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TECHNICAL NOTE

An Experiment Study on a Novel Self-Swelling Anchorage Bolt

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1 Introduction

Rockbolting, which is widely used in geotechnical and mining engineering, is a reinforcement technique to stabilize rock masses through high-strength members such as cablebolts, rebars and steel pipes (Graham 1996). Rock reinforcement improves the load-bearing capacity of rock masses by increasing the strength of the rock masses (Hoek and Brown 1980).

Rockbolts can be divided into three types based on the anchorage mechanism—mechanical bolts, bonded bolts and friction bolts (Hoek et al. 2000). Mechanical bolts are normally used as temporary supports because of its immediate support ability and low cost. The disadvantages of mechanical bolts include strict requirement for borehole drilling and high dependence of the mechanical grip on borehole diameter (Cai and Champaigne 2012).

The strengthening effect of bonded bolts depends on the adhesion of bonding materials grouted into the space between the rockbolt and the borehole wall. Bonded rockbolts include epoxy resin rockbolt, cement rockbolt and cement mortar rockbolt. Bonded rockbolts have high reinforcement capacity and are resistant to corrosion (Li and Doucet 2012; Pells and Bertuzzi 1999). The disadvantages of resin bonded rockbolts include high cost and the short shelf life of resin; in addition, the anchorage force depends on resin mixing quality. Bonded rockbolts are commonly used to maintain long-term stability of rock masses at shallow depth or to reinforce fractured rock masses under high stresses in deep underground mines (Kaiser and Cai 2012).

Friction bolts utilize the friction formed by the relative movement between the rockbolt and the surrounding rock mass. Split sets (Scott 1974) and Swellex (Wijk and Skogberg 1982) are typical friction bolts. Friction bolts have full load capacity after installation and can accommodate large wall deformation. This type of rockbolts is appropriate for primary support in fractured rock masses. However, the load capacity of friction bolt is low and the bolt is prone to corrosion; as a result, they are not suitable for long-term support. Hence, friction bolts are not recommended for roof support or for support in burst-prone grounds (Cai and Kaiser 2018).

Future mining relies on extracting minerals in highly-stressed orebodies at great depth. A much higher standard of rockbolting is required in complex mining conditions (Li 2011; Stacey 2011). In this paper, a novel self-swelling anchorage bolt (SSAB) is presented. The structure and the anchorage mechanism of the SSAB are introduced. The influence of the self-swelling roll length on the pull-out force and the relation between the pull-out force and the installation time are studied using static pull-out tests. Field pull-out tests of the SSAB are performed at Hongtoushan mine, China, to investigate the anchorage capacity of the SSAB.

2 Self-Swelling Anchorage Bolt (SSAB)

2.1 Components of SSAB

A SSAB consists of a threadbar, hollow self-swelling rolls, confinement nuts, gaskets, a plate and a plate nut (Fig. 1). Self-swelling rolls are inserted through the threadbar and placed along the bar. The ends of a roll are insulated with steel gaskets with a diameter slightly larger than that of the

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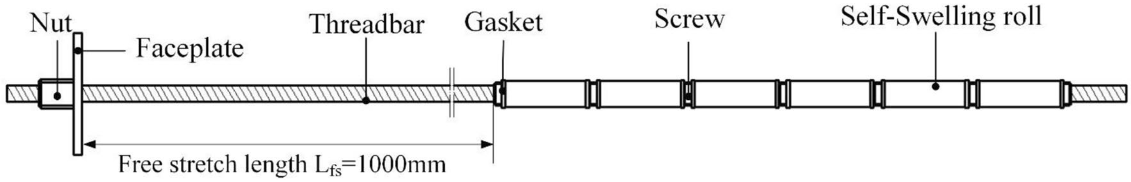

Fig. 1 Components of SSAB

rolls. Axial swelling of the rolls is confined by clamping the gaskets at the ends of the rolls with axial confinement nuts.

2.2 Installation Method

The self-swelling rolls of a SSAB are immersed in water for 5 to 8 min or water-sprayed for 10–15 min and then the saturated SSAB is inserted into the borehole; the rolls start to swell after 20–30 min and anchorage capacity is built up to secure the bolt in place for rock support.

2.3 Anchorage Principle of SSAB

2.3.1 Self-Swelling Roll

1. Components

    As illustrated in Fig. 2, a self-swelling roll consists of swelling agent, roll cover and wear-resistant protective cover. The main component of the self-swelling agent is 50–55% over-burnt calcium oxide (CaO), mixed with 35–38% binders, 1–2% water reducers and 2–4% retarders. The packing cover is made of kraft paper and sponge. A protective tube is inserted into the center of the packing cover to make the roll hollow inside. Self-swelling agent is filled into the packing cover. The unit weight density of the packed roll material is 1.8–2.1 g/cm^3. Figure 2b shows two self-swelling rolls used in the experiments conducted in this study.

2. Swelling principle

    The sweller is an inorganic powder material with high expansion characteristics. Its main component is free calcium oxide (f-CaO), warped by minerals (Goto et al. 1988). Chemical reaction occurs when CaO is in contact with water and this reaction leads to the formation of $Ca(OH)_2$ crystal after the surface minerals is hydrated. As more crystals are formed, the volume of the $Ca(OH)_2$ crystal increases, and the void volume between the crystals also increases, leading to macroscopic gradual expansion of the sweller (Gholinejad and Arshadnejad 2012). The expansion of the sweller can be limited under constrained condition, which will create a high swelling pressure. In other words, the self-swelling roll can apply a high expansion pressure to the borehole wall.

2.3.2 Anchorage Mechanism of SSAB

The anchorage mechanism of SSAB is illustrated in Fig. 3. The SSAB utilizes the hydration swelling of the self-swelling roll instead of the conventional grouts such as cement mortar and resin to secure a bolt in a borehole.

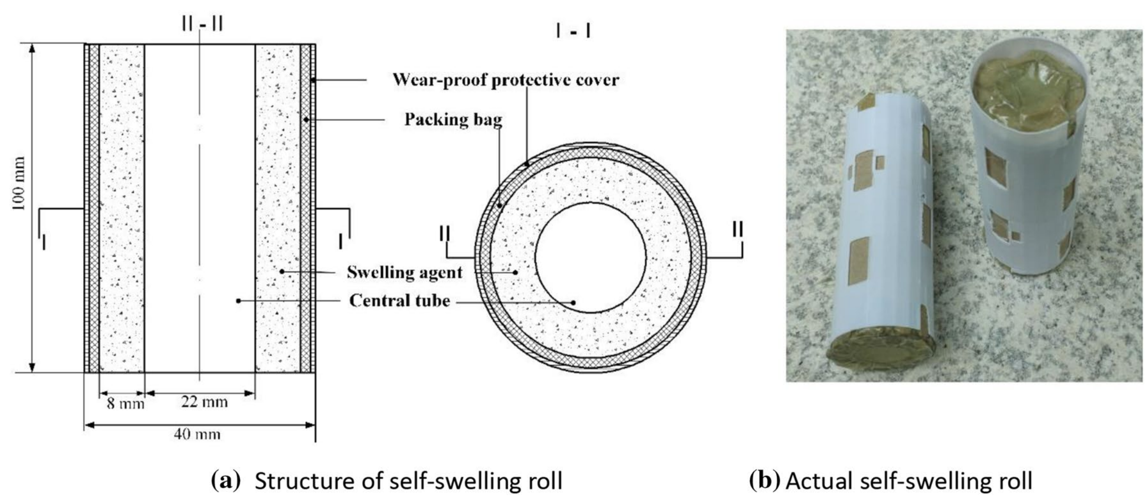

Fig. 2 Self-swelling roll

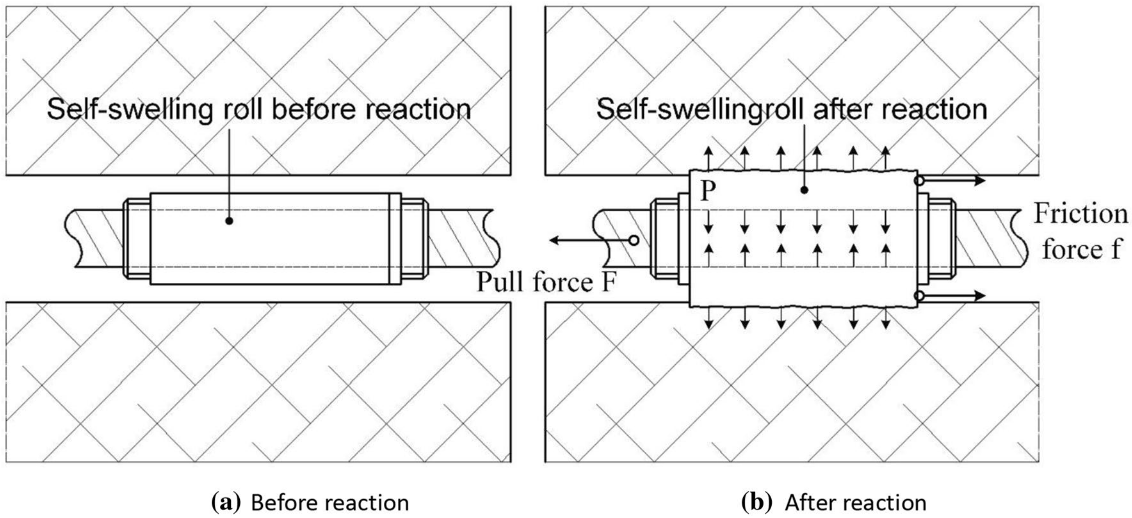

Fig. 3 Schematic of the anchorage mechanism of SSAB

The volumetric expansion rate (expanded volume divided by the original volume) of the self-swelling roll is 1.8–2.0 after chemical reaction. A dense and hard grout forms between the bolt and the borehole wall due to the constraint of the borehole wall and the ends of the roll, generating high expansion pressure between the borehole wall and the bolt. Axial movement of the roll is restricted by fixing the self-swelling roll to the bolt with gaskets and axial confining nuts (Fig. 1). High friction between the expanded roll and the borehole wall provides anchorage force to the bolt, which allows the bolt to fulfil the function of controlling rock mass deformation and preventing rock mass failure.

3 Laboratory Pull-Out Test

3.1 Test Equipment and Test Procedure

In this study, the direct pull-out test method (Kaiser et al. 1996) is used to evaluate the load and deformation capacities of SSAB. As shown in Fig. 4, the direct pull-out apparatus consists of a test platform, a hydraulic jack, an oil pressure control system, compressive load sensors, resistive spring displacement gages, a data acquisition system, an anchorage device, and skid-resistant nuts.

A levelling device in the test platform is used during installation to align the hydraulic jack and the compressive load sensors along the same axis. Force is applied to the hydraulic jack at a constant increment in the pull-out test by controlling the pumping rate of the oil. When the rockbolt

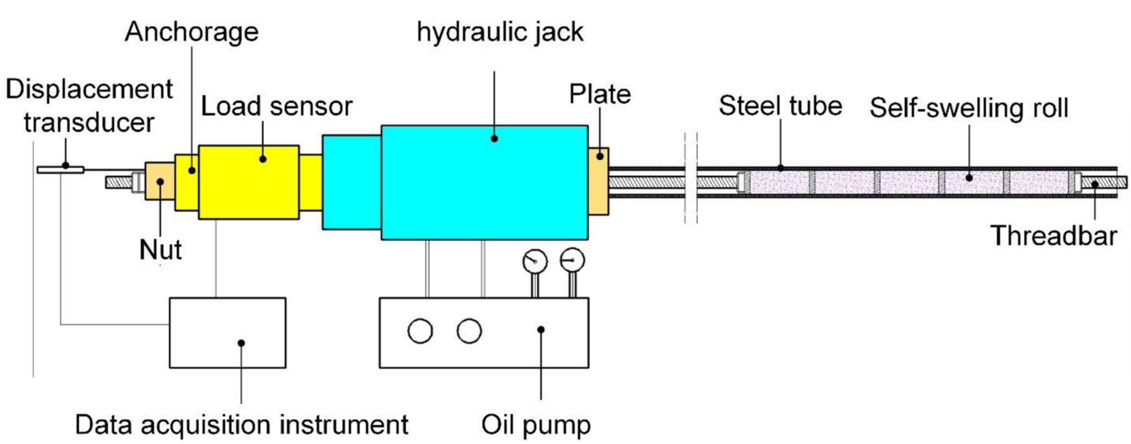

Fig. 4 Schematic diagram of the direct pull-out apparatus

Table 1 Main physical-mechanical properties of PSB 500-J20 threadbar

Yield strength (MPa)	Peak strength (MPa)	Cross section area (mm^2)	Elongation (%)	Linear weight (kg/m)
550	680	314	14.0	2.85

slides continuously or when the rockbolt fractures, the test is stopped.

3.2 Relation Between Roll Length and Pull-Out Force

Six laboratory pull-out test scenarios were designed to study the influence of roll length on the pulling force of the SSAB. The length of the roll varies from 10 to 60 cm, with a 10 cm increment. The bolts are made from 2.2 m long PSB 500-J20 left-hand threaded threadbars with a diameter of 20 mm. The mechanical and physical properties of the steel are shown in Table 1. The steel pipe used for installing the rockbolt is made from S45C steel with a wall thickness of 6 mm and a length of 2 m. Each self-swelling roll, which weights 170 g, has an outer diameter of 40 mm and a length of 100 mm. As shown in Fig. 1, the self-swelling rolls are placed continuously at the bolt end. The pull-out test was performed 24 h after the installation of the rockbolt; three tests were conducted in each test scenario.

The load–displacement curves of SSABs with different cartridge lengths are presented in Fig. 5a. For roll lengths varying from 10 to 50 cm at 10 cm increment, the peak pulling forces are 35, 75, 125, 152, 169 kN, respectively, and the SSABs show slippage failure. When the roll length is 60 cm, the pull-out force reaches 235 kN and the bolt fails in tension. Hence, 60 cm is the minimum roll length that can cause a bolt to fail in tension under the laboratory test conditions.

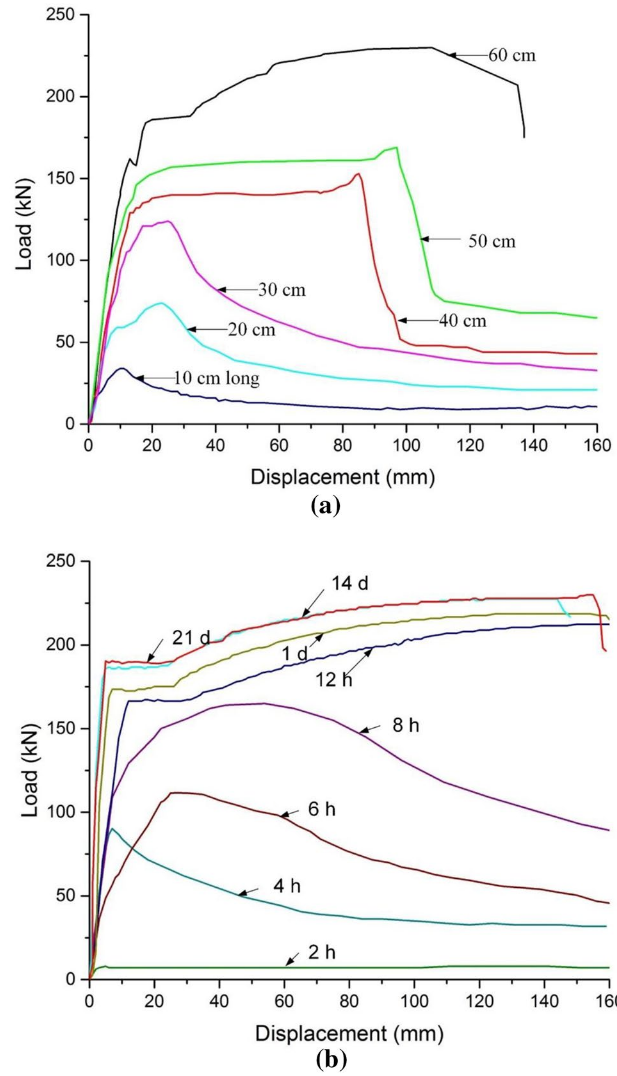

Fig. 5 Influence of self-swelling roll length (**a**) and reaction time (**b**) on pull-out force

3.3 Time Effect of SSAB Anchorage Force

Pull-out tests at different times after bolt installation were performed to study the time effect on the SSAB anchorage force. The test results presented in the previous section show that the SSAB can reach its ultimate tensile strength when six self-swelling rolls are used. Therefore, six rolls were installed at the end of each threadbar and pull-out tests were performed 2 h, 4 h, 6 h, 1 d (day), 7 d, and 21 d after bolt installation.

The load–displacement curves of SSABs tested at different times after installation are presented in Fig. 5b. The maximum pull-out forces are 10, 90 and 110 kN when the reaction times are 2, 4, and 6 h, respectively, and the bolts fail due to sliding of the bolts. The peak load is 212 kN when the reaction time is 12 h; it remains at 212 kN with the increase of displacement and due to the limited stroke length of the jack, the test was stopped at a displacement of 160 mm and the bolt did not fail. The pulling force reaches 230 kN when the reaction time is 1 d and the bolt fails in tension. The test results for 7 and 21 d reaction time show that the bolts break due to tensile failure. The load–displacement curves of the two tests overlap almost to each other.

4 Field Pull-Out Test

The field pull-out test examines the anchorage behavior of SSABs in underground mines. The goal is to determine the minimum self-swelling roll length of SSABs in field. The field tests were performed in a haulage drift in the no. 27 panel at the − 707 m level (at a depth of 1160 m) at Hongtoushan mine (a copper-zinc mine), Fushun City, Liaoning Province, China. The rock type at the test site is gneiss and the rock mass is moderately jointed. Rock joints are dry without groundwater infiltration. The rock properties at the field test site are shown in Table 2.

Similar to the laboratory tests, the lengths of the self-swelling rolls in the field tests range from 10 to 60 cm. Six test scenarios were designed and the details of each test case are listed in Table 3. Pull-out tests were carried out 24 h after the bolt installation and the test results are presented in Fig. 6.

Figure 6 indicates that the relations between the roll length and the pull-out force in the field tests are similar to those from the laboratory tests. The maximum pulling forces are 120, 180, 220, 235 kN when the roll lengths are 10, 20, 30, 40 cm, respectively. The bolt fails in the sliding mode when the roll length is less 30 cm. When the roll length exceeds 40 cm, tensile failure of the bolt occurs. When the roll length is longer than 50 cm, the pull-out force–displacement curves are similar to that with 40 cm roll length.

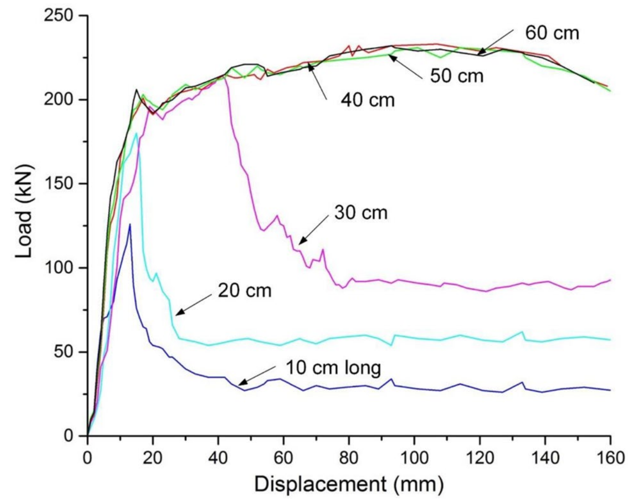

Fig. 6 Load–displacement curves obtained from field pull-out tests

5 Discussions

5.1 Laboratory Pull-Out Test

The laboratory test results presented in Fig. 5a show that when the roll length is between 10 and 50 cm, the bolt fails in the sliding mode and its elongation is 0 mm. This indicates that the maximum pulling force increases with the increase of roll length if the roll length is less than 60 cm. The anchorage force exceeds the ultimate tensile strength of the bolt when the roll length is 60 cm. In this case, the bolt fails in tension after sufficient plastic deformation of the steel. The slippage is only 2 cm and the elongation of the bolt is 13.3 cm, resulting in an average elongation ratio of 14%. The ultimate load-bearing capacity (i.e. the maximum pulling force) of the SSAB is 235 kN.

Table 2 Rock properties at the field test site

Rock type	Density (t/m^3)	UCS (MPa)	Elastic modulus (GPa)	Velocity of longitudinal wave (m/s)	Frictional coefficient
Gneiss	2.7	120–139	38.5–61	5500–6000	1.3–1.5

5.2 Time Effect of Pulling Force

Figure 7 presents the time effect of the maximum pulling force of the SSAB and the expansion pressure of the self-swelling roll. The expansion pressure increases from 0 to 15 MPa if the reaction time increases from 0 to10 h and there is only a slight increase of the expansion pressure from 10 to 24 h. The expansion pressure becomes steady and reaches a maximum of 20 MPa after 24 h. Hence, the peak load of the SSAB increases gradually as the reaction time increases up to 12 h. The rate of load increase reduces and the SSAB yields when the reaction time is between 12 and 24 h. The pulling force is almost constant after 24 h. The SSAB fails in the sliding mode if the time of test after installation is within 12 h and tensile failure of SSAB occurs if the test is performed 24 h after installation (Fig. 5b). A SSAB yields if the test time after installation ranges from 12 to 24 h. In this situation the bolt does not fail in the test because of the limited range of the hydraulic jack.

Table 3 Comparison of SSAB-bolt anchorage performances in laboratory and in-situ

Type	Cartridge length (cm)					
	10	20	30	40	50	60
Maximum load (Lab) (kN)	34	74	124	153	180	230
Maximum load (Field) (kN)	102	142	201	230	230	230
Percent increase (%)	200	92	62	50	27	0

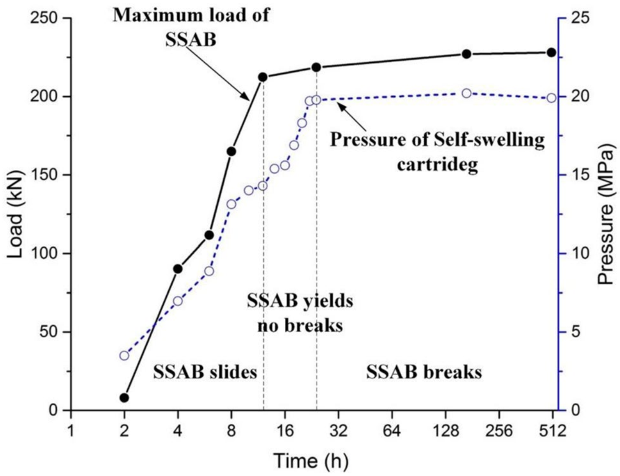

Fig. 7 Maximum load of SSAB and the expansion pressure of self-swelling cartridge

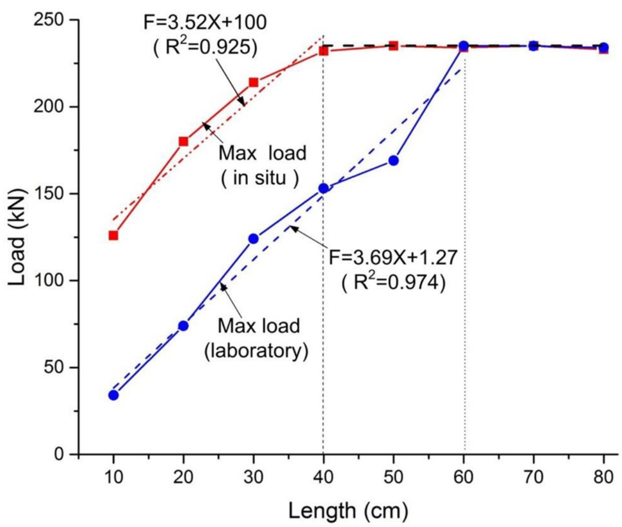

Fig. 8 Relation between load capacity of the SSAB and self-swelling roll length

5.3 Field Test Result

In the field tests, the SSABs fail in the sliding mode if the roll length is less than 40 cm (Fig. 6). In these cases, the anchorage force increases first, reaches a peak and then deceases to a steady level. When the roll length is longer than 40 cm, the anchorage force increases gradually with the increase of displacement and reaches the ultimate tensile force of the bolt material. Tensile failure of the bolt occurs in this situation and the bolt loses its load-bearing capacity after failure. The axial elongation of the bolt is 15 cm with an average elongation ratio of 13%.

Figure 8 presents the ultimate load–self-swelling roll length curves of SSABs obtained from the laboratory and the field pull-out tests. The pull-out force from the field test is consistently higher than that from the laboratory test regardless of the roll length. For example, at the roll lengths of 30 and 40 cm, the maximum pulling forces of the SSAB are 201 and 230 kN in the field test while the corresponding pulling forces in the laboratory test are 124 and 153 kN, respectively (Table 3). The pulling force in the field is 62% higher than that in the laboratory when the roll lengths are 30 cm.

When the roll length increases from 30 to 40 cm in the field, the increases of the peak load and the elongation of the bolt are higher and the failure mode changes from sliding to tensile fracture of the bar. The reason for such a difference between the laboratory and field test results of the same roll length could be attributed to rougher borehole wall and higher rock confinement in the field, which can result in higher friction between the SSAB and the rock mass. The borehole provides stronger constraint in the field. With the same expansion ratio of the self-swelling roll, the expansion pressure is higher in the in-situ condition. Hence, for the same roll length, the sliding resistance of the SSAB and the pulling force are higher in the field condition. Table 3 compares the maximum pulling forces obtained from the field and the laboratory test conditions. It shows that fewer self-swelling rolls are required to fully anchor a SSAB in the field condition.

The pulling force (F) of the SSAB increases almost linearly with the roll length (X) in the laboratory test condition if the roll length is less than 60 cm, which can be described by Eq. (1).

$$F = \begin{cases} 3.69X + 1.27 \text{ kN}, & X < 60 \text{ cm} \\ 235 \text{ kN}, & X \geq 60 \text{ cm} \end{cases} \tag{1}$$

The relation between the maximum pulling force and the roll length in the field test condition can be described by a piecewise linear function, which is given in Eq. (2).

$$F = \begin{cases} 3.52X + 100 \text{ kN}, & X < 40 \text{ cm} \\ 235 \text{ kN}, & X \geq 40 \text{ cm} \end{cases}. \tag{2}$$

Both the laboratory and field tests were carried out under similar experimental conditions. However, the pulling force can be influenced by many factors such as uniaxial compressive strength of rock, rigidity and roughness of boreholes. The minimum roll lengths required to fail the bolt can be different if the rock strength and stiffness are different. Hence, Eqs. (1) and (2) are specific for this study only and may not be generalized to other ground and laboratory test conditions. It is advised that the minimum roll length should be confirmed at each site using pull test.

Table 4 Cost analysis of SSAB-bolt

Type	Rod (US $)	Face-plate (US $)	Nut (US $)	Anchor head (US $)	Anchorage agent (US $)	Gasket and screw (US $)	Total (US $)
SSAB	5.2	1.2	0.5	0.5	2	0.7	10.1
Resin bolt	5.2	1.2	0.5	–	4	–	10.9

5.4 Cost Analysis

Table 4 compares the costs of the SSAB and the commonly used resin bolt. Each self-swelling roll costs 0.4 USD and five rolls are required for each SSAB, resulting in a total cost of 10.1 USD for a SSAB. A borehole with a diameter of 38 mm requires four 32 mm × 500 mm resin cartridges. Each resin cartridge costs 1.0 USD and the total cost of the resin bolt is 10.9 USD. Compared with the resin bolt, the novel SSAB has advantages of easier installation, lower installation cost and more persistent anchoring force. In comparison, the anchoring force of a resin bolt depends highly on installation quality.

6 Conclusions

The SSAB is a friction rockbolt through single-point or multiple-point anchorage. It supports and bolts the surrounding rock mass using the strength and deformability of the bolt bar material. Each self-swelling roll can function independently if the rockbolt is under axial loading. This can increase the load-bearing locations of the bolt and hence improve its anchorage performance.

The laboratory test results indicate that tensile fracture of the SSAB occurs if the self-swelling roll length exceeds 60 cm. In this case, the ultimate load of the SSAB depends on the ultimate tensile strength of the bolt. The deformation capacity of the SSAB depends on the free elongation length and the ultimate elongation ratio of the bolt bar material. The elongation ratio of the SSAB is 14% in the laboratory test.

The field test results show that the maximum pulling force reaches 235 kN if the self-swelling roll length is 40 cm or longer. The elongation ratio of the SSAB is 13%. The anchorage force of the SSAB is higher than the tensile strength of the bolt bar if more than 40 cm long self-swelling rolls are used. This leads to full anchorage of the bolt for rock support in underground engineering.

The installation cost of SSAB is low. In addition, the SSAB has the advantages of easy installation and persistent anchorage force.

Laboratory and field tests will be carried out in the future to study the SSAB performance under the long-term effects of acidic water and ionized water to optimize the structure and the performance of the bolt.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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