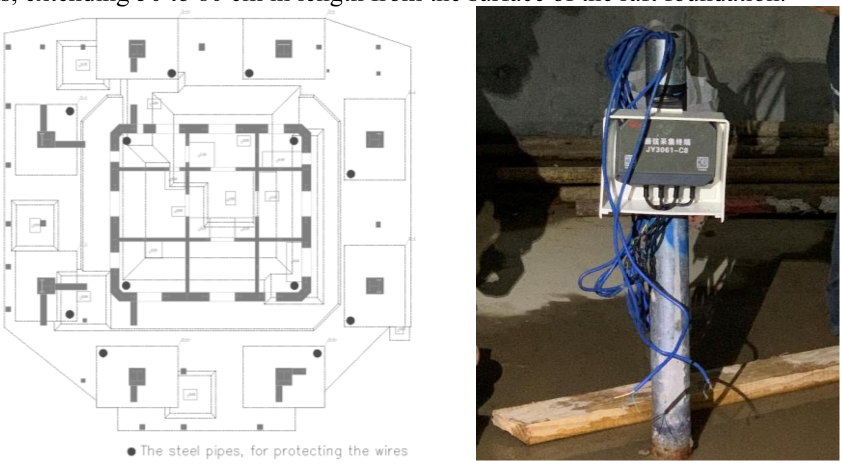
When the foundation pit was excavated to the base elevation, the soil pressure sensors were buried in the hole approximately 1 metre deep and pore water pressure sensors were placed on top of it, and then the holes were backfilled tightly. During the installation of the sensors, the wires were extended to the hole and properly protected. The installation is shown in Figure 6.

(a) Embedded sensors (b) The arrangement of wires

Fig. 6. Installation of soil pressure and pore water pressure sensors

4.2.2.Wire layout and protective measures.

As shown in Figure 7, the steel pipes, for protecting the wires, were installed on the surface of the raft foundation, avoiding the position of the vertical structure. Steel tubes with diameters of 50 to 80 mm were installed vertically in pre-determined positions, extending 50 to 80 cm in length from the surface of the raft foundation.



(a) Plan layout (b) Installation drawing

Fig. 7. Schematic diagram of the positions of the steel pipes

4.2.3.Data transmission system.

In this project, a low-power and low cost WAN based on LoRa technology[15], formed in a star topology, is adopted to transmit the sensor data collected in the basement to the remote monitoring cloud platform[16]. This method overcomes the problem of no signal transmission in the basement, and the operating principle of the monitoring system is shown in Figure 8.

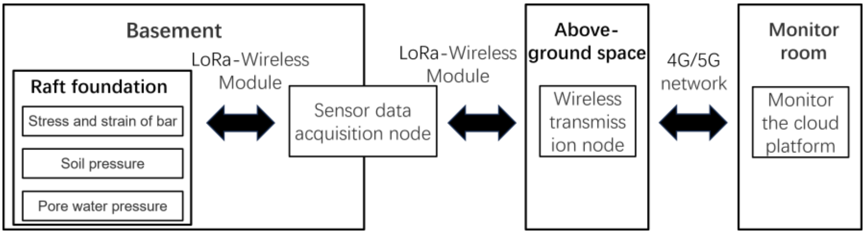


Fig. 8. Working principle of monitoring system

5 Analysis of measurement results

The variation curves of reinforcement stress, soil pressure, pore water pressure and raft settlement were derived from the collated data, and the change rule analyses were carried out for the basement construction stage, the shutdown period and the above-ground structure construction stage, respectively. In the variation curves of soil pressure shown in Figure 9, except for the curve of T3 of the outer frame column, all of them are in the state of positive pressure. The T4, T5, and T9 measurement points at the corners of the core have large soil pressure. Due to the data exceeding the maximum range, the sensors at the T8 and T12 measurement points have been damaged. Comparing different curves, it can be concluded that the raft slab in the core tube area is subjected to the greatest base pressure, which is about 1.0~2.0 times of the pressure in the outer frame area of the tower; the outer frame area on the southeast side of the raft slab is subjected to a greater pressure, which causes damage to the sensors of the T12 measuring point of the outer frame columns, and the symmetrical outer frame columns have the smallest pressure at the T3 measuring point; the distribution law of the base pressure of the raft slab presents the feature of large in the centre and small in the surroundings. Comparing the soil pressure changes at different stages, it is concluded that the variation curves of the soil pressure at the basement construction stage and the shutdown stage are unstable, and the trend of the curve changes has been basically determined from the construction stage of the above ground structure of the tower. Figure 10 shows the variation curve of pore water pressure. During the basement construction period, the pore water pressure at measurement point K9 was made negative due to pit drainage. Subsequently, because of the construction progress and rainfall, the pore water pressure at the K9 measurement point returned to a positive value, which is similar to the values at the K4, K5 and K8 measurement points at the corners of the core. The above analysis shows that the soil pressure condition can roughly reflect the force characteristics of the raft slab, which can be corroborated with the changes of reinforcement stress and settlement difference. The change of pore water pressure is mainly related to seasonal precipitation, which can indirectly reflect the change of groundwater level and assist in judging the effect of groundwater buoyancy.

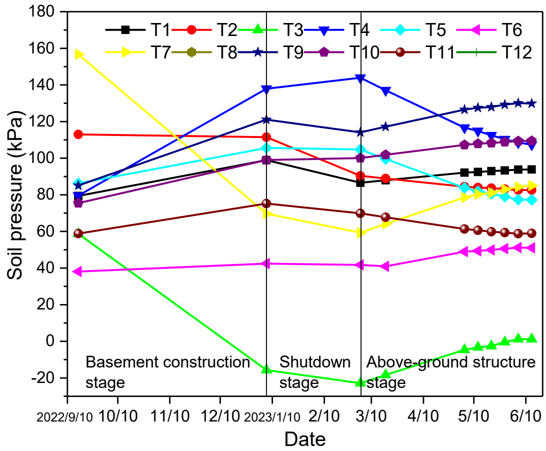


Fig. 9. Variation curve of soil pressure

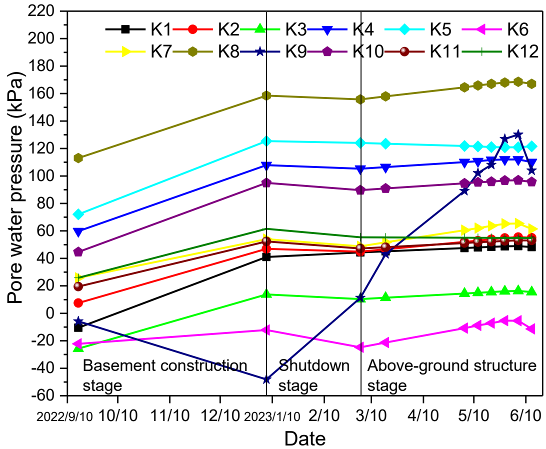


Fig. 10. Variation curve of pore water pressure

The maximum stress curve is shown in the Figure 11, which reflects the construction progress of the tower area. During the basement construction stage, which began on September 10, 2022, the material yards, construction machinery and construction tools are scattered all over the foundation pit, and the raft slab in the tower area is mainly subjected to the action of structural self-weight, so the stress curves of the reinforcement grow slowly. After the completion of the basement construction in the tower area on March 4, some of the material yards, construction machinery and tools were transferred to the tower area, which resulted in a rapid increase of the reinforcement stress in the raft foundation. During the standard floor construction stage, which began on May 5, the maximum stress of raft reinforcement remained at the same level and reinforcement bars are in elastic state.

The above analysis shows that in the early stage of the construction for the ground structure, the stress change of the reinforcement is the most drastic. If the maximum stress of reinforcement is less than a certain value will help to control the deformation state of the raft foundation and reduce the settlement difference of the raft foundation.

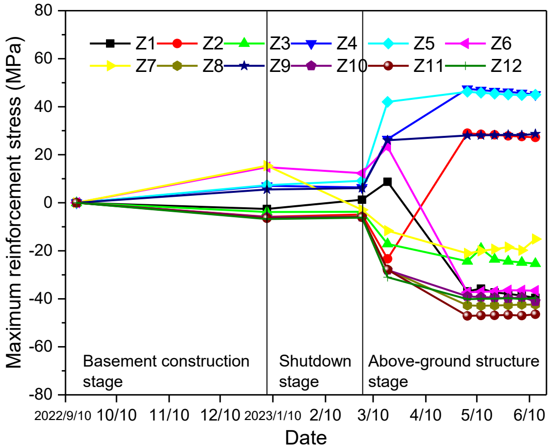


Fig. 11. Maximum stress curve of reinforcement

Maximum settlement difference between the peripheral frame columns and core tube of the tower is shown in Figure 12. The maximum settlement difference during the shutdown period accounted for about 76.2% of the total settlement difference in the pre-construction period, and concrete creep was the main factor causing the deformation of the raft foundation during the shutdown period. Figure 13 shows the positive settlement in the peripheral frame part and the negative settlement in the core tube part during the shutdown period so that the deformation of the foundation shows a pot-bottom shape bending.

From the beginning of the construction for the aboveground structure, the overall settlement of the structure is in stable variation tendency, and the settlement difference is about 23.8% of the total settlement difference in the pre-construction period. The deformation of the raft foundation mainly comes from the gravity effect of the structure in the above-ground structure construction stage. It can be seen that the settlement difference of raft foundation for the super high-rise structure in this paper is mainly affected by the early concrete creep, and its own gravity is the second influence factor.

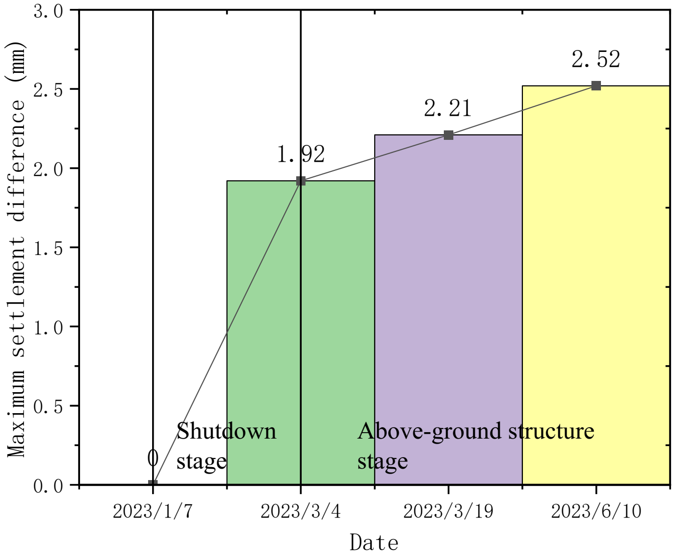
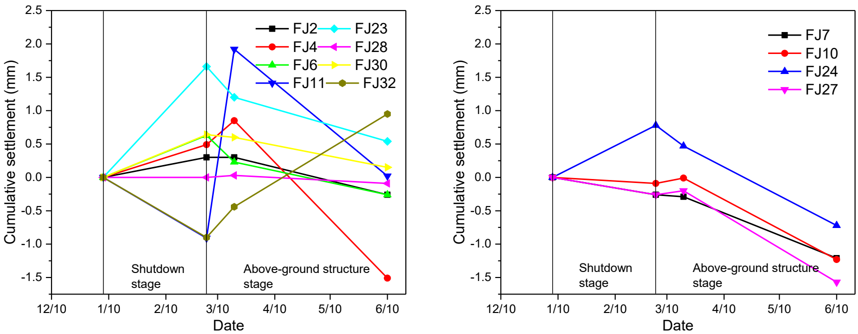


Fig. 12. Maximum settlement difference of raft foundation in tower area



(a) Peripheral frame column (b) Core tube

Fig. 13. Settlement curves of raft foundation in tower area

As shown in Figure 14 and 15, the maximum reinforcement stress has a certain functional relationship with the mass of the constructed tower and the average settlement[17]. The results show that the exponential function model generally have a good effect and high precision, and its R-square values are 0.8661 and 0.9982 for the fitting curves in the Figure 14 and 15. The larger the settlement is, the faster the maximum stress increases. When the maximum reinforcement stress is 25MPa, the average settlement grows rapidly, and the corresponding reinforcement strain of 1.25×10-4 has exceeded the ultimate tensile strain of C50 concrete, which makes the superposition of concrete deformation and foundation settlement significant.

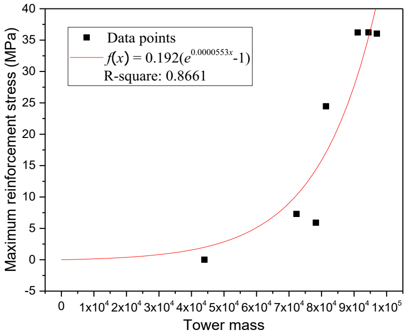


Fig. 14. Fitting curve between maximum reinforcement stress and tower mass

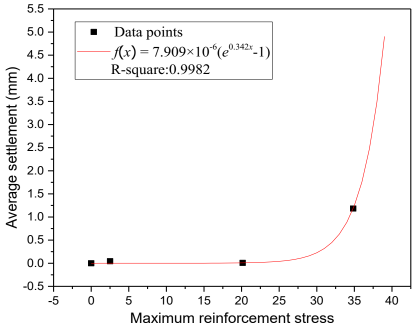


Fig. 15. Fitting curve between maximum reinforcement stress and settlement

6 Conclusion

(1) The settlement monitoring of the raft foundation is limited by the construction conditions, but the soil pressure, pore water pressure and raft reinforcement stress can be effectively measured in the preconstruction stage to monitor the whole construction process.

(2) The wireless data transmission mode of LORa technology can avoid the wiring difficulties caused by the complex construction environment in the basement, and realize unattended data monitoring with automatic acquisition technology.

(3) Soil pressure sensors are easily damaged due to the harsh environment of foundation, and it is necessary to develop related technologies to improve the survival rate of the sensors.

(4) Before the construction of aboveground structures, concrete creep is an important factor in causing settlement differences. After the construction of the aboveground structure, the effect of self-gravity mainly affects the increase of the overall settlement and has less influence on the settlement difference.

(5) During the construction of the first floor, raft reinforcement stress changes greatly, which can be used as the key monitoring stage to avoid the large settlement difference.

(6) Raft reinforcement stress can reflect the superstructure load in the construction stage, which is of great significance for controlling the construction load.

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