Comparative In-situ Test and Numerical Simulation on Underreamed Ground Anchor

Gang Guo 1*, Zizhou Xue 1, Xiaochen Hu 1, Guang Zhong 2 and Zhong Liu 1

1Central Research Institute of Building and Construction of MCC Group, Beijing 100088, China
2Nanchang Rail Transit Group Limited Corporation, Nanchang 330038, China
*Corresponding author’s e-mail: charlie4322@163.com

Abstract. Underreamed ground anchor is an anchorage technology of safety and economy. Engineering companies worldwide developed various types of underreamed anchors with partially enlarged anchor body. In recent years, a kind of cylindrical underreamed ground anchor with geotextile bag is applied in China. Because of its corrosion resistant performance and high construction guarantee rate, the underreamed ground anchor with geotextile bag is widely recognized. In order to study its mechanical performance, a comparative in-situ test between the underreamed anchor and normal shaft anchor is held in China. Through the test, the advantages of bearing capacity and deformation performance are analyzed. Based on the test, the numerical model of cylindrical underreamed anchor is established, and the relationship between its capacity and the response of the surrounding soil is researched.

1. Introduction

In the worldwide technology area, there are three method to increase the capacity of anchor: composite bolt anchor [1], re-grouting anchor [2], and underreamed anchor [3]. Among the three anchorage technologies, because of high capacity, durability, and safety, underreamed anchor has gained good development. Taiwan area invented a cone-shape underreamed anchor [4], Sweden applied Atlas Soilex anchor system [5], France developed Soletanche anchor, Czechoslovakia adopted Blasting underremed anchor [6], Jet-grouting underreamed ancho appeared in Europe [7], Soil-mixing underreamed anchor has been applied in Japan [8], and underreamed anchor with geotextile bag was invented in China [9].

The advantages of underreamed anchors are obviously, but there are still technical defects in some underreamed anchor systems. Article [9] and [10] reported technical problems of some underreamed anchors in applications, the anchors may acquire low capacity because of construction method, soil property, and mechanical equipment. For guaranteeing the construction quality, the Chinese engineering company developed the underreamed ground anchor with geotextile bag. The anchor body is shown in Figure 1.

In order to study the bearing mechanism of this type of underreamed anchor, a comparative in-situ test between the cylindrical underreamed anchor and normal shaft anchor is held in China. The test data states the advantages of underreamed anchor than normal anchor. Based on the test, the numerical simulation of cylindrical underreamed anchor under uplifting is established for analyzing the relationship between the bearing capacity and soil response. The research results can provide design basis for engineers and designers.
2. Comparative in-situ test

Test data of engineering technology is necessary for engineers to learn its properties. The comparison between the capacities of underreamed anchor and traditional shaft anchor can help to realize the engineering properties and mechanical characteristics.

Based on the above reasons, the comparative test is held in China to study the improvement of the mechanical properties of the anchor because of partial anchor body enlarged.

The soil formations corresponding to the test are as follows.

1) Fill with gray color and soft plastic property consists of silty clay, mucky clay, and some brickbat with humics. The filled years is more than 10 years.

2) Mucky clay with gray color and flowing plastic property includes some silty clay with soft plastic condition. The layer has medium dry strength and medium toughness.

The relationship between the soil layer and the anchors are shown in Figure 2.

Figure 2. Diagram of anchors and soil layers in the comparative test.

The physical and mechanical parameters of the soil in the test site are listed in Table 1.

Table 1. Physical parameters of the soil layers in the test site.

| No. | $W$ (%) | $g$ (kN/m$^3$) | $e$  | $c$ (kPa) | $\phi$ (°) | $E_s$ (MPa) | $I_l$ |
|-----|---------|---------------|------|-----------|------------|-------------|------|
| ①  | 36.4    | 17.7          | 1.063| 10        | 14.3       | 3.62        | 1.08 |
| ②  | 33.3    | 17.8          | 1.000| 12        | 14.6       | 3.87        | 0.92 |
In the test, 3 underreamed anchors (short for KM anchors) and 3 shaft anchors (short for PM anchors) are included, the sizes of the anchors are shown in Figure 2. Most of the anchor bodies are embeded in the mucky clay, as shown in Figure 2.

Twenty-eight days after the installation, the static test began to the 6 anchors. In the test, the load value and the displacement value of every load step are recorded, and the load versus displacement (Q-s) curves of the 6 anchors is drew. It is noteworthy that all the 6 anchors reached their ultimate bearing capacities.

Figure 3a shows the Q-s curves of the underreamed anchors. It can be seen that the three underreamed anchors have different ultimate bearing capacities, 450kN, 375kN and 525kN respectively when the anchors are failed, the mean ultimate bearing capacity of the 3 anchors is 450kN. And the ultimate displacements are 96.12mm, 103.00mm and 98.60mm corresponding to the ultimate bearing capacities of the 3 anchors.

Figure 3b demonstrates the Q-s curves of the 3 shaft anchors. It shows the ultimate bearing capacities of the 3 anchors are 300kN, 300kN and 245kN, and the mean value is 275kN, when the anchors are failed. Thus, it can be seen the bearing capacity of an underreamed anchor is 63.6% higher than a normal shaft anchor.

![Q-s curves of the 3 underreamed anchors.](image1)

![Q-s curves of the 3 shaft anchors.](image2)

Figure 3. Test curves of the anchors.

Table 2 lists the maximum load values and the corresponding displacement values of the 6 anchors. Besides, the load values of the load steps before the anchor fails are also listed in Table 2 together with the corresponding displacements, elastic deformations and plastic deformations.

| No. | Max. Load (kN) | Max. Displacement (mm) | Prior Load (kN) | Prior Displacement (mm) | Elastic Deformation (mm) | Plastic Deformation (mm) |
|-----|----------------|------------------------|----------------|-------------------------|--------------------------|-------------------------|
| KM1 | 450            | 96.12                  | 375            | 32.21                   | 14.37                    | 16.54                   |
| KM2 | 375            | 103.00                 | 300            | 31.56                   | 12.14                    | 19.42                   |
| KM3 | 525            | 98.60                  | 450            | 42.85                   | 19.07                    | 23.78                   |
| PM1 | 245            | 114.90                 | 225            | 40.50                   | 8.35                     | 32.15                   |
| PM2 | 300            | 59.20                  | 245            | 11.72                   | 4.32                     | 7.40                    |
| PM3 | 300            | 59.30                  | 245            | 19.12                   | 8.22                     | 10.90                   |

According to the data in Table 2, the plastic deformations of the 3 underreamed anchors account 51.4%, 61.55% and 55.5% in the total displacements. While the proportions of the plastic deformations of the 3 shaft anchors are 79.4%, 63.1% and 57.0% respectively. Thus, the proportion of the plastic deformation in the total displacement of the underreamed anchor is less than that of the normal anchor. It can be concluded that the underreamed anchor has better deformation control ability.

Besides, in order to compare the displacements and plastic deformation values of the two types of anchors, Table 3 lists the corresponding values when the uplift load values are 225kN and 300kN.
It can be seen in Table 3, when the load reaches 225kN, the mean displacement of the underreamed anchor is 15.65mm, and the mean plastic deformation is 11.41mm. Under the same uplift load value, the mean displacement of the shaft anchor is 21.67mm, and the mean plastic deformation is 16.31mm. Thus, the total displacement and plastic deformation of the underreamed anchor is less than those of the shaft anchor under the same load. When the load is 300kN, the total displacements of shaft anchors is much higher than that of underreamed anchor. The test phenomena illustrate the underreamed anchor has better deformation control ability.

Table 3. Deformation analysis on various anchors in comparison test.

| No. | Load of 225kN | Load of 300kN |
|-----|--------------|--------------|
|     | Displacement (mm) | Plastic Deformation (mm) | Displacement (mm) | Plastic Deformation (mm) |
| KM1 | 12.63         | 9.65         | 22.50         | 14.88         |
| KM2 | 20.92         | 16.35        | 31.56         | 19.42         |
| KM3 | 13.40         | 8.23         | 18.80         | 11.18         |
| PM1 | 40.50         | 32.15        | -             | -             |
| PM2 | 10.02         | 6.45         | 59.20         | -             |
| PM3 | 14.51         | 10.35        | 59.30         | -             |

3. Numerical simulation

Based on the above in-situ test, the numerical model of underreamed ground anchor under uplifting load is built. Besides the basic model of the in-situ test, the numerical models with various lengths of normal section, various lengths and diameters of underreamed section, together with various shear strength parameters of soil are all analyzed. By the numerical simulation, the load transfer law and the reaction of the soil are studied.

In accordance with the principle of controlling scale and guaranteeing accuracy, the numerical model is simplified as follows.

1) The model is three-dimensional axial symmetrical, so the model is a quarter of a whole model, as shown in Figure 4. While the data process will adopt the total force of a whole model.

2) There is a contact surface between the anchor and the soil. During the loading procedure, the friction parameter of the contact surface will be constant.

3) The anchor and soil are both isotropic bodies.

![a. Numerical model of underreamed anchor (part).](image1)

![b. Numerical model of underreamed anchor and soil.](image2)

Figure 4. Numerical model.

By applying displacement on top of the anchor model, the total load $Q$, the friction of normal section $Q_{sd}$, the friction of underreamed section $Q_{sD}$ and the end bearing force $Q_e$ of every
displacement step are gained respectively. Based on the above test data, the force versus displacement ($F$-$s$) curves are shown in Figure 5 together with the in-situ test data.

In Figure 5, the end bearing force increases in the total bearing capacity of the anchor, while the two friction components increase before the displacement of 20mm, and then they decrease. When the displacement reaches 40mm, the end bearing force takes account of 39.3% in the total bearing force. When the displacement is 160mm, the end bearing force takes account of 48.6%. So, the end bearing force is the main component in the bearing capacity of an underreamed anchor.

Figure 5. Force against displacement curves of the numerical model of underreamed anchor.

Figure 6 shows the plastic zone of soil in several load steps. Comparing the 4 patterns, when the displacement is less than 10mm, the plastic zone occurs around the shear surface of the anchor body. When the displacement reaches 30mm, a mass of soil around the anchor body and on top surface of the underreamed section gets plastic state. After that, with the displacement going on, the soil around the shear surface of the anchor remain its state, but more and more soil on top of the underreamed section gets plastic state. Combined with Figure 5, the shear force provides the bearing capacity of the anchor because of the resistance of the soil around the shear surface of the anchor at the beginning of loading. When the uplift displacement beyond 30mm, the shear resistance is constant, and the end bearing force becomes the main component of the bearing capacity. When the resistance of the soil acts sufficiently, the plastic zone performs like an ellipsoid.
Through the analysis of the plastic zone of soil, the cause of the development of the capacity components is clear. At the beginning of loading, the two friction components act and dominate the total bearing capacity. Under the friction of anchor, the soil around the shear face of the anchor becomes plastic state, and the plastic zone gets bigger with the increase of the anchor friction. After the displacement of 30mm, the friction components will not increase any more, and the plastic zone around the shear surface will not extend. While the end bearing force will increase with the extension of the plastic zone on top of the underreamed section. So, it can be assumed that the end bearing force will keep increasing only if the corresponding plastic zone cannot extend any more. When the displacement reaches 160mm, the height of the plastic zone on top of the underreamed section $h_0$ is 1.286m, and the semi-minor axis $a$ is 0.668m.

Based on the basic model, the diameter of the underreamed section $D$, the length of the normal section $H$, the cohesion of the soil $c$, and the friction angle of the soil $\phi$ are varied. Table 4 lists the sizes of the plastic zones of the underreamed anchor models with various working conditions. From the data, it can be seen the size of plastic zone is positive correlational with the diameter of the underreamed section $D$, and is negative correlational with the length of the normal section $H$, while is independent with the shear strength parameter of the soil.

| Working condition | Semi-minor axis $a$ (m) | Height of failure area $h_0$ (m) | Semi-major axis $b$ (m) | $t=b/a$ |
|-------------------|-------------------------|---------------------------------|------------------------|--------|
| $D=400mm$         | 0.331                   | 0.629                           | 0.493                  | 1.49   |
| $D=600mm$         | 0.57                    | 0.828                           | 0.821                  | 1.44   |
| $D=800mm$         | 0.668                   | 1.286                           | 0.972                  | 1.45   |
| $H=4m$            | 0.981                   | 2.062                           | 1.651                  | 1.68   |
| $H=8m$            | 0.818                   | 1.717                           | 1.312                  | 1.60   |
| $H=12m$           | 0.668                   | 1.286                           | 0.972                  | 1.45   |
| $H=16m$           | 0.529                   | 1.064                           | 0.715                  | 1.35   |
| $c=10kPa$         | 0.668                   | 1.286                           | 0.972                  | 1.45   |
| $c=30kPa$         | 0.668                   | 1.286                           | 0.972                  | 1.45   |
4. Conclusions
In order to get the mechanical performance of undreamed ground anchor, a comparative in-situ test between undreamed anchor and normal shaft anchor is held in China. Based on the test data, a numerical model of undreamed ground anchor under uplift is established. By the above research, some conclusions are achieved.

1) In muck clay, the ultimate bearing capacity of the undreamed anchor is 63.6% higher than that of the shaft anchor, and the total displacement of the undreamed anchor is 27.78%~38.50% lower than that of the shaft anchor in the same condition. Besides, the undreamed anchor has less plastic deformation.

2) Compared to normal shaft anchor, the undreamed anchor can shorten its length, control the displacement, increase its capacity with a part of anchor body expanded.

3) At the beginning of loading, the plastic zone occurs in the soil around the shaft surface of the undreamed anchor. With the uplift displacement increasing, an ellipsoid plastic zone extending in the soil on top of the undreamed section because of the end bearing force of the anchor.

4) The improvement of end bearing force comes from the shear strength of more soil. The size of plastic zone is positively correlational with the diameter of the undreamed section $D$, and is negatively correlational with the length of the normal section $H$, while is independent with the shear strength parameter of the soil.

Acknowledgments
This work was supported by Beijing Natural Science Foundation (8184098).

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