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Updated knowledge of inflatable rock bolts

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Abstract

Inflatable rock bolts can quickly stabilize loosened rock blocks in underground excavations. An inflatable bolt is made of a steel tube that is folded into an omega shape. During installation, high-pressure water is injected into the tube to expand it to the borehole size. A primary contact stress is established on the borehole wall after installation, resulting in frictional resistance that prevents rock blocks from moving. It is recommended in current installation specifications that bolts be installed in boreholes slightly smaller than the original diameter of the steel tube, and small boreholes are generally not preferred. Recent theoretical and experimental studies of inflatable bolts have provided new knowledge, including the optimal borehole size and the relationship between the radial stiffness of the partially unfolded tube and the diameter of the unfolded tube. These studies show that the pullout load is high in both large and small boreholes. In large boreholes, the high pullout load is due to the high radial stiffness of the bolt tube, while in small boreholes it is due to locked contact stress. Middle-sized boreholes should be avoided because the stiffness of the bolt is lowest, and the locked contact stress can also be very low in such boreholes. The high pullout load in small boreholes, which contradicts theoretical predictions, is a new finding. It is attributed to locked contact stress caused by the tight contact of the shoulders of the tongue flanks of the bolt in small boreholes. Therefore, small boreholes can be used for inflatable bolts.

Keywords

Inflatable bolt, Pullout test, Borehole size, Rock bolting, Rrock support.

1 Introduction

Inflatable (or expandable) rock bolts have been used for rock support in mines and civil rock excavation projects for a long time since it was invented in the 1980s.Inflatable bolt is made of a steel tube that is folded into an omega-shape in cross section (Fig. 1). After the bolt installation, contact stresses are established at the interface between the bolt of the borehole wall. The bolt is anchored in the rock mass through the frictional resistance and mechanical interlock at the bolt-rock interface. The bolt installation only takes minutes to finish, and the bolt provides reinforcement function immediately after installation. Infltable bolt cannot be used for permanent rock reinforcement mainly because of its vulnerability to corrosion (Hadjigeorgiou et al. 2019; Villaescusa et al. 2008) and relatively low shear resistance. The bolt is at present mainly used in weak rock masses to provide rapid reinforcement to prevent deterioration of the rock mass quality or in water-abundant environment where grouted rock bolts cannot be cured properly. The field pull tests by Kim et al. (2017) showed that the ultimate

pullout resistance of inflatable rock bolts was not noticeably affected by water leakage in the borehole. However, the pullout resistance of grouted rock bolts was dramatically reduced when the leakage was higher than 1 liter per minute.

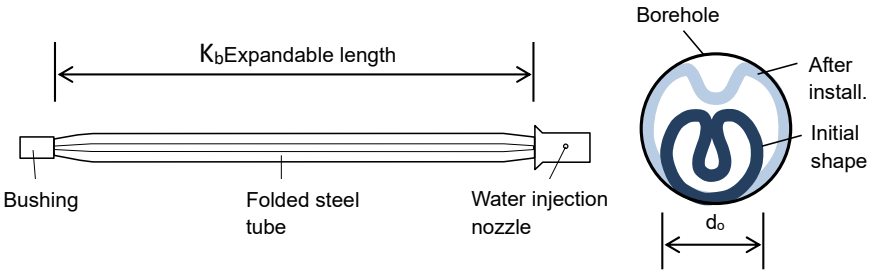


Fig. 1 Sketch illustrating the geometry of an inflatable rock bolt (Li et al. 2023).

It seems that inflatable rock bolt is a satisfactory rock reinforcement element in harsh rock conditions (e.g., Kim et al. 2017; Scolari et al. 2017). However, it was experienced in the practical use of the bolts that the pullout resistance of inflatable bolts varied in a wide range, which brings about confusion and difficulties in the design of rock reinforcement using inflatable bolts. The field pullout tests by Soni (2000) showed that the pullout resistance varied between 20 and 150 kN for the same bolt length and similar resistance values were obtained for different bolt lengths in the range of 0.5 - 3 m. The field tests conducted by Barnard et al. (2016) showed that the pullout resistance of inflatable bolts varied also in a wide range from 5 to 70 kN / m in rock masses of RMR ≈ 30. On the other hand, the pullout resistance remained the same in rock masses with RMR in a wide range from 20 to 80. Gregory (2014) carried out field pullout tests of inflatable bolts from four bolt suppliers, and he found that the pullout resistance of the bolts scattered in a range of 20 – 100 kN. The pullout resistance remained almost unchanged in rock masses of RMR 30 and 60. His tests conducted in Mines 1 and 2 showed that the pullout resistance had nothing to do at all with the rock mass quality.

The inconsistent results of the pullout resistance is certainly associated with the contact status between the bolt and the rock. Essentially the original theory for inflatable rock bolts has a too ideal assumption that the unfolded tube is assumed to be a closed ring, which misleads to an overestimation of the pullout resistance of the bolt. The theory cannot explain the deviations of the pullout results in various rock conditions so that it essentially cannot provide guidance for the design of rock reinforcement using inflatable bolts. Li (1997) and Li and Håkansson (1999) started to test inflatable bolts in artificial weak solid materials in the laboratory in the 1990s. the tests showed that inflatable bolts would become fully unfolded regardless of the borehole diameter, and the contact stress at the bolt-rock interface was relatively high, resulting in a high pullout resistance. After the laboratory tests, Li continued to study the mechanics of the bolt and proposed that the pullout resistance of inflatable bolt is associated with both the primary contact stress induced by the installation water pressure at the bolt-rock interface and a secondary contact stress induced by the borehole roughness that is mobilized when the bolt intends to slide (Li 2016). The primary contact stress is directly influenced by the unfolding degree, or the tongue length, of the bolt. The concepts of the primary and secondary contact stresses, the influence of the borehole roughness and the influence of the installation water pressure were verified afterward by pull tests in the laboratory (Li, Aure and Knox 2023). This laboratory study led to a new finding that high pullout resistance could be achieved in small boreholes which is not recommended in the current bolt installation specifications.

This paper will present an overview over the new knowledge of inflatable rock bolts that has been gained in the recent years, including the influences of the tongue length on the contact stresses, borehole roughness and borehole diameter.

2 Known knowledge

It is assumed that inflatable bolt slides in the borehole when it is mobilized by rock mass movements and the frictional resistant load on the borehole wall prevent the rock mass from disintegration. This mechanical mechanism can be achieved only when the embedment length of the bolt on one side of the opening rock joint is shorter than the critical embedment length of the bolt (Li, Kristjansson &

Høien 2016). Otherwise, the bolt will be locket in the rock mass and the bolt steel elongates until the steel strength is reached. Figure 2 shows the test results of Super Swellex under pull and shear loading, respectively (Stjern 1995; Li et al. 2014). The bolts were installed in two concrete cubes of high strength. The embedment length of the bolt in each block was 0.95 m. The bolt tested under pull sled so that the maximum pull load of 121 kN represented the ultimate frictional resistant load of the 0.95-m bolt segment, corresponding to a pull resistance of 127 kN/m. Under shear loading, the bolt tube became laterally clamped at a shear load of approximately 30 kN. The tube was locked at the joint of the two blocks afterward and the steel was stretched until the ultimate load of the steel was reached at 179 kN. The ultimate shear load is not dependent on the embedment length but on the steel strength.

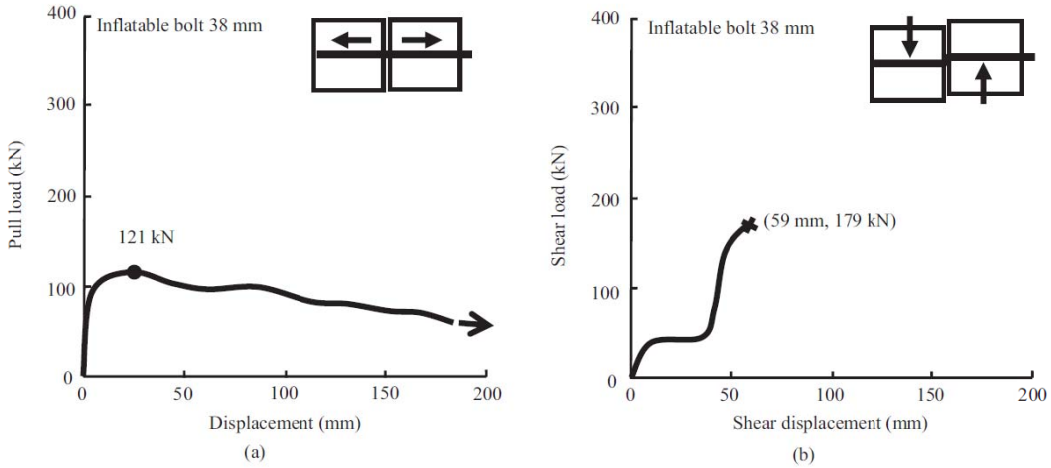


Fig. 2 Load–displacement curves of Super Swellex under pull and shear loading, respectively (Li, Stjern & Myrvang 2014).

The original theory of inflatable bolt was proposed by Wijk and Skogberg B (1982). The theory significantly overestimates the load capacity of the bolt. In practice, theload capacity was determined through pullout tests (Granström et al. 1982). Figure3 shows the pull load capacity versus the borehole size for Standard and Super Swellex bolts, reported by Atlas Copco in the 1990s. The nominal diameter of the steel tube is 42 mm for Standard Sellex and 54 for Super Swellex. The recommended range of borehole diameter is proposed based on the pullout test results. It can be seen in the diagram that the load capacity would be very low in small boreholes. In the current specifications for inflatable bolts, therefore, the recommended borehole diameter is usually in a range smaller than the original tube diameter and greater than the middle diameter between the initial profile diameter of the bolt (i.e., the diameter of the bolt in the folded state) and the original tube diameter (i.e., the diameter of steel tube after full unfolding). Boreholes smaller than the middle diameter are excluded in the recommended diameters. For example, a type of inflatable bolt, which is currently supplied to the market, has an initial profile diameter in 27 mm and an original tube diameter in 41 mm. It is stated that the bolt can be installed in boreholes of 32 – 40 mm, but the recommended borehole diameter is 36 -38 mm, which implies that the best reinforcement would be achieved in a borehole greater than the middle diameter (27 + 41) / 2 = 34 mm. The range of the recommended diameters is small, and the borehole could be drilled oversized, particularly in weak rock masses. The load capacity of inflatable bolt would be dramatically reduced and even drop to zero in extreme cases. In a small borehole, a non-zero resistant load is guaranteed, but it is considered too low, as shown in Fig. 3. The updated knowledge in Section 3 will prove that the load capacity in a small borehole could be as high as that in a large borehole when the bolt is properly installed.

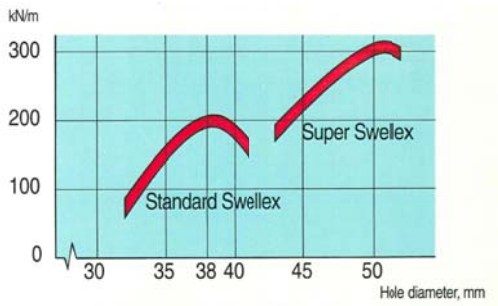


Fig. 3 The pull load capacities of standard and Super Swellex versus the borehole diameter.

3 Updated knowledge

The borehole to receive the bolt has deformed inward for U_0under the in-situ rock stresses before bolt installation (Fig. 4). During bolt installation, the pressured water inside the steel tube presses the

borehole wall to deform outward. The pressure on the borehole wall is p_i when the pre-defined maximum water pressure (24 or 35 MPa) is reached, at which the borehole displacement is U_0. After installation, the water pressure drops to zero and both the borehole wall and the partially unfolded steel tube moves inward toward the borehole centre under the ground pressure. The pressure on the borehole wall decreases with the inward displacement at the same time. The rock moves along the straight green line marked by K_r, while the steel tube moves along the black lines marked by K_b, see Fig. 4. To the end, the primary contact stress $q_1$is established on the borehole wall when the equilibrium is reached. This contact stress is expresses as (Li et al. 203):

$$q_1 = \frac{K_b - \lambda K_r}{K_b + K_r} p_i \qquad (1)$$

where K_b is the radial stiffness of the partially unfolded steel tube, K_r is the stiffness of the rock mass, and λ isa coefficient expressing the recovery of the outward elastic displacement of the steel tube after bolt installation. The coefficient λvaries in the range of 0–1 withλ= 0 for zero recovery (e.g., the elastic displacement is completely locked in),and λ= 1 for complete recovery (e.g., the elastic displacement rebounds completely and the bolt tube recovers to its non-stressing state) (Li 2016). The stiffness of the steel tube is much lower than the stiffness of the rock mass (only a few percentage of K_r). It is seen in Eq. (1) that the contact stress is negative, indicating that the bolt separates from the borehole wall, when the coefficient λis equal to 1 for complete recovery. Therefore, it is required that the outward elastic deformation of the steel tube during bolt installation must be partially locked to achieve a contact stress at the bolt-rock interface. The condition to guarantee a contact stress higher than zero is that the radial stiffness of the steel tube K_r must be greater than λK_r. A rough borehole surface can prohibit the elastic recovery and makes the recovery coefficient λ to be less than 1. That is the reason for the requirement that boreholes for inflatable bolts must be drilled percussively and the borehole surface must be rough.

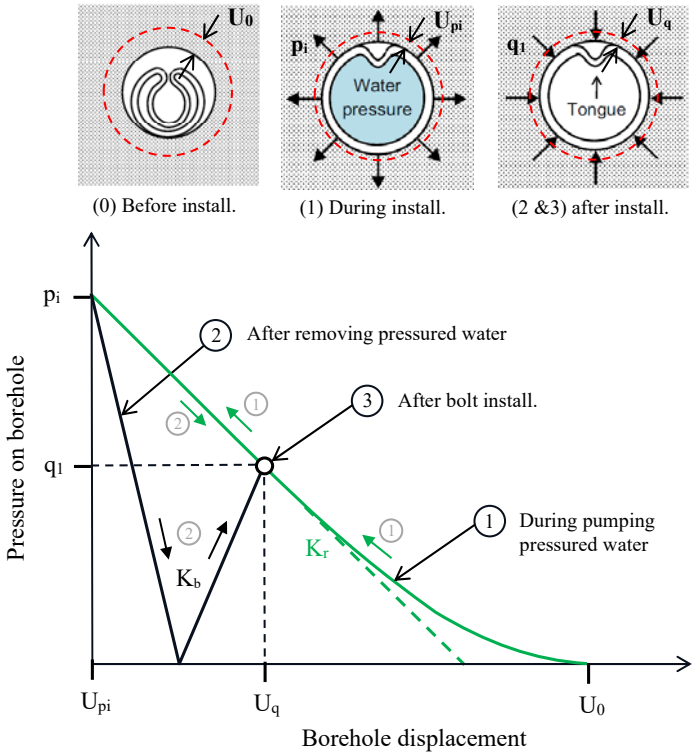


Fig. 4 Sketches illustrating the displacing moments of the borehole during and after bolt installation. Modified after Li (2016)

A secondary contact stress will be induced in a rough borehole when the bolt is stretched by opening rock joints. This contact stress is more important in hard rock masses than in soft rock masses.

The radial stiffness of the steel tube of the inflatable bolt directly determined the primary contact stress, and thus the pull resistant load capacity. Figure 5 shows the curve of the water pressure versus the unfolding degree of an inflatable bolt (the nominal diameter in the diagram) that was expanded outside a borehole. The folded tube started to expand after the water pressure passed the maximum at around point A. the water pressure declined with the opening of the folded tongue (points B and C) until the tube was unfolded to the original diameter of the tube at the middle of the bolt segment when the water pressure dropped to the minimum (before point D). Loading cycles were conducted during the test. The slope of the unloading-reloading line represents the radial stiffness of the partially unfolded tube. The stiffness of each loading of one tested bolt is presented in Fig. 6a versus the nominal diameter of the unfolding bolt tube. The stiffness of the bolt is minimum when the tube unfolded to diameter 32 mm that is slightly smaller than the middle diameter 34 mm.

A number of short inflatable bolt with a expandable segment of 360 mm were pullout tested in boreholes of various sizes drilled in a concrete block of high strength (UCS approximately 110 MPa).

The pullout results are presented in Fig. 6b. The tests confirmed that the pullout load increases with increasing the borehole size, as shown in Fig. 3, in the range above the middle diameter (34 mm in this case) in both the percussively rough boreholes and diamond-drilled smooth boreholes. Surprisingly, the pullout load in small boreholes was as high as in large boreholes, which is contradictory to the current belief that the pullout load is small in small boreholes. An advantage of using small boreholes is that one avoids the risk of oversized boreholes.

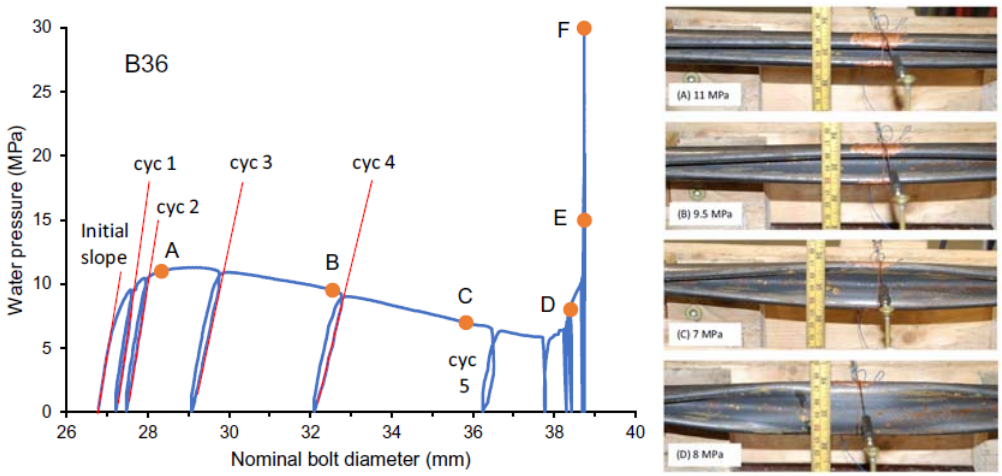


Fig. 5Water pressure versus the nominal diameter of a short inflatable bolt and the unfolding degrees of the folded tube at four moments (Li et al. 2023).

After the pullout tests, the bolts were cut through perpendicularly to the bolt length. The opening status of the folded tongue became visible as shown in Fig. 7. The shoulders of the two flanks of the tongue were not in contact in two larger boreholes (33.5 and 37 mm), see Fig. 7b and 7c. Because of the opening of the tongue shoulders, recovery of the outward elastic deformation of the tube is unavoidable after bolt installation, which leads to the recovery coefficient $\lambda > 0$. In these two boreholes, the pullout load in these two holes is directly associated with the radial stiffness of the bolt. In the small borehole of 31 mm, the tongue shoulders were tightly clamped together (Fig. 7a). The clamping prohibited the recovery of the outward elastic deformation of the steel tube so that the outward elastic deformation might be completely locked after bolt installation, that is, the recovery coefficient $\lambda \approx 0$. In this case, the pullout load would be not only dependent on the radial stiffness of the tube but also on the locked contact stress. This may be the mechanism why a high pullout load was achieved in small boreholes.

The test results in Fig. 6b confirmed that the pullout load is higher in a percussively drilled rough borehole than in a diamond drilled smooth borehole, and when the bolt is installed with a higher pump pressure than with a lower pump pressure.

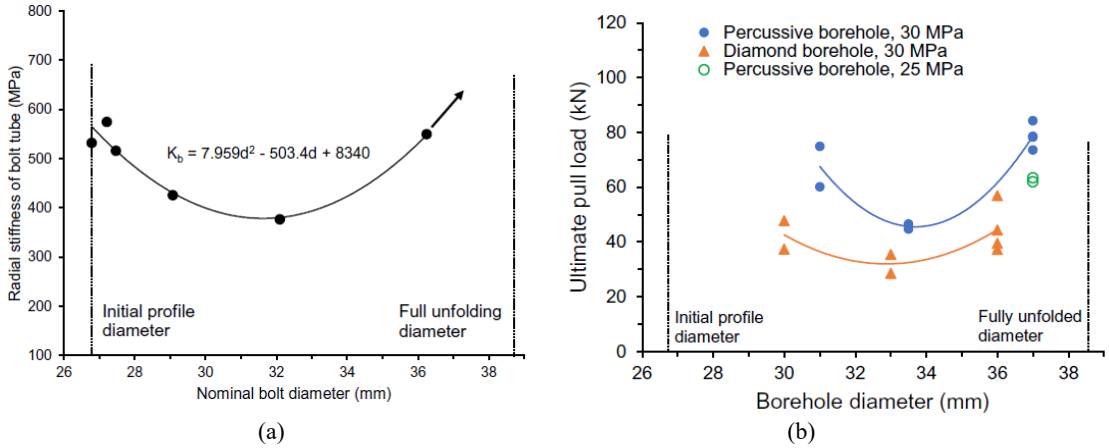


Fig. 6 (a) the radial stiffness of an inflatable bolt versus the nominal diameter of the unfolding bolt, and (b) the pullout loads versus the borehole diameter. (Li et al 2023)

4 Conclusions

The pullout load of inflatable bolt is high in small boreholes due to the tight clamping of the flank shoulders of the bolt tongue which prohibits the recovery of the outward elastic deformation of the steel tube after bolt installation. The quality of bolt installation is more guaranteed in a small borehole than in a large borehole because there is no concern of oversizing in small boreholes.

The radial stiffness of the folded steel tube is lowest in a borehole of around the middle-sized diameter of the bolt. The pullout load is also lowest in this hole.

The pullout load of inflatable bolt is dependent on both the primary and secondary contact stresses. The secondary contact stress is important in hard rock masses, while the primary contact stress is the major factor for the pullout load capacity in weak and soft rock masses.

The surface roughness of the borehole is extremely important in hard rock, but less important in weak and soft rock.



Fig. 7 The cross sections of inflatable bolts installed in boreholes of (a) 31 mm, (b) 33.5 mm and (c) 37 mm. (Li et al 2023)

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