Behavior of bladder-type inflatable anchors in sand: Physical modeling

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Abstract
This paper describes an investigation into the performance and pull-out capacity of a bladder-type inflatable anchor. The inflatable anchor is a type of support member used in foundation pit support engineering. Based on improvements and innovations, the multi-bladder-type inflatable anchor consists of two or more hydraulically inflated rubber membranes that are embedded in unconsolidated earth and then inflated to provide pull-out capacity. The primary objective of this study was to investigate the impact of inflation pressure, embedment depth, number of bladders, bladder length, and rubber film thickness on the pull-out capacity and displacement of the inflatable anchor. The tests were carried out in a cylindrical steel test chamber filled with medium coarse sand. The pull-out behavior of the bladder-type inflatable anchor and the five variables was investigated, and the benchmark values for all tests are determined by similarity ratio. Compared with the single bladder inflatable anchor, under the same conditions, the ultimate pull-out capacity of the two bladder-type inflatable anchor is 1.2 times higher, with ultimate displacement only 37.5% of the former, the ultimate pull-out capacity of the three bladder-type inflatable anchor is 1.7 times higher, with ultimate displacement only 32.3% of the former. The two bladder-type inflatable anchor is superior to the single bladder inflatable anchor and the multi-bladder-type has higher ultimate pull-out capacity and greater stiffness. The inflation pressure and the rubber film thickness have a significant influence on the bearing capacity. The number of bladders effectively controls the ultimate displacement.

Keywords
Physical model, bladder-type, inflatable anchor, ultimate pull-out capacity, ultimate displacement

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Engineered geotechnical anchors can improve the strength and stability of near surface slopes and soil masses and prevent potential hazards such as collapse, sliding, and subsidence by generating pull-out resistance due to interaction with deep, stable stratum. In 1891, anchoring technology was adopted in mine tunnel support in the U.S. for the first time. In recent years, anchoring technology developed rapidly in the engineering fields of deep excavation, dam reinforcement, anti-floating structures, slope, and so on. The requirement to tolerate higher tension forces with lower anchor displacements has resulted in the development of new types of anchors, such as end expanding anchors and inflatable anchors.

The end expanding anchor achieves the anchoring effect through end-bearing friction produced by high-pressure-jet grout injection technology. Grout injection through the anchor shaft results in a relatively large diameter grout bulb at the bottom of the anchor. The main disadvantages of the end expanding anchor include difficult construction and hole collapse. Inflatable anchors, which can be used instead of end expanding anchors, were designed and tested in soft clay and sand to eliminate the problems encountered when end expanding anchors are used. Inflatable anchor designs include an anchor rod and a rubber film, and were initially used to restrict the movement of remotely operated vehicles. Newson et al. conducted a simple laboratory test of inflatable anchors to identify and quantify the main factors controlling their pull-out capacity. Their study suggested a formula to calculate the bearing capacity and found that the ultimate pull-out capacity of the filled anchor is four times that of a screw anchor under comparable conditions. Newson’s subsequent study using offshore soft clay found the dissipation of excess pore water pressure can improve the bearing capacity of the inflatable anchor by 30%. Based on Newson’s test data, Newson et al. carried out finite element numerical analysis of the performance of the inflated anchor rod assembly. It was concluded that the inflation pressure and the anchor length were the major factors influencing the bearing capacity of the anchor. The ultimate pull-out capacity of the inflatable anchor is comparable to, or even higher than, that of the grouted anchors. Nevertheless, the inflatable anchors tested still could not meet the requirements for the ultimate bearing capacity and displacement. To improve the pull-out performance a multi-bladder inflatable anchor was proposed, which consists of a stainless-steel pipe and several deformable rubber bladders. When the inflation pressure is low, the weight of the anchor and the friction resistance between the rubber membrane and the soil make a major contribution to the ultimate pull-out resistance of the anchor. With the increase of inflation pressure, the rubber film gradually expands and the contact area between the anchorage section and the soil becomes larger and soil adjacent to the bladders is also compressed. This process causes the working mechanism of the anchor to transit from friction type to end resistance-friction type with an improvement of bearing capacity.

This paper describes our experimental exploration of the mechanical properties and deformation behaviors of bladder-type inflatable anchor systems in sand. Through a series of scaled physical model tests in a chamber filled with dry sand,
the impact of several variables on pull-out capacity and displacement were examined. These included inflation pressure, embedment depth, number of bladders, bladder length, and rubber film thickness. The tests help to identify the degree to which the various factors influence the ultimate pull-out capacity of bladder-type anchor systems.

**Model test chamber**

*Structure and characteristics of the bladder-type inflatable anchor*

The structure of the proposed multi-bladder-type inflatable anchor system is shown in Figures 1 and 2 and is designed to increase end resistance. This type of anchor consists of a stainless-steel tube with a sealed top and bottom and several bladders made of rubber film. The tube is 1.2 m in length with a wall thickness of 3 mm and a diameter of 27 mm. To provide sufficient inflation pressure, an air inlet orifice with a diameter of 4 mm is installed in the anchorage section. The upper and lower control valves at the top of the anchor are used to control the inflation pressure. The pressure gauge under the lower control valve is used to show the inflation pressure during the test. The bladders can be rapidly inflated with air which passes through multiple holes which are drilled in the steel tube prior to placing the one-piece bladder sleeves. The designed bearing capacity can be achieved as soon as the bladders are inflated, thus shortening the construction period relative to grouted anchors. When used in the field the anchor rod assembly can be deflated via the control valve and the rod can be removed and recycled as soon as construction is completed. The proposed multi-bladder system is simple to operate, conserves time and cost, is pollution-free, environmentally friendly, and does not change the original mechanical properties of the soil layer. In addition, the proposed design is especially suitable for applications in weak soil layers.

![Figure 1. Schematic of the structure of the three bladder-type inflatable anchor system tested.](image-url)
When the anchor is not pressurized or the inflation pressure is low, its pull-out force is mainly derived from the side friction resistance between the soil and the rubber membranes, and also from the anchor’s weight stress. When the inflation pressure is increased, the rubber membrane expands, and the increased volume compacts the surrounding soil, which not only increases the contact area between the anchoring section and the soil but also causes compaction of the soil adjacent to the bladder. The inflatable bladder anchor rod has thus been changed from the original friction type to the end bearing-friction type.

The similarity principle and model test design

The similarity principle as used in engineering and design points out that if systems of a prototype and a model are similar, each corresponding element (including geometric elements and physical elements) in them will have a certain proportional relationship. This makes it possible to predict the physical quantities of a prototype based on the physical quantities that can be measured in a model. The similarity ratio \((C)\) is the ratio of the model physical quantity \((m)\) to the prototype physical quantity \((p)\). If we define \(L\) for length, \(γ\) for unit weight, \(δ\) for displacement, \(σ\) for stress, \(ε\) for strain, \(E\) for elastic modulus, \(σ_t\) for tensile strength and \(σ_c\) for compressive strength, then,

1. Geometric similarity ratio, \(C_L = \frac{δ_m}{δ_p} = \frac{L_m}{L_p}\)
2. Stress similarity ratio, \( C_s = \frac{(\sigma_m)}{(\sigma_p)} = \frac{(\sigma_c)}{(\sigma_c)} = \frac{\sigma_m}{\sigma_p} \)

3. Strain similarity ratio, \( C_E = \frac{E_m}{E_p} \)

The similarity relationship for the model and prototype’s stress similarity ratio \( C_s \), unit weight similarity ratio \( C_g \), and geometric similarity ratio \( C_L \) is \( C_s = C_g \times C_L \).

The similarity relationship for the displacement similarity ratio \( C_d \), geometric similarity ratio \( C_L \), and strain similarity ratio \( C_E \) between model and prototype is \( C_d = C_L \times C_E \).

The relationship of the elastic modulus similarity ratio \( C_E \), the strain similarity ratio \( C_E \) and the stress similarity ratio \( C_s \) of the model and the prototype is \( C_s = C_g \times C_L \).

In the model test performed in this study, the known geometric similarity ratio \( C_L = 10 \), unit weight similarity ratio \( C_g = 1 \) and other similar coefficients are calculated from the relationships derived above, as shown in Table 1.

### Table 1. Model similarity coefficient.

| Parameter                  | Similarity Coefficient, \( C \) |
|----------------------------|----------------------------------|
| Displacement, \( u \)      | 10                               |
| Elastic modulus, \( E \)   | 10                               |
| Shear strength, \( \tau \) | 10                               |
| Cohesion, \( c \)          | 10                               |
| Stress, \( \sigma \)       | 10                               |
| Friction angle, \( \phi \) | 1                                |
| Unit weight, \( \gamma \)  | 1                                |
| Moisture content, \( e \)  | 1                                |

### Experimental setup

The tests were carried out in a sandbox which consist of rectangular steel and organic glass chamber, as shown in Figures 3 and 4. The sandbox is of 1.8 m in height, 1.0 m in width, and 1.8 m in length. The chamber was constructed with five # Angle steel (corner uprights and crossmembers) to accommodate walls of organic glass about 10 mm thick. The completed sand box was placed in the test frame and a set of crown blocks was used to transfer load. A three-phase motor attached to a gearbox (200:1 gearing ratio) and screw jack was used to pull out each anchor. The motor was controlled by computer-based software (JMZX-3001) to maintain a constant pull-out rate. The displacement at the anchor head was measured using a linear voltage displacement transducer (LVDT) mounted on the same load frame as the screw jack.
A high-pressure air pump was used to inflate the bladders using a stepwise approach, with one load made every 3 min, and each load stage providing about $1/10$ to $1/15$ of the ultimate load. Readings were taken every 1 min after loading began. The test device and a schematic are shown in Figures 3 and 4.

**Figure 3.** Schematic diagram of the experimental device.

**Figure 4.** Sandbox and pull-out experiment devices.

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**Instruments and equipment**

The main instruments and equipment used in the test are shown in Table 2.
Medium coarse sand with particle size distribution shown in Table 3 and Figure 5 was used for the test. Specific gravity was tested by following ASTM D854-14. The maximum and minimum dry densities were determined in conformance with ASTM D4253-16e1. According to the Unified Soil Classification System (USCS) and ASTM D2487-17, the sand was classified as well-graded (SW). Table 4 summarizes the physical and mechanical parameters.

### Materials and properties

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#### Table 2. The main instruments and equipment used in the test.

| Instrument and device | Model and specification | The role of instruments in experiments |
|-----------------------|-------------------------|---------------------------------------|
| Tension sensor        | The model is WTP301S and the measuring range is 1000 N | Measure the pull-out force on the anchor rod |
| Displacement sensor   | The model is JMDL-21XX, with a range of 50–100 mm and a sensitivity of 0.01 mm | Measure the displacement of inflatable anchor rod during pullout |
| Pressure gauge        | The measuring range is 0.25 MPa and the precision is 0.01 MPa | Measure the air pressure inside the anchor rod and bladders during the entire test |
| Digital pressure gauge| The model is PY500, and the instrument accuracy is 0.001 MPa | Display the change of the pressure on the tension sensor |
| Comprehensive tester  | The model is JMZX-3001, the measuring range is 600–3500 Hz, and the accuracy is 0.1% ± 0.1 Hz | Displays the displacement change of the displacement sensor |
| Loading system        | The loading system is composed of a group of crown block (two crown block) and several sandbags with the same weight | This loading system is used to carry out the graded loading of the inflatable anchor rod |
| Air pressure source   | A high-pressure pump, which is equipped with a pressure gauge with a measuring range of 2.0 MPa and an accuracy of 0.05 MPa | Provide air pressure source for inflatable anchor rod |

#### Table 3. The particle size distribution of medium-coarse sand.

| Grain diameter (mm) | Percentage (%) |
|---------------------|----------------|
| 5                   | 4.35           |
| 2                   | 1.56           |
| 1.25                | 44.17          |
| 0.315               | 43.60          |
| 0.16                | 3.36           |
| 0.15                | 2.5            |
| 0.08                | 0.52           |
Test procedure

The test soil was medium coarse sand taken from a nearby river bank and screened for 5 mm grain size after natural air drying. The sand test soil was prepared according to the methods and requirements of “Geotechnical test Method Standard GBT50123-1999.” Density, particle analysis, specific gravity and consolidation quick shear were determined for the sand. The procedure for the test included:

1. Cleaning up the test chamber before placing the anchor,
2. Burying the anchor in medium-coarse sand by air pluviation and compacting it in layers to reach the desired in-place physical properties.
3. Installing the tension sensor and LVDT, connecting the air compressor to the anchor, and recording the initial values.

Table 4. The physical and mechanical parameters of sand.

| Property                        | Sands  |
|---------------------------------|--------|
| Specific gravity, G_s           | 2.67   |
| Particle size distributions: D60(mm) | 0.40   |
| Particle size distributions: D30(mm) | 0.22   |
| Particle size distributions: D10(mm) | 0.20   |
| Coefficient of uniformity, Cu   | 2.00   |
| Coefficient of curvature, Cc     | 0.605  |
| Dry density, \( \rho_d \) max (g/cm^3) | 1.74   |
| Dry density, \( \rho_d \) min (g/cm^3) | 1.43   |
| Relative density, \( \rho_d \) (g/cm^3) | 0.69–0.76 |
| Void ratio, \( e_{max} \)       | 0.97   |
| Void ratio, \( e_{min} \)       | 0.634  |

Figure 5. Gradation curve of medium-coarse sand.
4. When the inflation pressure approached the design value, the pull-out tests were step loaded every 2 min and the test values were recorded until the anchor failed to resist the pulling force.

5. The pull-out capacity and displacement data were analysed.

The anchor we used, with 10 mm between bladders, and our experiment are based on a research paper by Peng Wenxiang, “Model Test Study on Bladder-type Inflatable Anchor.” The aim of choosing 10 mm between two 5 mm bladders was to make it possible to more easily compare our results with the 10 mm single-bladder anchor. The embedded depth values refer to the theory of sliding surface in soil mechanics, it is based on the sliding surface and the free section of the anchor.

Based on the previous studies on inflatable anchor systems, five factors (inflation pressure, embedment depth, the quantity of bladder, length of bladder, and thickness of rubber film) were investigated. Table 5 summarizes the conducted tests.

**Experimental results**

Through a series of tests, the pull-out behaviour of the bladder-type inflatable anchors was investigated. The variables studied cover inflation pressure, embedment depth, bladder length, rubber film thickness, and the number of bladders. The benchmark values for all tests were determined using a similarity ratio considering the boundary conditions and the properties of materials. The conditions for the experiments were, an inflation pressure of 50 kPa, embedment depth 600 mm, bladder length 50 mm, rubber film thickness 1 mm, the number of bladders two, and a spacing between the bladders of 10 mm.

**Effects of inflation pressure**

Figure 6 indicates the effect of adjusting inflation pressure on the pull-out resistance of the bladder-type inflatable anchor. The inflation pressure was varied from 0 to 100 kPa. It can be seen that the pull-out capacity and ultimate displacement of the anchor increases with the increase of inflation pressure. As the inflation pressure changes from 0 to 100 kPa, the pull-out capacity varies from 0.043 to 0.223 kN, and the pull-out capacity of the two bladder-type inflatable anchor with 50 mm anchorage length increases approximately 5.2 times. The displacement at the maximum pull-out capacity grows from 7.65 to 11.86 mm, an increase of approximately 4.6 times.

In Figure 6 the result of the 50 kPa-test is compared with the result of the 100 kPa inflation pressure test. When the inflation pressure is increased from 50 to 100 kPa, the pull-out capacity reaches 0.524 kN, which is 2.4 times more than before. Meanwhile, the ultimate displacement reaches 35.72 mm, which is three times more than before.
| No | Inflatable pressure (kPa) | Thickness of rubber (mm) | Anchorage length (mm) | Numbers of bladders | Distance between bladders (mm) | Embedded depth (mm) | Pull-out capacity (kN) | Ultimate displacement (mm) |
|----|--------------------------|--------------------------|-----------------------|---------------------|-------------------------------|---------------------|------------------------|---------------------------|
| 1  | 0                        | 1                        | 50                    | 2                   | 10                            | 600                 | 0.043                  | 7.65                      |
| 2  | 50                       | 1                        | 50                    | 2                   | 10                            | 600                 | 0.223                  | 11.86                     |
| 3  | 100                      | 1                        | 50                    | 2                   | 10                            | 600                 | 0.524                  | 35.72                     |
| 4  | 0                        | 1                        | 100                   | 1                   | 10                            | 600                 | 0.044                  | 7.73                      |
| 5  | 50                       | 1                        | 100                   | 1                   | 10                            | 600                 | 0.231                  | 31.91                     |
| 6  | 100                      | 1                        | 100                   | 1                   | 10                            | 600                 | 0.526                  | 52.31                     |
| 7  | 50                       | 1                        | 50                    | 2                   | 10                            | 400                 | 0.128                  | 5.80                      |
| 8  | 50                       | 1                        | 100                   | 1                   | 10                            | 400                 | 0.186                  | 17.81                     |
| 9  | 50                       | 1                        | 50                    | 1                   | 10                            | 600                 | 0.192                  | 31.62                     |
| 10 | 50                       | 1                        | 150                   | 1                   | 10                            | 600                 | 0.282                  | 33.29                     |
| 11 | 50                       | 1                        | 100                   | 2                   | 10                            | 600                 | 0.327                  | 18.17                     |
| 12 | 50                       | 1                        | 150                   | 2                   | 10                            | 600                 | 0.371                  | 31.27                     |
| 13 | 50                       | 2                        | 50                    | 2                   | 10                            | 600                 | 0.081                  | 5.57                      |
| 14 | 160                      | 2                        | 50                    | 2                   | 10                            | 600                 | 0.715                  | 36.45                     |
| 15 | 50                       | 1                        | 50                    | 3                   | 10                            | 600                 | 0.322                  | 10.23                     |
A single point in the graph for the test with 0 kPa and the last point of the curve slope refer to the failure of the anchor, and the conditions were:

1. Rubber film broken. After expansion, the rubber film can easily be punctured by sharp objects in the soil layer. In addition, the elastic plastic deformation norm of rubber film is limited. When the inflation pressure exceeds the ultimate inflation pressure, the rubber film will rupture due to over expansion.
2. The stress process in the soil around the enlarged bladder results in failure by passing through three stages: static soil pressure stage, transition stage, and densification and expansion stage of the plastic zone. If the external load tension on the bolt increases continuously, shear failure will occur when the soil reaches the full plastic state, and the anchor will be pulled out of the soil.

Referring to Figure 7, it can be seen that inflation pressure has similar influences on single and two bladder-type inflatable anchors. However, with the increase of pressure, the two bladder-type inflatable anchor more effectively reduces displacement than the single type. This is due to the number of contact points between the rubber membrane and the soil. Another factor is that the single bladder type inflatable anchor is attached to the steel tube at fewer points than the double bladder-type.

Effects of embedment depth

Figure 8 shows the comparison of pull-out performance between the single and two bladder-type, with the embedment depth from 40 to 60 cm. As the embedment depth increases, the ultimate pull-out capacity of the inflatable anchor is significantly improved. When the embedment depth of the anchor increases from 40 to 60 cm, the bearing capacity of the two bladder-type inflatable anchor varies from 0.128 to 0.223 kN, an increase of 73.6%. However, the pull-out capacity of the single bladder anchor changes from 0.186 to 0.231 kN, an increase of only 24%.

It can be seen that the bearing capacity of the two bladder-type inflatable anchor increases faster than the single bladder-type with the rise of embedment depth. This can be explained by two factors. The most important is likely the compression of
soil surrounding the inflated section of the anchor which results in higher confining pressure. The additional factor is a consequence of the addition of constant anchorage length (i.e. 10 cm). The increase in embedment depth is analogous to adding the length of the anchor rod, thus adding an additional mass to the column of soil above the bladder which must be lifted to allow displacement.

**Effects of bladder length**

Figure 9 presents the load-displacement curves of the bladder-type inflatable anchor with different bladder lengths. When the bladder length is 5 cm, the peak pull-out resistance and the ultimate displacement of the anchor are 0.223 kN and 11.86 mm. When the bladder length is increased to 10 and 15 cm, the peak pull-out capacities of the anchor increase by 0.104 and 0.148 kN; the displacements corresponding to the peak value increase by 6.31 and 19.41 mm, respectively. As shown in Figure 9, an increase of pull-out capacity of both single and double bladder-type inflatable anchors results from the increase of bladder length.

**Effects of rubber film thickness**

Figure 10 shows the effect of rubber film thickness on the pull-out performance of the two bladder-type inflatable anchor. With 1 mm thick rubber film, the ultimate pull-out capacity of the two bladder-type inflatable anchor is 0.223 kN with a displacement of 11.86 mm. When 2 mm thick rubber film was used the ultimate pull-out capacity of the two bladder-type inflatable anchor becomes 0.081 kN with a displacement of 5.57 mm, decreases of 63% and 53%, respectively. The decrease is due to the elastic modulus of the membrane. The film thickness restricts the membrane deformation (i.e. it does not enlarge as much).
The limit of inflation pressures for 1 and 2 mm thick rubber films are 100 and 160 kPa, based on our tests. The load-displacement curves of membranes with different thicknesses under their limit pressure are shown in Figure 11. It can be concluded that the limit pull-out capacity and the displacement of the 2 mm thick two bladder-type inflatable anchor are about 1.3 and 1.1 times more than the 1 mm thick two bladder-type.

**Effects of bladder numbers**

The test results of this section are shown in Figures 12 and 13. The pull-out performance of the anchor in Figure 12 is based on the bladder length of 10 cm for both

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**Figure 10.** Anchor pull-out force versus displacement for different rubber film thickness (the inflation pressure is 50 kPa and the embedment depth is 60 cm).

**Figure 11.** The load-displacement curves of rubber films with different thickness under limit pressure.
the single and the double bladder-type inflatable anchor. As shown in Figures 12 and 13 the ultimate pull-out capacity of the two bladder type agrees with the single bladder type. The ultimate displacement of the single bladder-type is higher in these tests compared with the two bladder-type. The ultimate displacement of the two bladder-type inflatable anchor is 37% less than the single bladder-type. This result indicates that more bladders can effectively control the ultimate displacement. The main influencing factors are that as more bladders are adopted, the contact surface of bladders on the soil is increased, and the friction-resistance force area is increased. Therefore, adopting more bladders under the corresponding conditions can effectively control the final displacement and deformation.
Figure 13 shows the relationship between the ultimate displacement and pull-out capacity of three bladder-type inflatable anchors with different anchorage lengths. The ultimate pull-out capacity and displacement of the two bladder-type inflatable anchor was 1.2 times more and 37.5% less than the single bladder-type inflatable anchor. The ultimate pull-out capacity and displacement of the three bladder-type inflatable anchor was 1.7 times more and 32.3% less than the single type.

**Comparative analysis**

To determine whether a new type of anchor has a higher bearing capacity than those currently in use, the most direct method is to compare and analyze it with traditional anchors. Screw-type anchors are widely used in China and overseas, with many scholars having conducted in-depth studies of them.\(^{23–26}\) In loose sand, the test conditions of the relevant literature are consistent with this article.\(^{27}\) The results are listed in Table 6. The data is based on calculation methods for inflatable anchor ultimate bearing capacity suggested by Peng et al.\(^{27}\)

It can be seen from the test results that in the loose sand used in this study, the ultimate bearing capacity of the traditional screw anchor is low. The ultimate bearing capacity of the bladder-type inflatable anchor is about 4.3 times that of the single screw anchor, as well as 1.9 times the double screw type. Bladder-type inflatable anchors provide obvious advantages over screw anchors.

**Conclusion**

Based on physical model tests of several bladder-type inflatable anchor systems in cohesionless soil, the following conclusions are drawn:

1. The pull-out performance of the bladder-type inflatable anchors is dependent on the inflation pressure, embedment depth, length of the bladder, rubber film thickness, and the number of bladders. Among the five main influencing factors, the inflation pressure and the rubber film thickness generate a significant influence on the bearing capacity of bladder-type
inflatable anchors. An increase in the number of bladders effectively reduces the ultimate displacement.

2. Multi-bladder inflatable anchors are superior to single bladder inflatable anchors with higher ultimate pull-out capacity and greater stiffness. Compared with single bladder inflatable anchors, under the same conditions, the ultimate pull-out capacity of the two bladder-type inflatable anchor is 1.2 times higher, with ultimate displacement only 37.5% of the former, the ultimate pull-out capacity of the three bladder-type inflatable anchor is 1.7 times higher, with ultimate displacement only 32.3% of the former. The results show clear benefits for the use of bladder-type inflatable anchors in engineering applications.

3. The study of the bladder-type inflatable anchor is based on ideal assumptions, and many problems still needed to be investigated.

4. If the anchor can be put into production, processing, and commercialization, it will solve the problems of insufficient anchor capacity, excessive rod length, and poor economics of traditional anchoring methods in soft soil areas. The design method of the bladder-type inflatable anchors in soft soil areas is proposed during our research, and calculation parameter values are provided according to the characteristics of different soil layers, which fills gaps both at home and abroad.

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