Test and Design Method for the Performance of Anchor Nodes between an Underreamed Anti-floating Anchor and the Bottom Structure

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Abstract. The number of applications of underreamed anchors with high bearing capacities rapidly increases with the increase in building volume. Scholars and engineers worldwide have reported their researches on the bearing mechanisms and failure modes of underreamed anchors. However, the high capacity of anchors generates new problems for building structures, including the key design point of the anchor node between the high-capacity anchor and the structure in anti-floating engineering. Currently, there is no relevant research report or technical standard. To address this issue, a series of full-scale tests on steel anchor plates are conducted in Nanjing, China. Through these tests, a regular set of test results is obtained. Based on the obtained results, a calculation method for the bearing capacity of the anchor plate is derived, and a complete design method for the anchor node is presented. Furthermore, waterproofing and anti-corrosive construction methods for the anchor node are discussed to perfect the design work of the anchor node.

1. Introduction
In recent years, underreamed anchor technology has been applied in geotechnical engineering worldwide. Because of its high bearing capacity, strong deformation control ability, and low cost, it has gained a wide acceptance in the construction industry. There have been numerous studies on the theoretical analysis and application of underreamed anchors. Articles [1–4] analyzed the failure modes of underreamed anchors using test methods. Articles [5–7] researched the bearing mechanism of the anchor using finite element methods. Articles [8–10] reported on the applications of the anchor in deep excavations and anti-floating projects. Articles [11–16] discussed various forms of underreamed anchors developed in different countries around the world.

The aforementioned studies illustrate the research status and application situation of underreamed anchors. However, new technical problems have appeared in the application procedure for underreamed anchors, such as in the design method for the anchor node between the underreamed anchor and the bottom structure. Because of its design, the bearing capacity of underreamed anchors is much higher than that of normal shaft anchors [4]. The high capacity of the anchor requires a steel bar with a reasonably high capacity. Screw-thread steel bars for the prestressing of concrete with diameters of 25–40 mm have been applied to the underreamed anchors to meet the high capacity..
requirements. The yield strength of this kind of steel bar ranges from 785 MPa to 1080 MPa, and the tensile strength is from 980 MPa to 1230 MPa. With a steel bar with a capacity up to 1000 kN anchored to the bottom structure, the anchor node needs to be designed using a unique technical method.

For the anchoring method of a steel bar in concrete, the Chinese technical code “Code for design of concrete structures” stipulates that the mechanical anchorage of a steel bar needs to include a hooks with angle of 90˚ or 135˚, a post weld, or a bolt anchor head. However, the international standard ISO 6934-5 stipulates that the screw-thread steel bars for the prestressing of concrete have a high carbon content, and bending or welding is forbidden on the steel bar. Therefore, anchor plates are currently applied to the anchor node between the steel bar of the underreamed anchor and the bottom structure according to experience, as seen in Fig. 1. However, the technical standards and research reports are both lacking in terms of addressing the issue of the anchor plate.

To determine a specific design method for the anchor node between the underreamed anchor and the bottom structure, a full-scale test and theoretical derivation are conducted. In addition, a specific case is utilized to verify the rationality of the design method. Finally, the waterproofing and anti-corrosion of the anchor node are discussed.

2. Full-scale tests on the anchor node
To determine the mechanical properties of the anchor plate between the steel bar and the concrete structure, a series of full-scale tests are conducted in Nanjing, China.

To verify the mechanical properties of the anchor node under various conditions, concrete slabs with thicknesses of 400 mm, 500 mm, and 600 mm, and screw-thread steel bars for the prestressing of concrete with diameters of 32 mm, 36 mm, and 40 mm are adopted for the tests. In addition to the traditional square anchor plate, a circular steel anchor plate with a diameter of 120 mm is also used in the test for comparison.

The full-scale tests mainly consider the thickness of the concrete slab h, the anchorage length of the steel bar in the concrete slab la, the diameter of the steel bar d, and the side length of anchor plate D as well as whether or not there is a spiral stirrup. The classification of the specimens and the arrangement are shown in Fig. 2 and Fig. 3.

(a)Traditional square anchor plate          (b)Anchor plate with spiral stirrup          (c) Circular anchor plate
Figure 2. Types of anchor plates

The steel bars in the test are of class PSB1080, steel plates are of class Q235, and the thickness of each steel plates is 20 mm. The concrete slab is cast with C30 concrete.
After 28 days of maintenance, the loading process of the specimens is as follows.

1) The loading device is set as shown in Fig. 4, including a ring manometer, jack, and electronic displacement meter.

2) An upward drawing force is applied to the specimen, and the force and displacement values are recorded separately.

3) The data are processed.

From the tests on the 12 specimens, the load against displacement curves (Q-s curves) of the specimens are acquired, as shown in Fig. 5.

There are two kinds of results for these tests. One is for the failure of the anchor node, in which the loaded anchor plate is pulled out of the concrete slab. The other is for the load value close to the ultimate strength of the steel bar, in which the test is stopped to prevent danger, such as with the No. 5, No. 10, and No. 12 specimens. The test results are listed in Table 2 for the two failure modes of the anchor nodes.

From Table 1, as the thickness of the concrete slab and the anchorage length of the steel bar in the concrete slab increase, the capacity of the anchor node increases, as can be seen from the comparisons.
between the No. 1 and No. 3 specimens and the No. 6 and No. 8 specimens. It can also be found from Table 2 that the anchor plate with a larger side length has a lower capacity when its thickness is fixed. This phenomenon can be seen from the comparison between the Nos. 1 and No. 2 specimens, together with the No. 6 and No. 12 specimens. In addition, the capacity of the anchor node in some cases can be improved when a spiral stirrup is set on the pressure surface of the anchor plate, as can be seen from No. 1 and No. 4. Finally, comparing the circular anchor plates with the square anchor plates, it can be found that the circular anchor plate has higher capacity than the square anchor plate under the same conditions, such as with the No. 5 and No. 6 specimens. However, from a comparison between the No. 7 and No. 10 specimens, it can be found that the bend strength of only one circular anchor plate cannot meet the high capacity of the steel bar. When two circular anchor plates are applied, they can provide enough bend strength; therefore, there needs to be more thread height in one circular anchor plate in engineering practice.

Furthermore, it can be found from the failure modes of the concrete slab and the anchor plates that when the square anchor plates are applied to the anchor node, most of the anchor nodes fail from the beginning of the large deformation of the anchor plate, and then the concrete is crushed locally by the anchor plate. Finally, punching shear damage occurred in the concrete slab during the loading.

| No. | Thickness of concrete \(h\) (mm) | Anchorage length of steel bar in concrete \(l_a\) (mm) | Diameter of steel bar \(d\) (mm) | Side length of anchor plate (Diameter) \(D\) (mm) | Spiral stirrup | Max. load value \(F\) (kN) |
|-----|--------------------------------|---------------------------------|-------------------------------|---------------------------------|----------------|-------------------|
| 1   | 400                            | 350                             | 40                            | 180                             | no             | 675               |
| 2   | 400                            | 350                             | 32                            | 200                             | no             | 594               |
| 3   | 400                            | 400                             | 40                            | 180                             | no             | 1200              |
| 4   | 400                            | 350                             | 40                            | 180                             | yes            | 825               |
| 5   | 500                            | 450                             | 40                            | 180                             | two circular steel plates on one steel bar | 1350             |
| 6   | 500                            | 450                             | 40                            | 180                             | no             | 825               |
| 7   | 500                            | 450                             | 32                            | 180                             | one circular steel plate on one steel bar | 792                |
| 8   | 500                            | 500                             | 40                            | 180                             | no             | 1125              |
| 9   | 500                            | 450                             | 40                            | 180                             | yes            | 1125              |
| 10  | 500                            | 450                             | 32                            | two circular steel plates on one steel bar | 990              |
| 11  | 600                            | 550                             | 40                            | 180                             | no             | 900               |
| 12  | 500                            | 450                             | 32                            | 120                             | no             | 990               |

Figure 6. Failure modes of anchor nodes

3. Design method for the anchor node

The calculation method is derived to correct a defect in the design method for the anchor node between a ground anchor with a high capacity and the concrete structure. Additionally, the calculation methods for checking the punching resistance and local compression in the Chinese technical standard
“Code for design of concrete structures” are introduced to complete the design method for anchor nodes.

From the above-mentioned full-scale test results, it can be found that in addition to checking the punching resistance and local compression of the concrete structure, checking the strength of the anchor plate is one of the most crucial tasks. Because in the case of steel structures, the shear strength of steel structural members can always meet the requirement of material strength checking when its bending strength checking meets the requirement, only the calculation method on the bending strength of the anchor plate is derived in this article.

As determined from the above-mentioned test results, the circular anchor plate has superior mechanical properties than the square anchor plate. Thus, the steel anchor plate is analyzed. The nut on the plate causes stress on the steel plate $p_1$. The concrete under the anchor plate causes stress on the steel plate $p_2$. To simplify the analysis, the stress caused by the concrete on the anchor plate to the plate is neglected, as shown in Fig. 7.

![Figure 7. Force analysis diagram of the anchor plate](image)

The bending strength of the anchor plate under $p_1$ needs to meet the formula:

$$\frac{M}{W} \leq f,$$

where $M$ —— the bending moment of the anchor plate (N•mm);
$W$ —— the section modulus of the anchor plate (mm$^3$);
$f$ —— the bending strength of the anchor plate (N/mm$^2$).

The bending moment of the anchor plate $M$ can be derived according to Fig. 7(b):

$$M = \int_0^{2\pi} \int_{r_1}^{R} p_1 (\rho - r_1) \rho d\rho d\theta = 2\pi p_1 (\frac{R^3}{3} - \frac{R_1^3}{2} + \frac{r_1^3}{6}),$$

where $p_1$ —— the stress applied on the anchor plate from the concrete (N/mm$^2$);
$R$ —— the outer diameter of the anchor plate (mm);
$r_1$ —— the fixed diameter of the anchor plate (mm).

For the section modulus of the anchor plate $W$, the maximum bending moment appears at the shear face in Fig. 7(a). Therefore, the section modulus $W$ is:

$$W = \frac{2\pi r t^2}{6},$$

where $t$ —— the thickness of the anchor plate (mm).

For the value of stress $p_1$, it can be assumed that the total force of the underreamed ground anchor applies to the entire anchor plate except the hole, which has a radius $r$ in Fig. 7.

$$p_1 = \frac{T}{\pi (R^2 - r^2)},$$

where $T$ —— the force of the underreamed ground anchor (kN);
$r$ —— the inner radius of the anchor plate (mm).

Substituting Formula (2), Formula (3), and Formula (4) into Formula (1), the thickness of the anchor plate can be acquired.
Except for the strength of the anchor plate, the punching shear strength of the concrete slab applied by the anchor plate should be checked with Formula (6) according to the “Code for design of concrete structures”. Additionally, the local bearing capacity of the concrete slab should also be checked with Formula (7).

\[
t \geq \frac{2R^3 - 3R^2r_1 + r_1^3}{\pi r T},
\]

(5)

where

\[ P_w \] —— the groundwater buoyancy applied on the bottom of the punching failure cone (kN);

\[ f_t \] —— the axial tensile strength of the concrete (kPa);

\[ \beta_h \] —— the influence coefficient of section height;

\[ u_m \] —— the calculating section circumference, shown in Fig. 8;

\[ h_0 \] —— the effective height of the punching section (m).

\[
0.7 \beta_u u_m h_0 \geq T - P_w,
\]

(6)

\[
4.05 \beta_c f_c A \geq T,
\]

(7)

where

\[ \beta_c \] —— the influence coefficient of concrete strength;

\[ f_c \] —— the axial compressive strength of concrete (kPa).

4. Waterproofing and anti-corrosion of the anchor node

The waterproof structure of the anchor node is an important element in the ground anchor system. The waterproof structure and measure should be arranged according to the waterproofing grade, and the
grade should be higher than the waterproofing grade of the entire underground structure. The waterproofing measures for the prestressed anchor steel bar through the bottom structure should be the strictest. For important underground structures under high water environments, there should be drainage channels or water-collecting wells for draining away any possible water from the anchor node. A steel bar is always adopted as the anchor tendon to the non-prestressed anti-floating anchor, and the entire anchor node is cast inside the concrete slab. This waterproof configuration is always reliable. Following several years of investigation, the waterproof measures for the anchor node were proved to be effective (Fig. 9).

(a) Sketch of the waterproof node (b) Crystal and seal ring (c) Waterproof node
1—concrete slab, 2—anchor tendon, 4—seal ring, 5—waterproof layer, 6—sealant, 7—cushion layer structure, 8—anchor grouting, 14—anchor plate, 16—nut, 17—nut, 18—crystal

Figure 9. Waterproof structure of the anchor node

Some articles have reported that several anchor heads were corroded by the surrounding soil, water, and air. In the anti-corrosive design and construction procedure, it should be noted that anti-corrosive measures to the anchor head and the anchor tendon near the anchor head are quite important. For key projects, the anchor tendon should be protected by an isolating cube in case of contact with the surrounding soil, water, and air, while the anchor head should be cast inside the concrete or grease to be isolated. During the installation procedure of the anchor head, protection of the anchor head is of utmost significance. Through practice, the anchor node, as depicted in Fig. 9, has a reasonable anti-corrosive function.

5. Conclusions
Through the 12 full-scale tests on the anchor node between the anchor plate and the tendon of the underreamed anchor, the mechanical properties of the anchor node were analyzed. Based on the test results, the capacity of the anchor plate was derived, and the design method was presented together with the waterproofing and anti-corrosion measures. The following conclusions were made based on our investigations.

1) With the help of a spiral stirrup, when the anchor length of the steel bar and anchor plate in a 400-mm-thick concrete slab is 350 mm, the anchor node can reach a capacity of 825 kN. When the anchor length of the steel bar and anchor plate in a 500-mm-thick concrete slab is 450 mm, the anchor node can reach a capacity of 1125 kN.

2) The capacity of the anchor node increases with the anchorage length of the steel bar. The capacity of the anchor node decreases with the increasing side length of the anchor plate when the thickness of the concrete slab is constant. The circular anchor plate has superior bearing properties than does the square anchor plate. In addition, the spiral stirrup has positive effect in improving the capacity of the anchor node.

3) The calculation procedure of the anchor node between the ground anchor and the concrete slab is as follows. First, the diameter of the anchor plate is calculated according to the local compressive strength of the concrete slab. Subsequently, the thickness of the anchor plate is calculated according to the diameter of the plate and the force of the ground anchor. Finally, the punching shear strength of the concrete slab is checked.
4) Waterproofing and anti-corrosive measures are important in the design procedure of the anchor node. Following several years of research, an effective anchor node structure with waterproof and anti-corrosive functions is presented.

5) The above-mentioned design method can not only be applied to underreamed ground anchors but also be adopted in anchor node designs for other types of anchors.

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