Underreamed Anchor with Geotextile Bag and Its Hyperbolic Load versus Displacement Model for Capacity Prediction

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Abstract. Underreamed ground anchor technologies have been developed to increase the capacity of ground anchors referring to reamed piles worldwide. To solve the problem of low anchor cement strength caused by muck and slag in the borehole for a traditional underreamed anchor, this paper introduces an underreamed ground anchor with a geotextile bag. Its structure and installation process are both discussed in detail. Based on the test data from 24 underreamed anchors with geotextile bags at 6 construction sites all over China, a hyperbolic model of the relationship between the load and displacement is presented to predict the capacity of a cylindrical underreamed anchor. Compared with the measured values, the predicted capacities of pointed displacements out of the tested range were sufficiently accurate for engineering practice.

1. Introduction

In the traditional ground anchor engineering field, the capacity of an anchor is one of its most important properties, and increasing the load capacity can improve the economic benefit. Scholars and engineers worldwide believe that an anchor’s capacity is proportional to its length, diameter, and interaction with the soil [1–2]. Further, because of soil property limits, the friction between the anchor and soil is hard to improve. Moreover, the capacity will not increase when the anchor section reaches a certain length [3–5].

Increasing the diameter of a portion of the anchor section not only increases the friction area between the anchor section and the soil, but also changes the bearing mechanism because of the appearance of the underreamed section. Moreover, because the end surface of the expanded section compresses the soil, it brings the end capacity into the capacity of the underreamed anchor, and completely changes the simple frictional bearing mechanism of a traditional shaft anchor. The force distribution of an underreamed ground anchor is shown in Figure 1.

To meet the need for a geotechnical tensile member with high capacity in modern building construction, underreamed ground anchor technologies have been rapidly developed in recent decades. These underreamed ground anchor technologies include those based on jet grouting [6–7], mechanical reaming [8–9], and blasting [10–11].

In the first two reaming techniques, it is difficult to guarantee a clear borehole, which causes the anchorage section to become mixed with soil chips and the strength to become weak. In addition, many countries forbid blasting in cities for blasting anchors because of safety concerns.
To improve the capacity and resistance to permanent deformation of a ground anchor by expanding a portion of the anchor section, and overcome the drawbacks of the above existing underreamed anchor technologies, this paper will introduce a new kind of underreamed ground anchor with a geotextile bag (GB). With the assumption of a reliable strength for the anchor cement, a hyperbolic model for describing the load versus displacement relationship and predicting an unknown capacity value corresponding to a specific displacement value is presented based on the test data from 24 GB anchors at 6 construction sites across China. It is worth pointing out that this hyperbolic model is also suitable for other types of underreamed anchors with cylindrical underreamed sections.

![Diagram of force distribution of an underreamed anchor](image)

**Figure 1.** Diagram of force distribution of an underreamed anchor with (d) diameter of the normal anchor section; (H) embedment depth; (L) length of underreamed section; (D) diameter of underreamed section; (Q_{sd}) friction of normal section; (Q_e) end bearing capacity; (Q_{sd}) friction of underreamed section.

2. Underreamed anchor with geotextile bag
In contrast to the existing underreamed anchorage technologies, this innovative underreamed anchor with a GB consists of a specially designed structure for the GB device, which comprises two sealing chamber plates held in place by steel tubes, a sleeved grouting pipe, and a thin inflatable bag. The tendons, which are either strands or bars, pass through the steel tubes and are fixed to the end bearing plates with anchor blocks and gripping wedges or nuts, as seen in figure 2. The capsule is made of geotextile materials, including high-density polyethylene, polyvinylchloride, and poly-p-phenylene terephthalamide.

The bag around the central steel structure can be folded to a diameter of 130 mm, which allows it to be inserted into a borehole with a diameter of 160 mm. During the construction process, the GB device with tendons can be installed by means of borehole drilling, or reaming by jet grouting or a mechanical reamer. Cement grout is then injected into the bag. By utilizing such a GB device, a cement grouted cylindrical body with the designed volume can be achieved underground. In practice, the nominal diameter of a GB device ranges from 0.4 to 1.0 m, and the length varies from 1.0 to 3.0 m, depending on the soil properties and designed uplifting load.

Relying on the above special structure and assembly technique, the GB device with tendons can easily be inserted into a borehole with a diameter of 150–180 mm, and the bag can be inflated by cement grout with a water-cement ratio of 0.4–0.5, with an injection pressure of 1–3 MPa in practice. According to the project’s design and ground conditions, the actual geometrical shape and dimensions of the GB device can be adjusted based on the required uplift load. In addition, the compressive strength of the grout inside the bag can be greater than 25 MPa, and the bag can be enclosed in surrounding dense cement soil.
In recent years, because of their significant technical, environmental, and economic advantages, innovative anchoring systems have been applied in deep excavation, anti-floating, and slope protection projects [12].

![General configuration of GB anchor with (1) external grouting pipe, (2) joint, (3) proximal sealing chamber, (4) internal grouting pipe, (5) unidirectional grouting valve, (6) cement grout, (7) geotextile bag, (8) tendon, (9) steel tube, (10) distal sealing chamber, (11) sealing strip, (12) bearing plate, (13) anchorage point, and (14) end cap.](image)

Figure 2. General configuration of GB anchor with (1) external grouting pipe, (2) joint, (3) proximal sealing chamber, (4) internal grouting pipe, (5) unidirectional grouting valve, (6) cement grout, (7) geotextile bag, (8) tendon, (9) steel tube, (10) distal sealing chamber, (11) sealing strip, (12) bearing plate, (13) anchorage point, and (14) end cap.

Briefly, the construction team will assemble the tendons with the GB device, and drill a borehole at the designed position. Then, they will ream the borehole at the designed level, and install the whole anchor system, which includes the tendons and GB device, as shown in figure 2. Finally, cement grout will be pumped into the bag of the GB device and the borehole. The construction flow chart is shown in figure 3.

![Construction process flow of underreamed anchor with capsule.](image)

Figure 3. Construction process flow of underreamed anchor with capsule.
It is worth pointing out that the GB device isolates the cement grout from the surrounding soil and soil chips produced from reaming. Thus, the GB device can ensure that the anchor’s strength is higher than that of the surrounding soil foundation. All of the field tests mentioned below in this paper adopted GB anchors as an underreamed anchor technology.

3. Hyperbolic model for capacity prediction of underreamed anchor

Under most engineering conditions, the capacities of underreamed anchors are controlled by the displacements of the anchor heads. On the one hand, underreamed anchors are tensile members that connect structures and the soil, and a large displacement will be dangerous. On the other hand, ground anchors are all flexible members. They are easier to break because of a large deformation, which makes them unsuitable for further service without reaching the limit state of their bearing capacity [13].

Test data from field tests are the most reliable means of determining the capacity of an anchor. However, because field tests are always affected by many factors and the high capacity values and many failure modes of underreamed anchors must be taken into consideration, it is difficult to determine the ultimate uplift bearing capacity, which is controlled by the soil foundation under most conditions. For example, because the ultimate bearing capacity of an underreamed anchor is always higher than that of a shaft anchor, most of the existing loading equipment and counterforce devices for anchors cannot reach the high loading demand. In another situation, the construction budget or anchor structure limit causes the ultimate bearing capacity to be controlled by the tendons, and it is hard to load the anchor to its ultimate uplift bearing capacity or the displacement value specified by the designers. Because the underreamed anchor is a new anchoring technique, determining its ultimate bearing capacity or the capacity corresponding to some certain displacement not only assists in acquiring its bearing characteristics, but also assists in a reasonable design.

To solve the contradiction between the high load demand and the test condition limit, this paper establishes a hyperbolic model that describes the load versus displacement relationship of a GB anchor based on 24 GB anchors at 6 construction sites across China, as shown in equation (1). It is noteworthy that a hyperbolic model is sometimes adopted in the pile engineering field [14]. This paper first presents a hyperbolic model that is suitable for an underreamed anchor and its application.

\[
Q = \frac{a \cdot s}{b + s} \quad (1)
\]

where, \(a, b\) -constant terms, \(s\) -displacement of anchor head.

From equation (1),

\[
\frac{s}{Q} = \frac{1}{a} \cdot \frac{s + b}{a} \quad (2)
\]

set \(\frac{1}{a} = A, \frac{b}{a} = B\) in equation (2),

\[
\frac{s}{Q} = A \cdot s + B \quad (3)
\]

In equation (1), the constant terms \(a\) and \(b\) have clear mathematical meanings; when \(s \rightarrow \infty\) and \(Q \rightarrow a\), this illustrates that the constant term \(a\) is the asymptote as the displacement approaches infinity. In the model, it can represent the theoretical ultimate bearing capacity, which is noted as \(Q_t\). While \(s \rightarrow 0\), the derivative of \(Q, Q' \rightarrow ab\), and \(ab\) is the initial slope of the hyperbolic curve.

In practice, equation (1) can calculate the theoretical ultimate bearing capacity \(Q_t\), and predict the capacity value corresponding to some displacement specified by the designers based on test data.
Although equation (1) can directly illustrate the relationship between the load and displacement of an underreamed anchor, it is difficult for engineers to fit by hand in practice. For this reason, equation (3) is more convenient and recommended.

Using equation (3), it is possible to plot the scatter diagram between \( s/Q \) and \( s \) based on the test data. Then, a straight line needs to be drawn according to the distribution state of the test points, and the points of \( s/Q-s \) must be uniformly distributed on the two sides of the line. Finally, the values of \( A \) and \( B \) can be determined by measuring the slope of the line and the intercept of the vertical axis. This process will become much easier when a computer is adopted. From equation (3), the reciprocal proportion of \( A \) is the theoretical ultimate bearing capacity \( Q_u \).

The test data from 24 GB anchors at 6 construction sites were used to verify the above method. In order to analyze the errors in this method, this study assumed that the last test point of every GB anchor was unknown, and the last test points were not used in the fitting. These last test points were all used as verifying points. When verifying, the displacement values \( s_u \) of the last test points were substituted into the corresponding fitted formulas separately, and the corresponding capacity values \( Q_c \) were calculated according to equation (4). Then the calculated capacity values \( Q_c \) were compared with the load values \( Q_u \) of the last test points. After several trials, the first point of every GB anchor was found to be unsuitable for fitting, and these first test points were all removed from the fitting. Figure 4 to figure 9 show the test data and fitting results by equation (3).

\[
Q_c = \frac{s_u}{As_u + B} \tag{4}
\]
value of anchors that reached the limited state, the calculation error of only the GB anchors tested in East China and North China reached their limit state. Among the test anchors, average value of 0.982. This shows that the fitting is reasonable.

In addition, the error of \(t\) is calculated according to equation (4).

The data in table 1 show that the correlation coefficient \(R^2\); theoretical ultimate bearing capacity \(Q_u\); and the capacity \(Q_c\) corresponding to the last “unknown” displacement \(s\), where \(Q_c\) is calculated according to equation (4), are all listed in table 1.

| Anchor Name | \(A\)  | \(B\)  | \(R^2\) | \(Q_u\) (kN) | \(Q_c\) (kN) | Error of \(Q_u\) | \(s\) (mm) | \(Q_c\) (kN) | Error of \(Q_c\) |
|-------------|-------|-------|-------|-----------|-----------|----------------|-----|-----------|----------------|
| East No.1   | 1.52  | 38.20 | 0.978 | 450       | 657       | 46.10%         | 96  | 521       | 15.84%         |
| East No.2   | 1.15  | 68.95 | 1.000 | 375       | 871       | 132.15%        | 103 | 550       | 46.67%         |
| East No.3   | 1.28  | 41.12 | 0.984 | 525       | 779       | 48.30%         | 99  | 588       | 11.95%         |
| South No.1  | 0.27  | 55.16 | 0.999 | 1166      | 3689      | 216.49%        | 117 | 1346      | 15.47%         |
| South No.2  | 0.24  | 54.21 | 0.992 | 1034      | 4230      | 309.10%        | 71  | 1005      | -2.77%         |
| South No.3  | 0.41  | 41.29 | 0.988 | 1166      | 2410      | 106.80%        | 98  | 1194      | 2.43%          |
| Capital No.1| 0.47  | 18.22 | 0.997 | 1360      | 2150      | 58.14%         | 73  | 1401      | 3.02%          |
| Capital No.2| 0.51  | 19.34 | 0.995 | 1360      | 1976      | 45.30%         | 84  | 1360      | 0.05%          |
| Capital No.3| 0.50  | 17.80 | 0.979 | 1458      | 1998      | 37.09%         | 83  | 1398      | -4.08%         |
| Southeast No.1| 0.52 | 74.71 | 0.993 | 840       | 1938      | 130.67%        | 134 | 930       | 10.76%         |
| Southeast No.2| 0.85 | 48.39 | 0.996 | 800       | 1170      | 46.28%         | 124 | 804       | 0.51%          |
| Southeast No.3| 0.60 | 54.50 | 0.958 | 950       | 1659      | 74.59%         | 132 | 984       | 3.56%          |
| Central No.1| 0.52  | 65.61 | 0.966 | 1000      | 1923      | 92.34%         | 143 | 1022      | 2.16%          |
| Central No.2| 1.00  | 49.51 | 0.932 | 650       | 1005      | 54.62%         | 82  | 626       | -3.64%         |
| Central No.3| 0.91  | 50.89 | 0.984 | 900       | 1101      | 22.33%         | 213 | 872       | -3.13%         |
| Central No.4| 1.27  | 51.45 | 0.994 | 800       | 785       | -1.92%         | 281 | 686       | -14.23%        |
| North No.1  | 0.78  | 26.46 | 0.991 | 781       | 1289      | 65.11%         | 84  | 918       | 17.57%         |
| North No.2  | 1.12  | 22.53 | 0.995 | 639       | 891       | 39.49%         | 98  | 739       | 15.68%         |
| North No.3  | 1.20  | 15.72 | 0.982 | 609       | 830       | 36.29%         | 99  | 734       | 20.49%         |
| North No.4  | 1.26  | 13.81 | 0.998 | 568       | 793       | 39.54%         | 79  | 696       | 22.49%         |
| North No.5  | 0.64  | 30.77 | 0.986 | 1092      | 1553      | 42.20%         | 170 | 1213      | 11.05%         |
| North No.6  | 0.52  | 33.16 | 0.967 | 1183      | 1926      | 62.84%         | 132 | 1298      | 9.73%          |
| North No.7  | 0.48  | 27.68 | 0.995 | 1045      | 2083      | 99.36%         | 61  | 1073      | 2.66%          |
| North No.8  | 0.66  | 39.06 | 0.977 | 1045      | 1524      | 45.87%         | 179 | 1144      | 9.51%          |

The data in table 1 show that the correlation coefficient has a range of 0.932–1.000, with an average value of 0.982. This shows that the fitting is reasonable.

In addition, the error of \(Q_c\) is quite large. The largest error is 309.1%. This is because most of the tested GB anchors did not reach the limit state of their uplift bearing capacity. Among the test anchors, only the GB anchors tested in East China and North China reached their limit state. Among the 11 GB anchors that reached the limited state, the calculation error of \(Q_c\), compared with the last tested load value of \(Q_u\) accounted for 36.29–99.36%, except for the East No. 2 anchor. Because the ultimate...
bearing capacity of the East No. 2 anchor is much lower than those of the other two tested anchors under the same test condition, it is believed that this phenomenon was caused by accident, and the value is not representative of the statistical analysis.

The calculation errors for the results of $Q_e$ are small compared to the measured values of $Q_u$. With the exception of the East No. 2 anchor, the calculation errors for the other 23 tested GB anchors ranged from −14.23% to +22.49%, which is sufficiently accurate for engineering practice. It is noteworthy that the prediction results for the above GB anchors could be higher than the measured values. This may cause a danger in engineering when using the predicted capacity values, but when a safety factor range of 1.5−2.0 is taken into consideration in anchor design, the prediction is reasonable and sufficiently safe.

4. Conclusions
This paper first introduced an innovative underreamed ground anchor with a GB, together with its structure and installation method. Based on the GB anchor technology, the test data for 24 anchors at 6 construction sites across China were gathered. Finally, a hyperbolic model describing the relationship between the load and displacement was presented and verified.

1) The particular GB device for a GB anchor could effectively isolate the grout cement of the anchor from the surrounding borehole environment in order to ensure the quality and dimensions of the anchor section of the GB anchor. In contrast to the traditional underreamed ground anchor, the GB anchor can enable the soil foundation to exert its bearing capacity adequately.

2) A hyperbolic model describing the relationship between the load and displacement of a cylindrical underreamed anchor was established. Using this model, the theoretical ultimate bearing capacity and a capacity value corresponding to a specified displacement value outside the scope of the test data could both be acquired. Between the above two predicted capacity values, the latter had a fairly high accuracy. This prediction method is suitable to use in engineering practice to solve the difficulty of reaching the ultimate uplift bearing capacity of an underreamed anchor in field tests.

3) Underreamed ground anchor technologies have been widely used in China in recent decades. While their use is always based on experience, so their applications are not in economical and reasonable conditions. Much more test data need to be accumulated, especially for test anchors that have reached that limit states. The test data are not only helpful in engineering practice, but also contribute to a correct understanding of its bearing mechanism.

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