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Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance

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ABSTRACT

This paper presents an innovation work on the development of a novel energy-absorbing bolt characterized by an extraordinarily large elongation and high constant resistance. The bolt has a compound structure consisting of a cone-like piston sliding inside an elastically-deformable sleeve pipe. The frictional resistance generated by the sliding of the cone body relative to the internal surface of the sleeve pipe was mathematically formulated which is dependent on the elastic property of the sleeve pipe, the geometry of the cone and the frictional properties of the sliding interface, and independent of the external loads under the static loading conditions. A dashpot element for the cone-sleeve relative motion, termed "stick-slip element", was proposed in construction of the lumped-mass model of the bolt for development of the constitutive equations that exhibits a frequency-dependent frictional behavior and a stick-slip oscillating response. The results from the static pull tests compared very well with the predicted working resistances, energy-absorbing capacity and elongations. The time-marching scheme of the bolt's impact load from the weight-dropping tests evolves with the pulsation response in the initial phase, stick-slip oscillation in the subsequent regime over which the dynamic energy is consumed, and a quasi-linear attenuation in the later phase. It demonstrates the fact that this bolt is robust in damping the dynamic load. The analytical work in this study provides solutions in the assessment of the large deformation and establishment of the forewarning precursors associated with deep mines.

1. Introduction

Tunnels being built in deep ground are often subjected to high stresses and complex geological conditions. Accordingly, surrounding rock masses in deep ground tend to experience large static deformation such as the creep and dynamic deformation which is associated closely with various underground disasters such as coal bumps, coal and gas outbursts, rockbursts [1,2]. Due to the large uncertainty and variability in rock mass properties (e.g., rock mass strength) and boundary conditions (e.g., in situ stress), all engineering design, calculations, and seismicity monitoring will have to rely on effective rock support as the final line of safe guard workers, equipments, and mine operation [3,4]. Therefore, in developing a ground support used in deep underground engineering, the capability to counteract the dynamic impact and retain the large rock mass deformation should be taken into account.

Over years, various ground support techniques and products have been developed for support and retention of the newly exposed faces and internal reinforcement of the soil and rock masses surrounding the excavations. Nevertheless, according to their performance, the rock supports can be classified into three types [5], i.e. a strength bolt, a yieldable bolt and an energy-absorbing bolt. The strength bolt is essentially elastic and provides a support load equal to or close to the intrinsic strength of the bolt material such as rebar which has a high stiffness and tolerates small deformations prior to failure. The yieldable bolt is essentially plastic but with low stiffness which is able to accommodate large rock deformation, such as the Split sets [6–9]. The energy-absorbing bolt should have the strength of rebar and deformation capacity of the Split Set bolts, with the ability to be rapidly mobilized to a load level similar to strength of the material [5]. The basic requirement for the energy-absorbing bolt is the intrinsic "plastic" nature which means that the bolt can yield at high strength with a large elongation (at least 200–300 mm) so as to adapt to the deformation of the surrounding rockmass [10,11]. Many efforts for realizing that goal could be dated back to the early works on the different types of rock bolts [6–8,11–14] including the yieldable rock bolts, Split Set and Swellex; the Garford bolt,

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Durabar bolt, and Roofex bolt. True energy-absorbing bolts that can meet the said requirement were developed in recent decades, such as the Garford Solid Dynamic Bolt [15,16], Roffex [16], energy-absorbing rock bolt [17]; cone bolt [18–20]; MCB conebolt (modified conebolt with elongation as much as 180 mm) [4,19,21,22]; and D bolt with large load-bearing and deformation (elongation as long as 400 mm) [5].

With the growing demands for energy resources, mining depths for both metal ore and coal mines across the world have went beyond 1000 m. Some metal and nonferrous metal mines in China have entered into 800–1200 m such as Ling Long gold mine (beyond 800 m) and Lion Mountain copper mine (1100 m) located in Shandong Province. The depths in many coal mines has entered into 1000 m below, such as Dong Xing coal mine (1287 m) in Shangdong Province and Caitun colliery of Shenyang coal mining bureau (1197 m) in Liaoning Province. It was expected that in the coming 20 years, many coal mines in China will be entering into mining depths ranging from 1000 m to 1500 m. In order to adapt to the increasing demands for the support system and bolt device in deep underground engineering, a novel energy-absorbing bolt possessing ultra-high energy-absorbing capacity by deforming with an extraordinarily large elongation at high constant resistance was developed by Manchu He (known as the “He bolt”; [23]). The present innovative work on the He bolt involves the structural design, analytical formulation of the constitutive equations, and static and dynamic experimental experiments.

2. New energy-absorbing bolt

2.1. Structure

Fig. 1 shows schematically the structure of the He bolt which is actually a compound device consisting of following elements: a piston-like cone body installed on a bolt shank (a rebar), a sleeve pipe with its inner diameter slightly smaller than the diameter of the large-end diameter of the cone, a face pallet and a tightening nut functioned as the retention elements. The fixed length of the shank bar is bonded by means of grout. When the axial external load (pull load) is applied on the far end (the face pallet end) of the bolt in the direction opposite to the anchored end, the sleeve pipe will displace in the same direction relative the cone which is actually the elongation of the He bolt. The motion of the sleeve is equivalent to the displacement of the cone relative to the internal surface of the elastically deformable sleeve pipe. The small-end diameter of the cone is designed a little smaller than the internal diameter of the sleeve in order to allow for the easy fitting of the cone body into the pipe. The large-end diameter of the cone is slightly larger than the inner diameter of the sleeve pipe in order to generate the frictional resistance (i.e. the working resistance of the He bolt) during the relative sliding between the cone and sleeve pipe. The elastic limit of the shank bar is less than the frictional resistance. Thus the shank only deforms elastically when the bolt is subjected to the external load.

The anchored end of shank bar is a semi-conical shaped paddle anchor with its size only slightly larger than the bolt shank, allowing it to be inserted into small boreholes. The paddle anchors are suitable for both resin and cement grouts. This guarantees that the bolt shank can be firmly capsulated in the grout. The pallet and tightening nut constitute the external fixture functioned as the surface retention elements. Such measures are used in the practical use of the He bolt, including the anti-rust painting on the surface of the shank bar and cone body and internal surface of the sleeve pipe, as well as grouting of the free length of the bar outside of the sleeve pipe and sealing the sleeve pipe at the anchorage side with slow setting resin, for protection of corrosion of the free length and prevention the ground water from entering into the sleeve pipe. One of the structural merits of the He bolt is the fact that the most part of the free length of the shank bar is located in the sleeve pipe which is isolated with the surroundings in the case of well sealing of the sleeve pipe with grout. Therefore, as long as the sealing material and anti-rust paint properly chosen, the He bolt can work over a long period without the change of the sliding mechanism.

2.2. Working principle

Fig. 2 shows the working principle of the He bolt in stabilizing the surrounding rockmass. Fig. 2a shows the original working state of the He bolt where the full free length of the shank bar is contained in the sleeve pipe and the fixed length of the shank, with a paddle anchor at the anchored end, is encapsulated in the borehole using either resin or cement grouts. The anchored end of the shank bar is bonded by means of grout located in the stable interior region beyond the volume of material undergoing deformation and displacements. The sleeve pipe of He bolt is also encapsulated in the borehole and the pallet and nut provide necessary surface retaining support. The bolt is loaded by deformation of the rock surrounding a borehole and displacements associated with the extension of the virginal discontinuities as shown in Fig. 2b. During the dilation of the surrounding rock, the bolt system will restrain the dilation so that a tensile load is induced at the face pallet end, i.e. the pull force, exerted by the pallet and nut on the sleeve pipe when retaining rock deformation, exceeds a threshold resistance force P_0 which is the static friction force when the cone slides inside the sleeve pipe (will be formulated in later sections), the sleeve pipe will displace in the direction opposite to anchored end of the bar, exporting elongations. The cone and the elastically-deformed segment of the sleeve are referred to as the “cone unit” thereafter.

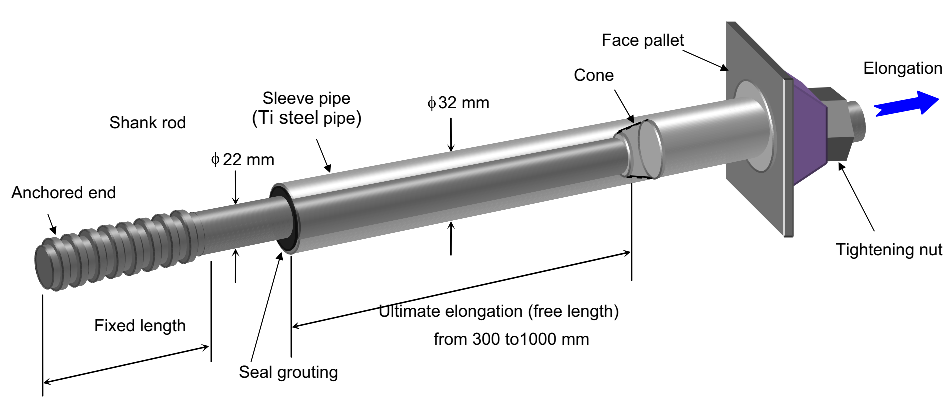

Fig. 1. Schematic of the three-dimensional view of the He bolt.