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Analysis of Monitoring and Numerical Simulation on Anchor Force of Foundation Pit

***Abstract**. Pile anchor supporting structure is a common method in deep foundation pit engineering. To a certain extent, anchor forces can reflect the earth pressure acting on the supporting structures. In the process of the deep foundation pit construction, the layers with different types of groundwater are often encountered. Improper control of groundwater may lead to engineering safety problems and many other cases which can cause bad effects on the surrounding environment. Therefore, it is of practical significance to conduct the optimal designs for supporting structures of deep foundation pit by monitoring the anchor forces in-situ. Through studying and analyzing the monitoring data, the earth pressure's magnitude and distribution law can be further understood. In this paper, foundation pit engineering is taken as a base, a whole monitoring of the actual anchor forces is made in the process of tensioning, locking and working of anchors, and the monitoring data is analyzed. A numerical analysis based on the fluid-solid coupling theory of unsaturated soil is performed, and tests of the soil water characteristic curve (SWCC) for typical unsaturated soil are carried out. Finally, the test results are applied to numerical analysis. The results of anchor forces calculated by considering the coupled condition and ignoring the groundwater's effect are compared with the monitoring results of engineering site. The comparison indicates that numerical results are inconsistent with measured results. The numerical results are close to the measured results only when the fluid-solid coupling theory of unsaturated soil is considered.*

***Streszczenie.** W artykule przedstawiono wyniki badań dotyczących budowy głębokich fundamentów oraz ich utrzymania, w odniesieniu do ich odporności na pojawiające się czynniki (siły) zewnętrzne. Analizie poddano dane dotyczące sił kotwiczących fundamentów, zapewniających stabilność budowli, a w szczególności tzw. roztwór glebowy. Otrzymane wyniki zostały porównane z wynikami badań nie uwzględniającymi roztworu glebowego oraz wielkościami pomierzonymi. W ten sposób wykazano duży wpływ tego czynnika na wyniki analiz. (**Symulacje i analiza danych monitorowania sił kotwiczących w głębokich fundamentach**)*

Keywords: Sensors, Anchor forces, Numerical simulation, Soil water characteristic curve.
Słowa kluczowe: czujniki, siły kotwiczące, symulacja numeryczna, charakterystyka roztworu glebowego.

1. Introduction

With the development of high-rise buildings and utilization of underground space, the number of deep foundation pit engineering is increasing, and supporting structures security problems and economic issues become more and more prominent. Excavating and supporting of deep foundation pit, which is related to projects' own security, as well as security of adjacent buildings and facilities, is one of the most risky tasks in engineering construction. Therefore, it is highly regarded by designers, project managers, and even surrounding residents. However, the design of supporting structures is affected by many uncertain factors, among which great variability of the spatial distribution and property parameters of soil is especially essential. The security of supporting structures cannot rely merely on calculation results, but on quality control, management, and the use of information-feedback construction. Deformations and forces of the supporting structures should be monitored in real time. It can not only ensure the project's security, but also deepen the understanding of changing law of forces and deformations of supporting structures by accumulating measured data, and provide scientific and reliable basis for further optimal designs.

Earth pressure is the major load acting on the foundation pit supporting structures. Therefore, reasonable and accurate determination of earth pressure is critical for the security and economy of supporting structures. Pile anchor supporting method is a widely used supporting form at present. The method of determining the earth pressure is still based on Rankine or Coulomb's earth pressure theory. However, the existing research results show that the values of actual earth pressure acting on the supporting structures are far different from those calculated by using the Rankine or Coulomb's earth pressure theory [1]. Thus the determination of earth pressure remains an important issue which needs to be tackled urgently. The actual measurement of earth pressure is rather complex, and there are many factors affecting the test results, among which the laying quality of earth pressure cell is especially important. Relatively speaking, the monitoring process of anchor forces is simpler and easier, and the influencing factors are fewer. At the same time, the test techniques are simpler, and the test results have higher accuracy. Therefore, it is a simpler and more reliable way to understand the earth pressure by monitoring the anchor forces. This is because the anchor forces of the pile anchor supporting structures, to some extent, reflect the values of soil pressure acting on the supporting structures. The anchor forces are monitored in situ, the measured data is analyzed, and finally, the values and distribution law of earth pressure acting on the supporting structures can be known [2]. It is of great practical significance for optimizing the designs of supporting structures of deep foundation pit.

In this paper, a case of deep foundation pit engineering is studied, a whole monitoring of the actual anchor forces is taken in the process of tensioning, locking and working of anchors, and the monitoring data is analyzed. On this basis, problems of earth pressure acting on the supporting structures are studied further. The research results have significant reference value to the design of similar engineering.

2. Sensor monitoring technology in deep foundation pit

At present, the remote automatic monitoring system is more and more popular. It is mainly composed of the in-situ signal acquisition section, remote monitoring unit and data processing and analysis section. In-situ signal acquisition section is a sensor, which is a key element of foundation pit monitoring. Data acquisition equipment is the core component of remote monitoring unit, together with the power supply, lightning protection device, data transmission equipment and other facilities. Data processing and analysis section is made up of computer equipments and application software which can be used for data analysis and processing.

Remote monitoring acquisition unit installed in the construction site is the core component of the automatic monitoring system. It is mainly made up by data acquisition system, power system, data transmission terminals, lightning protection devices and chassis components and other equipments. Remote monitoring collection equipment should have the following characteristics:

(1) Reliability and stability. Long-term stability is an important indicator for evaluating the monitoring system. The monitoring acquisition devices, which are well-known domestic or foreign brands and have high precision and reliability, should be selected.

(2) Compatibility of acquisition equipment. Sensors using for foundation pit monitoring are various. The acquisition equipment must be able to acquire various electrical measuring signals, and easily connect, adjust and replace the sensors.

(3) Power performance fitting for the field. The overall energy consumption of monitoring and acquisition system should be as small as possible. When selecting the data acquisition system, it is preferential to choose the equipment with low power operating mode including automatic timing inspection, auto save and sleep.

(4) Anti-interference performance. The remote monitoring acquisition device should have such characteristics as resistance to high temperature, low temperature, waterproof, lightning protection, prevention of electromagnetic interference. In addition, the self-hardware's isolation device should be able to solve the problems including ground loop problem of the sensor and acquisition system, so as to ensure the accuracy of the acquisition signal in poor natural slope zones.

(5) Remote communication. Remote monitoring acquisition equipment should meet the needs of modern multi-communication mode interface. The transmission distance should be unlimited. It should have RS232 interface and network interface in general, and can use GPRS / CDMA or wireless data transmission device to transmit monitoring data.

In this paper, the anchor force monitoring of deep foundation pit is mainly discussed. Through monitoring the tension change of the anchor rope, the change of slope load can be directly reflected. The anchor forces can be measured by using the resistance strain gauge or anchor dynamometer. Common sensors can be divided into common strain sensor, steel-wire sensor, differential transformer sensor and differential resistance sensor. Generally, the differential resistance sensor and vibrating-wire sensor are mainly selected. According to the actual situation, the sensors should be used selectively. Differential resistance sensor is conducive to long-distance signal transmission, whereas the sensitivity and accuracy of vibrating-wire sensor can be very high, and for that the manufacturer's product quality and processing techniques are highly required correspondingly. For instance, the ANCLO resistance strain load gauge of Roctest Ltd. in Canada is often used in automatic monitoring of the slope. Its sensor is a high strength steel, heat treated or aluminum cylinder which can bear a heavy load and can work in harsh environment. The resistance strain gage is attached to the outer surface by the form of full bridge. So the structure can be used to compensate for the unbalanced load distribution. Using high impedance strain gage can not only reduce the impact of the electric cables, but also compensate for temperature changes from the surrounding environment. The KCB load sensor of TML Ltd. in Japan can also meet the needs of monitoring the slope anchor forces.

3. Case study

3.1 Project overview

A project is presented in this section, and the pile-anchor supporting structure is selected to reinforce the deep foundation pit. The top of the pile is 2.5 m below natural ground, the retaining wall is taken above -2.5 m, and the slope protection piles with three prestressed anchors are taken below -2.5 m. Main formation parameters are presented in Table 1. Groundwater condition is shown in Table 2. Prestressed anchor parameters are shown in Table 3. Other details such as the monitoring program and the measuring points are shown in Literature 2 and 3.

Table 1. Physico-mechanical parameters of soil layers

Layers	Soil type	Layer thickness [m]	Unit weight [kN/m^3]	Cohesion [kPa]	Internal friction angle [°]
1	Plain fill	2.0	19.0	4	8
2	Silty clay	2.0	18.7	16.3	30
3	Sandy silt	2.0	20.2	8.5	30.7
4	Fine silty sand	1.0	20.0	0	30
5	Clay	3.2	19.3	27.9	11.4
6	Fine sand	3.5	20.0	0	35
7	Silty clay	10.0	20.1	33	16

Table 2. Groundwater conditions

NO.	Type of underground water	Still water level of ground water	
		Buried depth [m]	Elevation [m]
The first layer	Phreatic water	12.50 ~ 13.20	31.90 ~ 33.35
The second layer	Macro-artesian	33.60 ~ 34.50	15.71 ~ 16.20

3.2 Analysis of monitoring data

Fig.1 shows the axial forces of the anchor during construction, namely, change curve of the axial forces over time. The prestress loss caused by the tensioning and locking is large. The next few days after tensioning and locking, there is a slight loss of the prestress in the anchor, then each anchor force does not continue changing with the underneath soil excavation, and remains at a stable value. When excavating to the design elevation, the average tension of the first, second and third anchor are respectively

180 kN, 305 kN and 210 kN, which are respectively only 53.65%, 32.87% and 39.95% of the designed tension. It indicates that the actual soil pressure has great difference with Coulomb and Rankine's earth pressure theories. The values of designed prestress and real values of each layer after tensioning and locking are shown in Table 4. Notice that the prestress loss can be up to 30 ~ 50%.

These monitoring results show that the actual tension of the anchor is only about 1/2 of the designed tension calculated by theoretical calculation and it is much smaller than the theoretical value. It can be concluded that the practical earth pressure acting on the supporting structure is much smaller than the theoretical value of earth pressure.

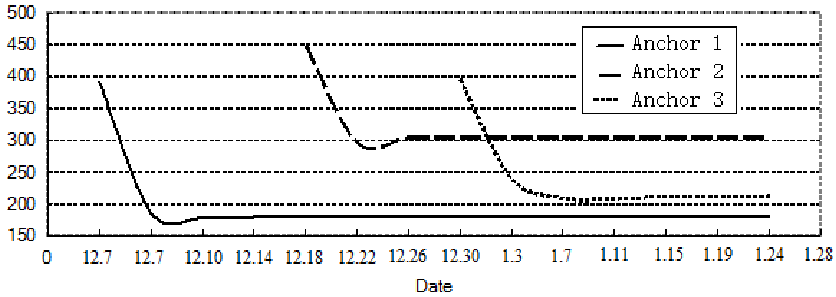

Fig.1. Change curves of the anchor forces with time

Table 3. Prestressed anchor parameters

Anchors	Buried depth [m]	Bore diameter [mm]	Reinforcement of anchor [mm]	Length of anchor [m]
The first anchor	2.7	150	3×7Φ5	24 (The free section is 8.0m)
The second anchor	8.0	150	4×7Φ5	22 (The free section is 6.0m)
The third anchor	12.0	150	4×7Φ5	22 (The free section is 5.0m)

Table 4. Prestress loss conditions

Anchors	Designed tension [kN]	Designed prestress [kN]	Prestess values after locking [kN]	Tension values after excavating to the designed elevation [kN]	Rate of prestress loss [%]
The first anchor	450	400	185.4	180.0	53.65
The second anchor	540	450	302.1	305.0	32.87
The third anchor	450	400	240.2	211.4	39.95

4. Numerical analysis of fluid-solid coupling model of unsaturated soil

4.1 Fluid-solid coupling equation

The fluid-solid coupling mathematical model of unsaturated soil consists of stress field control equation, seepage field control equation and corresponding boundary and initial conditions [3]. Based on former study, the following equations are obtained,

(1) Equilibrium equation

For unsaturated soil, the relationship between stress and deformation can be described as follows:

$$\{\Delta\sigma\}=[D]\{\Delta\varepsilon\}-[D]\{m_H\}(u_\alpha-u_w)+\{\Delta u_\alpha\} \quad (1)$$

Base on principle of virtual displacement, the finite element equation of formula (1) is:

$$\int\{\varepsilon^*\}^T\{\Delta\sigma\}dV=\int\{\delta^*\}^T\{F\}dV \quad (2)$$

Solve Eq. (2) and get:

$$\sum[B]^T[D][B]\{\Delta\delta\}+\sum[B]^T[D]\{m_H\}\langle N\rangle\{\Delta u_w\}=\sum F \quad (3)$$

In Eq. (3):

$[K]=[B]^T[D][B]$, $[L_d]=[B]^T[D]\{m_H\}\langle N\rangle$, $\{m_H\}^T=\left\langle\frac{1}{H}\ \frac{1}{H}\ \frac{1}{H}\ 0\right\rangle$, and the equilibrium equation is:

$$[K]\{\Delta\delta\}+[L_d]\{\Delta u_w\}=\{\Delta F\} \quad (4)$$

(2) Porous medium equation

Based on Darcy law, porous medium equation of unsaturated soil is:

$$\frac{k_x}{\gamma_w}\frac{\partial^2 u_w}{\partial x^2}+\frac{k_y}{\gamma_w}\frac{\partial^2 u_w}{\partial y^2}+\frac{\partial\theta_w}{\partial t}=0 \quad (5)$$

In Eq. (5), k_x, k_y is the osmotic coefficient in the direction of x, y; γ_w is the volume weight of water; θ_w is the volumetric water content; t is time.

Base on principle of virtual displacement, the following equation of virtual work can be obtained,

$$\int u_w^*\left[\frac{k_x}{\gamma_w}\frac{\partial u_w^*}{\partial x^2}+\frac{k_y}{\gamma_w}\frac{\partial^2 u_w^*}{\partial y^2}+\frac{\partial\theta_w}{\partial t}\right]dV=0 \quad (6)$$

By the finite element theory, Eq. (6) can be simplified as,

$$-\int \frac{1}{\gamma_w}[B]^T[K_w][B]\{u_w\}dV$$

(7) $$-\int \langle N^T\rangle\langle N\rangle\left\{\frac{\partial(\omega u_w)}{\partial t}\right\}+\int\langle N\rangle^T\{m\}^T[B]\left\{\frac{\partial(\beta\delta)}{\partial t}\right\}dV$$

$$=\int\langle N\rangle^T v_n dA$$

In Eq. (7):

$[K_f]=[B]^T[K_w][B]dV$, $[M_N]=\langle N^T\rangle\langle N\rangle$,

$[L_f]=\int\langle N\rangle^T\{m\}^T[B]dV$.

Solve the above formula and get

(8) $$\beta[L_f]\{\Delta\delta\}-\left(\frac{\Delta t}{\gamma_w}[K_f]+\omega[M_N]\right)\{\Delta u_w\}=$$

$$\Delta t\left(\{Q\}|_{t+\Delta t}+\frac{1}{\gamma_w}[K_f]\{u_w\}|_t\right)$$

Through solving the balance equation, the continuity equation and the corresponding boundary conditions, the coupled equation can be obtained. The volumetric water content θ_w can be obtained by using soil-water characteristic curve tests.

(3) Soil water characteristic curve

Soil water characteristic curve (SWCC) can describe the relationship between unsaturated soil matric suction and water content. By analyzing and researching the relationship between unsaturated soil matric test data of the SWCC, researchers can initially establish the SWCC equation and apply this equation to the actual engineering analysis.

Through a lot of lab tests, several SWCCs of some typical soil in Beijing are shown in Fig. 2. Some typical soil values of undisturbed soil intake are similar; the value is approximately equal to 0.1 kPa. As for the residual, the value is about 1MPa to 3 MPa. For silt, the value is approximately equal to 1.2 MPa. Undisturbed soil that has similar physical properties can be evaluated by using the reference values [4].

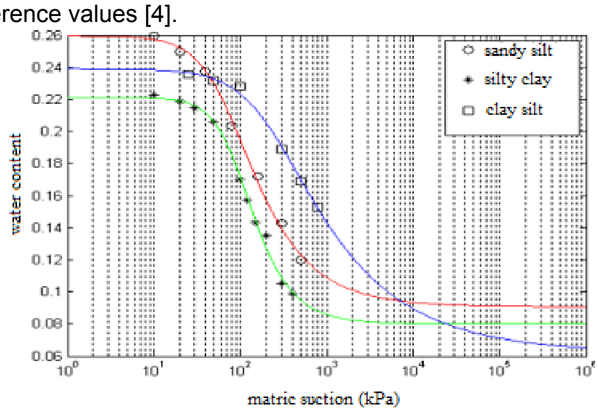

Fig.2. Soi water characteristic curves of some typical soil

4.2 Numerical model and numerical results

This project is simulated by using the GEO-Studio2007 which is a finite element program [5]. The length of the model is 55 m, while the height is 30 m; as to theEexcavation range, the length is 22 m and the height is 12 m, and the finite element model is shown in Fig. 3.

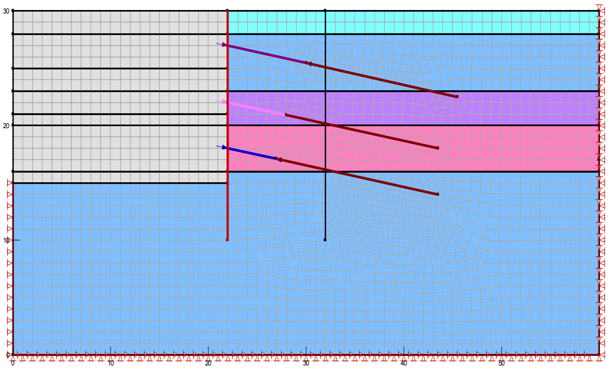

Fig.3. A finite element model

In this model, two cases are considered, one is not to take groundwater into account, and the other one is to use the fluid-solid coupling model of unsaturated soil. The numerical results are shown in Fig. 4 and Fig. 5.

Fig. 4 shows the changes of anchor forces with time when groundwater is considered. The axial force of the first anchor is 192.3 KN, while the second is 290.4 KN and the third is 203.9 KN.

In Fig. 5, the groundwater is not considered. The axial force of the first anchor is 178.7 KN, while the second is 262.8 KN and the third is171 KN.

The numerical calculation and field measurement values are shown in Table 5. Table 5 shows the comparison of measured anchor forces with the calculated ones. The results of the fluid-solid coupling model of unsaturated soil are close to the measured ones.

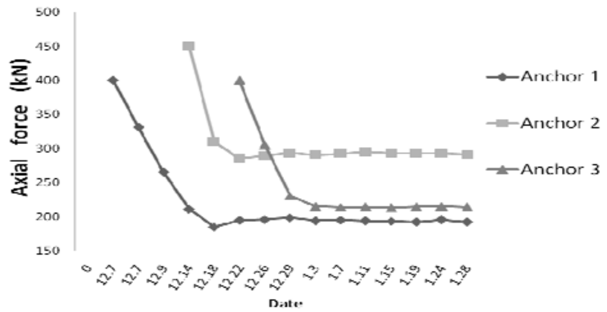

Fig.4. The anchor forces when coupling

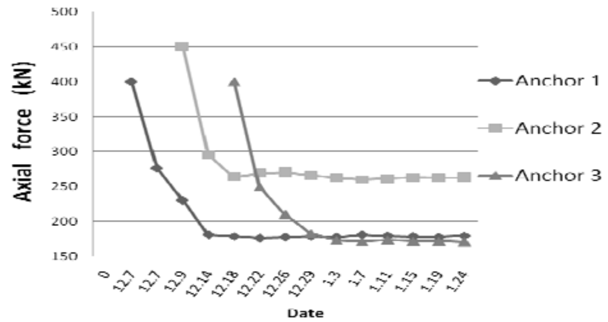

Fig.5. The anchor forces when groundwater is not considered

Table 5. The comparison between measured values and calculated values

Anchor	The first [kN]	The second [kN]	The third [kN]
Measured values	197.4	297.5	212.0
Calculated values	192.3	290.4	203.9
Calculated values without considering groundwater	178.7	262.8	171.0

5. Conclusions

(1) The prestress loss caused by the tensioning and locking is large, and it does harm to the control of the support structure's deformation. So it deserves more attention.

(2) The next few days after tensioning and locking, there is a slight loss in the prestress. Then, anchor forces do not change obviously over time, which ultimately remains at a relatively stable value. It is different from the theoretical calculation and numerical analysis results.

(3) In the process of foundation pit construction, the fluid-solid coupling model of unsaturated soil can properly describe the coupling relationship between stress field of soil and groundwater seepage field. Values of anchor forces obtained by calculation are close to measured values obtained by field monitoring, and the results are slightly different while not considering the groundwater effects.

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