Experimental investigation of the anchoring properties of special-shaped cross-section self-drilling bolts

Peng Ningbo¹,² · Hong Jie¹,³ · Dong Yun¹ · Chen Jiarui¹ · Zhu Ye¹ · Sun Bo⁴

Received: 14 November 2021 / Accepted: 21 June 2022 / Published online: 18 July 2022
© The Author(s) 2022

Abstract
This paper designed a special-shaped cross-section hollow self-drilling bolt with discharge grooves, in which Mindlin’s solution of displacement was used in the elastic solution of a wholly grouted bolt. Theoretically, the ultimate pulling force and the residual pulling force were analyzed by considering the average distribution assumption of residual stress. The bolts’ performance with 2, 3, and 4 discharge grooves was compared with circular cross-section bolts, which experimental results are consistent with the theoretical results. The ultimate pulling force and the residual pulling force of the special-shaped cross-section bolt improved significantly according to the circular bolt. The bonding properties of special-shaped cross-section bolts present significant difference to circular section bolts. The residual pulling strength was contributed both by the bar-grout and grout-grout frictions. Upgrading the grout strength may further enhance the pulling strength of special-shaped cross-section bolts.

Keywords Special-shaped cross-section · Self-drilling bolt · Theoretical analysis · Pull-out testing · Anchoring properties

Introduction
Grouted bolts could mobilize and improve the bearing capacity and steady ability of rock masses, reinforce structures with smaller volumes, and further improve construction safety, which have been widely used in contemporary civil engineering constructions such as water conservancy and hydropower, railway transportation, urban construction, underground engineering, mining engineering, etc. (Li and Stillborg 1999; Chen et al. 2016; Masoud et al. 2020; He et al. 2021, 2022; Yang et al. 2022). With continuous technical logical advancements in anchoring bolts and structures, the anchorage force of single bolt has been increased, which consequently inspired innovations in new anchoring technology (Kilic et al. 2003; Chu et al. 2011; Kumar et al. 2021). Hollow self-drilling anchor bolt is one of these new technologies which have been recently developed and applied in various complex geological conditions such as loose sandy soil, soft soil, fluid-plastic soil, and extreme engineering environments. The hollow self-drilling anchor bolt could enable drilling, rod installation, grouting, tensioning, and anchoring in one process, with comparable advantages as higher probability of hole formation, shorter construction period, higher strength, and more considerable economic return.

The anchoring mechanism of hollow self-drilling rock bolts was similar to general full-length bond rock bolts (He et al. 2015; Yang et al. 2022). The load distribution of rock bolts and the interface characteristics of rock and soil masses were regarded as key issues that need to be studied (Ghadimi et al. 2016; Li et al. 2020; Wang et al. 2020; Zou et al. 2020). Ferrero (1995) showed that the failure modes of bolts in hard rock were shear and tensile failure but those in soft rock were tensile and bending failure by studying the discontinuous rock-pin model through model experimentation and numerical
simulation. Cai et al. (2004) established an analysis model of rock bolts based on improved shear lag model, presented the pull-out test characteristics, and then proposed a back analysis method to calculate the shear strength of the interface medium. Ren et al. (2010) presented an analytical solution for predicting the full-range mechanical behavior of grouted rock bolts in tension which based on a realistic tri-linear bond-slip model with residual bond strength at the grout–bolt interface. Martin et al. (2011) proposed an analytical method that could predict the mechanical properties of full-length bond bolts and proposed the constitutive relationship between the bolt and surrounding rock, which was in good agreement with the load–displacement curve of the pull-out test. You et al. (2013) analyzed the deformation and damage process of the interfacial layer between anchorage body and grouting material, and divided the anchorage section into elastic region, plastic slide region, and debonding region, and then established the inter-facial layer model for the anchorage body, rock, and soil.

Due to the poor bore chipping discharge occurring in drilling process, greater resistance acted on the bit is commonly emerged with consequences as aggravating bit wear, increasing drilling torque, and reducing drilling depth (Fan and Xu 2005; He et al. 2021). This greater resistance could easily cause hole collapse that consequently affects the grouting compactness and leads to a decrease in anchoring force. To find a solution to these defects, a special-shaped cross-section self-drilling bolt was designed to explore the interface bonding characteristics and anchoring mechanisms of this new section bolt. Theoretical and experimental studies were carried out to provide a theoretical basis for engineering application.

**Design of special-shaped cross-section bolt**

By improving bore chipping discharge capacity, the stress caused by bore chipping plugging within the drilling process could be released, and the resistance of anchor rod drilling and the drilling torque could be reduced. Furthermore, the depth of drilling could be increased, the hole formation rate could be improved, and the loss of alloy bits was reduced with less replacement bit and construction cost. With regard to these theoretical and practical considerations, a bore chipping discharge groove was added to the bar to improve its bore chipping discharge capacity, as shown in Fig. 1. The bolt could be divided into 2, 3, and 4 sections according to the number of bore chipping discharge grooves.

**Theoretical models**

**Force analysis approach of circular bolt**

As Mindlin (1936) explained, it was assumed that the rock mass and the binder were elastic materials with the same properties or that the binder is thin, and the rock mass acted on by the anchor bolt was regarded as a semi-infinite plane. A concentrated force $Q$ (as shown in Fig. 2) was applied at a depth of $c$ inside the planar half-space. The vertical displacement at point $B(x, y, z)$ could be determined by Mindlin’s elastic solution of displacement:

$$u = \frac{Q(1 + \mu)}{2\pi E \epsilon} \left[ \frac{3 - 4\mu}{R_1^2} + \frac{(1 - \mu)(3 - 4\mu)}{R_2^2} + \frac{(2 - \mu)(3 - 4\mu)R^2}{R_1^2 R_2^2} + \frac{(1 - \mu)R}{R_1^2} + \frac{(1 - \mu)R}{R_2^2} + \frac{6c(1 + \mu)}{R_1^2 R_2^2} \right]$$

where $E$ is the elastic modulus, $\mu$ is Poisson’s ratio, $R_1 = \sqrt{x^2 + y^2 + (z - c)^2}$, and $R_2 = \sqrt{x^2 + y^2 + (z + c)^2}$.

Assuming that the bolt was infinitely long, and there was only elastic deformation occurring between the bolt and the rock mass, the following equation could be used:

$$u = \frac{Q(1 + \mu)(3 - 2\mu)}{2\pi E \epsilon}$$

**Fig. 1** Design of a special-shaped cross-section hollow self-drilling bolt. **a** Overall design diagram of the bolt; **b** Different cross-section designs, including double, three, and four grooves

**Fig. 2** Sketch of Mindlin’s solution
The displacement of rock mass at the orifice was equal to the total elongation of bolt, then the following equation could be used:

\[
\int_0^\infty \frac{(1 + \mu)(3 - 2\mu)}{\pi E_r} \tau dx = \int_0^\infty \frac{1}{E_r A} \left( Q - 2\pi r \int \tau dx \right) dx
\]

According to the boundary conditions of \( z \rightarrow \infty \) and \( \tau = 0 \), the bond stress distribution of the full-length grouting bolt along the bar could be obtained (You 2000):

\[
\tau(x) = \frac{P \alpha x}{2\pi r} e^{-\frac{1}{2} \alpha x^2} \quad (1)
\]

where \( \alpha = 1/[(1 + \mu)(3 - 2\mu)] \left( E_r / E_b \right) \), \( r \) is rock elastic modulus, \( r \) is the radius of the bar, \( E_b \) is bar elastic modulus, and \( P \) is the pulling force of the anchor bolt.

The distribution of the axial force in the anchor bolt could be obtained by integrating Eq. (2):

\[
P(x) = \int_x^\infty \tau(x) \cdot 2\pi r dx = \int_x^\infty \frac{P \alpha x}{2\pi r} e^{-\frac{1}{2} \alpha x^2} \cdot 2\pi r dx
\]

\[
= \int_x^\infty P \alpha x e^{-\frac{1}{2} \alpha x^2} dx = Pe^{-\frac{1}{2} \alpha r^2} 
\]  

Bond-slip model

Benmokrane et al. (1995) developed a tri-linear model which could present the relationship of shear stress versus slippage at the bolt-grout interface, as indicated in Fig. 3. As it was validated to express the bonding between the bolt–grout interface, this model was adopted in this study to derive the theoretical solution.

With regard to this model, the shear bond stress \( \tau \) linearly increased with the interfacial slip \( \delta \), within an ascending slope of \( k_1 \). This increasing trend stopped when the shear bond stress \( \tau \) reached the ultimate shear stress \( \tau_u \), and meanwhile, the value of the interfacial slip \( \delta \) was denoted by \( \delta_u \). Such process could indicate that the anchorage lied in elastic zone. Once interfacial slip \( \delta \) exceeded \( \delta_u \), softening occurred, and the shear stress decreased within a descending slope of \( k_2 \). Then, when \( \delta \) increased to \( \delta_f \), the shear stress reached \( \tau_f \), as the residual shear stress. Thereafter, debonding occurred, and the pullout load was resisted by the residual shear stress. Mathematically, the tri-linear bond stress-slip model could be expressed as

\[
\tau(\delta) = \begin{cases} 
  k_1 \delta & (0 \leq \delta \leq \delta_u) \\
  k_2 \delta + \frac{\tau_f \delta_u - \tau_u \delta_f}{\delta_u - \delta_f} & (\delta_u < \delta \leq \delta_f) \\
  \tau_f & (\delta > \delta_f)
\end{cases}
\]  

\[
(3)
\]

Using the tri-linear bond-slip model defined above, the shear slip and shear stress distributions along with the interface, the axial stress in the bolt, and the load–displacement relation could be obtained on every loading stage (Ren et al. 2010; Martín et al. 2011, 2013; Huang et al. 2020). As Fig. 4 illustrated, when the bond length was significantly longer than that of an effective bond, the ultimate load could be transferred within the evolution of the interfacial shear stress distribution. On other end, the pullout load was determined by the embedded length of the bolts, as shown in Fig. 5. Within the tests, short lengths, such as 100 mm, 200 mm, and 300 mm, were characteristic of laboratory scale, and long lengths, such as 600 mm or even longer, were characteristic of engineering scale.

Theoretical analysis

Toward a circular bolt, take the derivative of \( x \) in Eq. (1) and obtain the extreme value. When \( x = \sqrt{1/\alpha} \), \( \tau \) took the maximum values as follows:

\[
\tau_{\text{max}} = \frac{P \sqrt{\alpha}}{2\pi r} e^{-\frac{1}{2}}
\]  

\[
(4)
\]

When the maximum bonding stress was equal to the ultimate bonding stress \( (\tau_u) \) value provided from the grout and bolt, the pull-out force was the ultimate pulling force of the bolt:

\[
P_u = \frac{2\pi r}{\sqrt{\alpha} e^{-\frac{1}{2}}} \tau_u
\]  

\[
(5)
\]
\[
\frac{t}{E_t} = \frac{1}{(1 + \mu)(3 - 2\mu)} \left( E_t/E_b \right), \quad \text{then} \quad \frac{t}{E_t} = \frac{1}{r^2}.
\]

Make \( t = \frac{1}{(1 + \mu)(3 - 2\mu)} \left( E_t/E_b \right) \), then \( \alpha = t/r^2 \).

\[
P_u = \frac{2\pi r^2}{\sqrt{t}} e^{-\frac{1}{2} \tau_u}
\]

Fig. 6 Sketch of the geometric analysis of a special-shaped cross-section bolt

Apparently, after determining the material of the grout and rod, the ultimate bonding stress \( \tau_u \) was mainly determined by the material properties. Therefore, the ultimate pulling force of the bolt was proportional to the square of the bolt radius. If only consider the influence of the elastic modulus \( E_b \) of the bar was, the value of \( E_b \) would be larger and the value of \( t \) would be smaller, and the corresponding ultimate pulling force would be larger as well. The ratio of the ultimate pulling force of bolts with different elastic moduli could be obtained as follows:

\[
P_{u1} : P_{u2} = \frac{E_{b1}}{E_{b2}}
\]

Fig. 5 Load–slip relationship at the loaded end for different embedded lengths (Zhang et al. 2000)

For the special-shaped section bolt, the boundary distance of the bar was taken as an example by the 4-groove section bolt, as shown in Fig. 6, \( r_1 \) was the outer radius of the bolt, and \( r_2 \) was the radius of the bore chipping discharge groove, which were integrated into a piecewise function over cross-section.

\[
\rho = \sqrt{r_1^2 + r_2^2 - 2r_1r_2 \cos \theta}, \quad \text{in which,} \quad 0 \leq \theta \leq \theta_2, \quad \theta_2 = \arccos \left( r_2/2r_1 \right)
\]

\[
\theta_1 = 4 \arccos \left( r_2/2r_1 \right) - 3\pi/2 \quad (4 \text{ grooves})
\]

\( r_1 \): Outer radius of the bolt
\( r_2 \): Radius of the bore chipping discharge groove

\( \rho \): Boundary distance

\( \theta \): Angle

\( t \): Ultimate pulling force

\( \tau_u \): Ultimate bonding stress

\( \alpha \): Proportionality constant between ultimate pulling force and bolt radius

\( E_b \): Elastic modulus of the bar

\( E_t \): Elastic modulus of the grout

\( \mu \): Poisson’s ratio

\( r \): Bolt radius

\( P_u \): Ultimate pulling force

\( P_{u1} \): Ultimate pulling force of bolt with elastic modulus \( E_{b1} \)

\( P_{u2} \): Ultimate pulling force of bolt with elastic modulus \( E_{b2} \)
Evidently, $R_1 - R_2 \leq \rho \leq R_1$.

This transformation made $t = \frac{1}{1 + \rho \mu(3 - 2\rho)(E_1/E_0)}$, $\alpha_1 = t/r_1^2$, and $\alpha_2 = t/r_2^2$.

Based on arc AB, as shown in Fig. 7a, the following could be obtained:

$$\tau(x) = \frac{P\alpha_1 x}{2\pi r_1} e^{-\frac{1}{2} \alpha_1 x^2}$$

(8)

On BC, as shown in Fig. 7b, the following could be obtained:

$$\tau(x) = \frac{P\alpha_2 x}{2\pi \rho} e^{-\frac{1}{2} \alpha_2 x^2}$$

(9)

$$P(x) = \int \tau(x) dx$$

$$= 4 \int_{\theta_s}^{\theta_t} \frac{Ptx}{2\pi r_1^2} e^{-\frac{r_1^2}{2}} d\theta dx + 8 \int_{\theta_s}^{\theta_t} \frac{Ptx}{2\pi \rho} e^{-\frac{r_1^2}{2\rho^2}} d\theta dx$$

$$= \frac{20}{\pi} Pe^{-\frac{r_1^2}{2\gamma_1^2}} + 4Pt \int_{\theta_s}^{\theta_t} \frac{x}{\rho^2} e^{-\frac{r_1^2}{2\rho^2}} d\theta dx$$

(10)

The special-shaped section anchor bolt could have a stronger pull-out resistance, without considering the ultimate shear strength. The maximum shear strength of this special-shaped section anchor bolt was consistent with that of the circular bolt, and it firstly reached the ultimate shear strength at the arc top of the groove.

**Model test**

**Specimen preparation**

To simulate different cross-section forms and bolts of different materials, steel/aluminum rods with a radius of 10 mm was chosen as the rod with a circular cross-section, and the lathe on the steel/aluminum rods was used to make the bore chipping discharge grooves. The bore chipping discharge groove was a circular arc with a 3-mm radius, and the center of the circular arc was on the outer boundary of the circular steel cross-section. With regard to the bore chipping discharge groove, the 2-groove and 4-groove anchor rods were made symmetrically, and the 3-groove anchor rods were arranged in equal parts along the circumference. The specimen length was 330 mm, and the reserved anchorage section length was 300 mm. To prevent slipping between the fixture and the bolt of the testing machine during the pulling process, a thread with a length of 30 mm was made. Furthermore, a bolt connection was used between the bolt and the testing machine to avoid slip caused by the ordinary fixture. The anchor bolt specimen was placed into the center of a PVC pipe, with a length of 300 mm and a diameter of 10 mm. The grouting material was cement mortar, with a cement–sand ratio of 1:3. After grouting process, the whole specimen was put on a shaking table for vibration to ensure that the specimen had the same grouting compactness. The specimen was cured for 14 or 28 days after production.

**Experimental facility**

To ensure the effectiveness of the pulling test, a reaction frame was adopted, as shown in Fig. 8a. A steel plate with a
thickness of 20 mm was arranged on both sides of the reaction frame, and 4 Φ25 high-strength bolts were used between the steel plates. The deformation of the reaction frame is negligible. The lower steel plate was welded with the tie-rod converting head, and the upper steel plate is reserved with a round hole with a diameter of 30 mm. The upper end of specimen was connected with the upper tie rod converting head by bolt.

The universal Changchun Kexing WDW-300 testing machine was used in these tests, which have the closed-loop control of test force, deformation, and displacement; and it enabled automatically controlling and switching the uniform stress rate and uniform test speed in testing process. Besides, it supplied uniform strain rate control throughout whole process and enabled the measurement of the full load–displacement curve, the ultimate load, and the residual load. Pins were used to fix the test piece and the testing machine. The installed test piece was shown in Fig. 8b.

**Test procedure and results**

The steps of this test were as follows:

1. The specimen was installed as shown in Fig. 8b, the specimen was preloaded with a load of 300 N, and the initial displacement was set to 0.
2. The load test was carried out with a 5 mm/min uniform rate. During the test, the load and displacement data were recorded automatically. Once the displacement reached 20 mm, the loading recording was automatically ended.
3. The test was run until the bolt was completely pulled out, then the debonding characteristics of the bolt were observed.

The main parameters and experimental results of the bolt are shown in Table 1.

**Analysis and discussion**

**Pullout load–slip**

Within the test, 8 kinds of bolts were pulled out with mixed applications of 2 kinds of materials and 4 kinds of section forms. Among specimens, steel bolts were compared with each other over 14 and 28 days of maintenance, and the pullout load–slip curves were obtained. Figure 9a shows the whole process of part load–slip curves, while the load–slip curves of other specimens were presented in similar form. The analysis of the load–slip curve indicated that the whole process from loading to failure includes elastic stage, softening-debonding stage, and debonding stage. It was worth noting that, at the softening-debonding stage, as Fig. 9b shows, the pullout load–slip curves of the aluminum (position in the dotted line box) and steel bolts were different in terms of rate, which was due to the different bonding properties between aluminum and iron bolts in grouts. The aluminum bolt surface was relatively smooth; hence, once local slip occurs, the whole bolt soon reaches debonding stage.

**Debonding mode**

If the ultimate shear strength was consistent, according to Eq. (10), theoretical analysis indicated that the tensile strength of shaped cross-section bolt was less than circular cross-section bolt, but this analytical result was conflict to
the test results as presented in Table 1. With this stance, the debonding mode should be considered to explain this conflict.

Once the round section bar was completely pulled out, the bar was smooth and there was almost no residual grout, which indicated that the ultimate shear stress of the interface between the bar and grout was less than the ultimate shear stress in the grout. The debonding mode of the anchor bolt with circular section was developed under sliding failure between the bar and grout. After pulling out the anchor rod containing the bore chipping discharge groove, mostly, there was residual grout surficial attached to grooves, as shown in Fig. 10, which was due to the bulk expansion of the grout, resulting in radial pressure in the interface layer during at slip stage. This radial pressure could be limited or released by the application of a small-sized cambered surface, which could be applied into the bore chipping discharge groove. As the consequence, the radial stress $\sigma_r$ between the grout and the bore chippings discharge groove was larger than that $\sigma_s$ between the grout and the outer diameter surface of the bolt, and the ultimate shear stress of the interface between the grout and bore chippings discharge groove was greater than the outer diameter surface, as shown in Fig. 11. Therefore, there were two debonding modes at the location of the bore

| Sample number | Material | Section form | Curing period/day | Ultimate pulling force/kN | Residual pulling force/kN |
|---------------|----------|--------------|-------------------|---------------------------|--------------------------|
| S0-1          | Steel    | Circular     | 14                | 19.8                      | 5.0                      |
| S0-2          |          |              |                   | 18.9                      | 2.4                      |
| S0-3          |          |              |                   | 15.5                      | 3.5                      |
| S2-1          |          | 2 grooves    |                   | 20.2                      | 5.1                      |
| S2-2          |          |              |                   | 17.6                      | 3.8                      |
| S2-3          |          |              |                   | 21.4                      | 4.1                      |
| S3-1          |          | 3 grooves    |                   | 24.1                      | 7.1                      |
| S3-2          |          |              |                   | 21.8                      | 6.0                      |
| S3-3          |          |              |                   | 18.1                      | 4.4                      |
| S4-1          |          | 4 grooves    |                   | 22.9                      | 6.0                      |
| S4-2          |          |              |                   | 22.0                      | 7.0                      |
| S4-3          |          |              |                   | 26.7                      | 6.5                      |
| A0-1          | Aluminum | circular     | 28                | 17.3                      | 2.4                      |
| A0-2          |          |              |                   | 21.4                      | 2.2                      |
| A0-3          |          |              |                   | 16.7                      | 1.5                      |
| A2-1          |          | 2 grooves    |                   | 22.3                      | 2.5                      |
| A2-2          |          |              |                   | 23.0                      | 2.3                      |
| A2-3          |          |              |                   | 20.8                      | 2.7                      |
| A3-1          |          | 3 grooves    |                   | 24.2                      | 2.4                      |
| A3-2          |          |              |                   | 24.7                      | 3.3                      |
| A3-3          |          |              |                   | 21.2                      | 3.6                      |
| A4-1          |          | 4 grooves    |                   | 26.5                      | 2.4                      |
| A4-2          |          |              |                   | 26.5                      | 3.4                      |
| A4-3          |          |              |                   | 23.4                      | 4.7                      |
| T0-1          | Steel    | circular     | 28                | 31.4                      | 6.7                      |
| T0-2          |          |              |                   | 38.8                      | 10.3                     |
| T0-3          |          |              |                   | 35.3                      | 10.3                     |
| T2-1          |          | 2 grooves    |                   | 41.5                      | 11.6                     |
| T2-2          |          |              |                   | 41.0                      | 11.3                     |
| T2-3          |          |              |                   | 37.9                      | 12.2                     |
| T3-1          |          | 3 grooves    |                   | 43.3                      | 13.7                     |
| T3-2          |          |              |                   | 41.5                      | 11.6                     |
| T3-3          |          |              |                   | 44.2                      | 15.3                     |
| T4-1          |          | 4 grooves    |                   | 51.8                      | 18.7                     |
| T4-2          |          |              |                   | 45.4                      | 15.9                     |
| T4-3          |          |              |                   | 47.0                      | 12.3                     |
chipping discharge groove: (1) slippage failure between the grout and bar (2) shear failure in the grout. This debonding mode provided the solution to the conflict between the theoretical and experimental results.

Integral analysis
As shown in Table 1, the test data of the steel bolt and aluminum bolt specimens cured for 28 days were compared. The ultimate pull-out strength of the steel bolt was higher than the aluminum bolt, and the ratio was almost 1.7. The elastic modulus of steel was approximately 210 GPa and that of aluminum was 72 GPa. The ultimate pulling force of the steel bolt was approximately 1.7 times that of the aluminum bolt, which was consistent with the previous theoretical analysis.

In terms of its residual tensile strength, the steel bolt was better than the aluminum bolt and reached an ultimate tensile strength falling within the same order of magnitude as that of the aluminum bolt. Certain reasons might be related to the difference in friction between steel/aluminum and the grout. As the surface of the aluminum bolt in this test was relatively smooth, the friction force between was smaller after debonding, with an outcome of a smaller residual pulling force. The curing time was also an important factor affecting the friction force between steel/aluminum and the grout. As indicated in Table 1, the test results of the specimens cured for 28 days were substantially better than 14 days as the strength of the grout was improved, the bond strength in grout and bar gets enhanced, and its pulling capacity was also improved accordingly.

There was no deterministic relationship between the ultimate pull-out force and the residual pulling force. The test results related to specimens with larger ultimate pulling force did not indicate a larger residual pulling force existed, which was due to the ultimate pull-out force was mainly determined by the bond strength, while the residual pulling force was greatly affected by the friction force.

As shown in Table 1, the test data of the steel bolt and aluminum bolt specimens cured for 28 days were compared. The ultimate pull-out strength of the steel bolt was higher than the aluminum bolt, and the ratio was almost 1.7. The elastic modulus of steel was approximately 210 GPa, and that of aluminum was 72 GPa. The ultimate pulling force of the steel bolt was approximately 1.7 times that of the aluminum bolt, which was consistent with the previous theoretical analysis.

In terms of its residual tensile strength, the steel bolt was better than the aluminum bolt and reached an ultimate tensile strength falling within the same order of magnitude as that of the aluminum bolt. Certain reasons might be related to the difference in friction between steel/aluminum and the grout. As the surface of the aluminum bolt in this test was relatively smooth, the friction force between was smaller after debonding, with an outcome of a smaller residual pulling force. The curing time was also an important factor affecting the friction force between steel/aluminum and the grout. As indicated in Table 1, the test results of the specimens cured for 28 days were substantially better than 14 days as the strength of the grout was improved, the bond strength in grout and bar gets enhanced, and its pulling capacity was also improved accordingly.

There was no deterministic relationship between the ultimate pull-out force and the residual pulling force. The test results related to specimens with larger ultimate pulling force did not indicate a larger residual pulling force existed, which was due to the ultimate pull-out force was mainly determined by the bond strength, while the residual pulling force was greatly affected by the friction force.

As shown in Table 1, the test data of the steel bolt and aluminum bolt specimens cured for 28 days were compared. The ultimate pull-out strength of the steel bolt was higher than the aluminum bolt, and the ratio was almost 1.7. The elastic modulus of steel was approximately 210 GPa, and that of aluminum was 72 GPa. The ultimate pulling force of the steel bolt was approximately 1.7 times that of the aluminum bolt, which was consistent with the previous theoretical analysis.

In terms of its residual tensile strength, the steel bolt was better than the aluminum bolt and reached an ultimate tensile strength falling within the same order of magnitude as that of the aluminum bolt. Certain reasons might be related to the difference in friction between steel/aluminum and the grout. As the surface of the aluminum bolt in this test was relatively smooth, the friction force between was smaller after debonding, with an outcome of a smaller residual pulling force. The curing time was also an important factor affecting the friction force between steel/aluminum and the grout. As indicated in Table 1, the test results of the specimens cured for 28 days were substantially better than 14 days as the strength of the grout was improved, the bond strength in grout and bar gets enhanced, and its pulling capacity was also improved accordingly.

There was no deterministic relationship between the ultimate pull-out force and the residual pulling force. The test results related to specimens with larger ultimate pulling force did not indicate a larger residual pulling force existed, which was due to the ultimate pull-out force was mainly determined by the bond strength, while the residual pulling force was greatly affected by the friction force.
Empirical equation

As Eq. (10) could not obtain an analytical solution, it was difficult to apply in engineering practice. The equivalent radius was used to simplify the analysis of the special-shaped section bolt by considering engineering practices. If the total perimeter of the special-shaped section was $C$, its equivalent radius $r = C/2\pi$; once $r$ was substituted into Eq. (5), the following could be obtained:

$$P_u = \frac{C^2}{2\pi \sqrt{I}} e^{-\frac{1}{2}f} \tau_u$$

(11)

The result indicated that anchors with different section girths have various ultimate pulling forces, as the section circumference was greater than the ultimate pull-out resistance would be greater.

It was assumed that the residual stress at the interface between the anchor bolt and grout at debonding stage was uniform. The residual pulling force between the bolt and grout could be obtained as follows:

$$P_f = Clf$$

(12)

$\tau_u$ is the residual stress between the grout and bolt and $l$ is the length of the anchor section.

As the residual stress was a variable related to the material and confining pressure, $\tau_f$ was constant and the residual pulling force would be consistent with the girth of the bolt section.

Influence of section type on anchorage performance

Taking a steel anchor rod with a curing age of 28 days as an example, according to Eqs. (11) and (12), the experimental results, considering anchors with circular cross-sections, were taken as the initial theoretical calculation values to calculate the ultimate and residual pulling forces of anchors with different cross-sections. The results were shown in Fig. 12. The experimental results of the ultimate pulling resistance were in coordination with the empirical formula. When increasing bore chipping discharge chutes, the equivalent radius of the bolt increases, with the ultimate pull-out force accordingly increases. The average test value of the ultimate pulling force of the four-groove bolt was 37%, which was higher than that of the circular bolt. Moreover, the residual pulling force also increased, and the average test value of the residual pulling force of the 4-groove bolt was 64% higher than circular bolt.

The experimental result of the residual pulling force was greater than the theoretical calculation result, which was determined by debonding characteristics of the special-shaped cross-section anchor bolt. The shear strength of the interface between the bar and grout was less than that between grout and grout, while the residual pulling force of the special-shaped section anchor bolt was provided by the friction force between the bar and grout as well as that in the grout. The residual stress in theoretical calculation was calculated according to the residual stress of the interface between the bar and grout, which lead to a small calculation result. With regard to this difference between experimental and theoretical analyses, it could be inferred that increasing the strength grade of grout would further improve the pull-out resistance of the special-shaped section anchor bolt.

Considering the above performances in practical application, especially in case of the same bolt outer diameter, there could be more bore chipping grooves and a smaller cross-sectional area. This application would easily lead to the insufficient tensile strength. Moreover, in practical process, it was necessary to check the tensile strength of the anchor bolt according to the design strength value of the anchor. To avoid the damage caused by insufficient strength of the anchor bolt, a reasonable section form should be considered under condition of satisfying the tensile strength. From another perspective of the same volume of steel, the equivalent radius of the shaped section anchor bolt could be larger to provide a greater pulling force. Therefore, in condition of the same pull-out force, the special-shaped section bolt saves more material than the circular bolt, which could have a reasonable cost reduction in engineering practices.

Conclusion

To remedy the practical defects of current hollow self-drilling bolts, this paper designed a special-shaped section-hollow self-drilling bolt. Based on elastic solution of the force
distribution of the anchor bolt, the pulling performance of the abnormal section anchor bolt was analyzed theoretically and experimentally. Comparatively, the pulling performance of a special-shaped cross-section anchor bolt was discussed, and a simplified algorithm based on the equivalent radius was proposed. The conclusions were obtained as follows:

1. Theoretically, in case of bolts with the same outer diameter, the pull-out force of the special-shaped section anchor bolt should be less than that of the round-shaped section anchor bolt. However, due to the radial pressure generated by the bulging of the interface layer, the shear strength in grout and the groove surface in the bore chipping discharge groove were enhanced, and the ultimate pull-out strength of the irregular section anchor bolt was greatly increased.

2. Experimentally, the material and curing periods of bolts were important factors affecting the pulling performance of bolts. The ultimate pull-out force of the bolt with high grout strength and elastic modulus was larger, and the residual pull-out force was greatly affected by the friction force between the bar and grout. If the ultimate pull-out force was greater, the resistance to deformation of the bolt could be greater accordingly.

3. The residual pulling strength of special-section anchor bolt was determined by the joint application of the bar–grout and grout–grout interfaces. The pulling resistance of the special-section anchor bolt could be further improved by increasing grout strength grade.

**Funding** The authors acknowledge the support of the National Natural Science Foundation of China (No. 51808246), the National Key Research and Development Program of China (No. 2019YFC1520500), and the Open Foundation of the Jiangsu Engineering Laboratory of Assembly Technology on Urban and Rural Residence Structure (No. JSZP201901).

**Declarations**

**Conflict of interest** The authors declare that they have no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

Benmokrane B, Chennouf A, Mitri HS (1995) Laboratory evaluation of cement-based grouts and grouted rock anchors. Int J Rock Mech Min Sci Geomech Abstr 32(7):633–642

Cai Y, Esaki T, Jiang Y (2004) A rock bolt and rock mass interaction model. Int J Rock Mech Min Sci 41(7):1055–1067

Chen J, Hagan PC, Saydam S (2016) Parametric study on the axial performance of a fully grouted cable bolt with a new pull-out test. Int J Min Sci Technol 26(1):53–58

Chu M, Wang B, Xia J (2011) Study of formation mechanism of floor heave at goaf side of roadway and prevention technology. Rock and Soil Mechanics 32(2):413–417 (in Chinese)

Fan X, Xu S (2005) The application of self-drilling bolt to wall support in soft soil. Geotech Eng World 8(5):67–69 (in Chinese)

Ferrero AM (1995) The shear strength of reinforced rock joints. Int J Rock Mech Min Sci Geomech Abstr 32(6):595–605

Ghadimi M, Shariar K, Jalalifar H (2016) A new analytical solution for calculation the displacement and shear stress of fully grouted rock bolts and numerical verifications. Int J Min Sci Technol 26(6):1073–1079

He L, An X, Zhao Z (2015) Fully grouted rock bolts: an analytical investigation. Rock Mech Rock Eng 48(3):1181–1196

He M, Zhang Z, Zhu JW, Li N, Chen Y (2021) Correlation between the rockburst proneness and friction characteristics of rock materials and a new method for rockburst proneness prediction: field demonstration. J Pet Sci Eng 205:108997

He M, Zhang Z, Zhu J, Li N (2022) Correlation between the constant of Hoek-Brown criterion and porosity of intact rock. Rock Mech Rock Eng 55(2):923–936

Huang P, Sun Y, Mei K, Wang T (2020) A theoretical solution for the pullout properties of a single FRP rod embedded in a bond-type anchorage. Mech Adv Mater Struct 27(4):304–317

Kilic A, Yasar E, Atis CD (2003) Effect of bar shape on the pull-out capacity of fully-grouted rockbolts. Tunn Undergr Space Technol 18(1):1–6

Kumar R, Mandal PK, Narayan A, Das AJ (2021) Evaluation of load transfer mechanism under axial loads in a novel coupler of dual height rock bolts. Int J Min Sci Technol 31(2):225–232

Li C, Stillborg B (1999) Analytical models for rock bolts. Int J Rock Mech Min Sci 36(8):1013–1029

Li D, Li Y, Asadizadeh M, Masoumi H, Hagan PC, Saydam S (2020) Assessing the mechanical performance of different cable bolts based on design of experiments techniques and analysis of variance. Int J Rock Mech Min Sci 130:104307

Martin LB, Tijani M, Hadj-Hassen F (2011) A new analytical solution to the mechanical behaviour of fully grouted rockbolts subjected to pull-out tests. Constr Build Mater 25(2):749–755

Martin LB, Tijani M, Hadj-Hassen F, Noiret A (2013) Assessment of the bolt–grout interface behaviour of fully grouted rockbolts from laboratory experiments under axial loads. Int J Rock Mech Min Sci 63:50–61

Masoud, Ghorbani K, Shahriar M, Sharifzadeh R, Masoudi (2020) A critical review on the developments of rock support systems in high stress ground conditions. Int J Min Sci Technol 30(05):6–23

Mindlin RD (1936) Force at point in the interior of a semi-infinite solid. J Appl Phys 7:195–202

Ren FF, Yang ZJ, Chen JP, Chen WW (2010) An analytical analysis of the full-range behaviour of grouted rockbolts based on a tri-linear bond-slip model. Constr Build Mater 24(3):361–370

Wang N, Zhang J, Wang Y, Zhang H, Ma Y, Zhao L, Guo Q (2020) Experimental study on mechanical properties of grout-soil interface in anchor system of rammed earthen sites. Int J Geomech 20(6):04020064
Yang B, He M, Zhang Z, Zhu J, Chen Y (2022) A new criterion of strain rockburst in consideration of the plastic zone of tunnel surrounding rock. Rock Mech Rock Eng 55(3):1777–1789
You C (2000) Mechanical analysis on wholly grouted anchor. Chin J Rock Mech Eng 19(3):339–341 (in Chinese)
You C, Zhan Y, Liu Q, Sun L, Wang K (2013) Shear lag-debonding model for anchorage section of prestressed anchor cable. Chin J Rock Mech Eng 32(4):800–806 (in Chinese)
Zhang B, Benmokrane B, Chennouf A (2000) Prediction of tensile capacity of bond anchorages for FRP tendons[J]. J Compos Constr 4(2):39–47
Zou X, Sneed L, Dantino T (2020) Full-range behavior of fiber reinforced cementitious matrix (FRCM)- concrete joints using a trilinear bond-slip relationship. Compos Struct 239:112024