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Progress and Perspectives of Geotechnical Anchor Bolts on Slope Engineering in China

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Geotechnical anchoring technology is an important tool for disaster prevention and mitigation in slope engineering. Anchor bolts which are commonly used in slope engineering can be divided into prestressed anchors and non-prestressed anchors. Due to the superiority of anchor support technology, research on various aspects of anchor bolts, such as mechanical mechanism, anchorage effect, and the development of new-type anchor bolts, has been a significant research topic for scholars. This mini-review sums up the diverse past and current literature on anchor support technology of slope engineering in China. It focuses on the characteristics, applications, research methods, and practical cases of anchor bolts and briefly describes the history of slope anchor bolt development in China in the past 3 decades. Nowadays, the demand for engineering construction processes is increasing, and engineering geological conditions are becoming more complex, which promotes the development of anchor support technology. At the international level, achieving carbon neutrality is both an international trend and a general objective. Against the background of global commitment to carbon neutrality, the potential future perspectives for the developments of anchor support technology have been prospected in light of actual engineering needs.

Keywords: slope engineering, anchor bolt, energy-absorbing anchor, nonmetal bolt, carbon neutrality, ecological slope protection

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1 INTRODUCTION

Landslide is one of the most common geological disasters in the world, which causes great harm to the life and property of people. Geotechnical anchoring technology is an important tool for disaster prevention and mitigation. As a significant branch of geotechnical engineering, geotechnical anchoring techniques are widely applied to engineering construction due to their economy and efficiency (Ding et al., 2022). Anchor bolts play a crucial role in geotechnical anchoring (Shan et al., 2021), which could restrain the displacement of rock and soil mass (Nie et al., 2014b) so as to prevent disasters, such as landslides (Xu et al., 2014) and rock avalanches (Fan et al., 2017).

Anchor bolts have been exploited for over 100 years to reinforce rock and soil mass, which dated back to 1913, where they were generally utilized in the American mining industry until the 1940s (Grasselli, 2005). Due to the superiority of anchor support technology, China has been using anchor bolts in coal systems since the 1950s (Kang, 2016). With the development of China's hydraulic engineering, power engineering, and urban construction, the application of anchor support technology in China entered a boom period in the 1980s (Cheng, 2001).

The reinforcement effects of anchor bolts are apparent as they can transfer the tension caused by rock deformation to the stable rock layer. The dangerous rock mass is combined with the stable rock mass through bolts (Li et al., 2016; Li Y. et al., 2017). Compared with the original rock, the uniaxial compressive strength and elastic modulus of the bolted rock improve to some extent (Yang et al., 2020). The bolting area can limit the extension and propagation of tensile cracks and slow down the failure process (Zong et al., 2014).

In this mini-review, we sum up the diverse past and current literature about anchor support technology of slope engineering in China. The characteristics, applications, and practical cases of various types of anchor bolts are the focus of our attention. Some research methods and the development history of anchor support technology are briefly described, and finally, the potential future perspectives for developments in the field are highlighted.

2 CLASSIFICATION OF ANCHOR BOLTS IN SLOPE ENGINEERING

In slope engineering, anchors bolts are divided into two categories: the prestressed anchors and the non-prestressed anchors; the former can also be called prestressed anchor cables if the reinforcement body consists of steel strands and wires, while the latter are often called full grouted bolts (Cheng et al., 2015). The prestressed anchor implements the pre-stress in advance is a sort of active supporting technology, while the non-prestressed anchor is activated by the deformation of the surrounding rock; this is a sort of passive supporting technology (Guo et al., 2019).

2.1 The Prestressed Anchors

Prestressed anchors have excellent characteristics of lightweight and high strength, which could decrease the amount of material for reinforcing structures so that the weight of the supporting structure would be controlled (Deng et al., 2021). In order to ensure the optimal position and length of the prestressed anchors, previous scholars have carried out remarkable studies. Hryciw (1991) proposed a theoretical research to confirm the optimum orientation of anchors by surface load. Yang et al. (2015) obtained a better reinforcement arrangement of prestressed anchors which relied on slope stress and displacement fields. An et al. (2020) presented a new three-dimensional optimization equation for the anchorage direction angle. Although the prestressed anchors can efficiently reinforce slopes, they still have many limitations. Elices et al. (2012) found that the common prestressed anchors with damage fail to warn against brittle failures. In addition to brittle failures caused by loads greatly exceeding the strength, stress corrosion cracking in complex geotechnical environments is another major cause of the deterioration (Karalis et al., 2012; Mak et al., 2019). Wang Y. et al. (2019) showed that the anchor head is relatively fragile through the collection and analysis of field samples. Sun et al. (2021)demonstrated that shear failure occurs with the extension and evolution of cracks by means of laboratory simulation tests. As a main defect of the prestressed anchors, it is necessary to study the mechanism of prestressing loss (Gao et al., 2021). Zhang et al. (2009) showed that the prestressing loss is divided into three parts according to the construction process: tensioning, locking, and time-dependent and specified the calculation formulas. Chen et al. (2013) further divided the prestressing loss into two parts based on a soft rock slope measurement analysis: instantaneous loss and time loss. Liu et al. (2021) revealed that the accelerated creep of the rock mass will contribute to tension failure or debonding failure of the bolt. Prestressed anchors are suitable for most projects, and they are most suitable for the excavation of high-steep slopes (Yang et al., 2020).

2.2 The Non-Prestressed Anchors

Passive, fully grouted bolts can provide extra tensile and shear strength to the joints it intersects at the anchorage part when installed in a jointed rock mass, and it is a crucial support technology for the joint rock slope (Siad, 2001). The rock–bolt interface of fully grouted bolts is formed by bonding the grout materials (cement, resin, etc.), which generates the load-bearing capacity by its shear strength (Nie et al., 2014a). This shear strength is related to the frictional rather than bonding strength of the rock–bolt interface (Hyett et al., 1992). Furthermore, the relatively high axial load may motivate the formation of slippage at the rock bolt–grout interface, which results in the loss of supporting capability (Kaiser et al., 1992). Freeman (1978) explored the behavior of fully grouted bolts relatively early. The following scholars used laboratory tests, analytical methods, and numerical models in studying the mechanical property of fully grouted bolts (Hyett et al., 1996; Li and Stillborg, 1999; Blanco Martín et al., 2013; Liu and Li, 2020; Singh and Spearing, 2021). The increase in bolt length and cross-sectional area can boost the bearing capacity of the fully grouted bolts through the data of tests (Benmokrane et al., 1995; Kılıc et al., 2002). The strength of the rod material is one of the main factors in the bearing capacity of the fully grouted bolts (Li and Liu, 2019), and the bolting angle, properties of grouting materials, and rock mass quality also have an impact (Feng et al., 2017; Li and Liu, 2019). It is understood that ultima failure is caused by debonding of the rock–bolt interface if the bolt tensile strength is relatively strong (Li and Stillborg, 1999). Ho et al. (2019) confirmed that under high confining pressures, the damage is mainly due to shear failure, while under low confining pressures, the grout is destroyed by cracking from expansion. Luga and Periku (2021) also obtained similar results through multiple *in situ* fully grouted bolt pull-out tests.

It is indispensable to rationalize the anchoring scheme and maximize the supporting effect of anchor bolts. This is possible through the research of the optimal installation position and failure mechanism, mentioned above, which have their own unique contributions. Revealing the failure mechanism facilitates the innovation of new-type anchor bolts. **Table 1** summarizes the features, advantages, disadvantages, applications, examples, and practical cases of some geotechnical anchors.

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TABLE 1 | Summary of the features, advantages, disadvantages, examples, and practical cases of some geotechnical anchors (Siad, 2001; Wu et al., 2005; Qin et al., 2007; Wang et al., 2008; Dong et al., 2010; Nie et al., 2014a; Cheng et al., 2015; Xu and Yin, 2016; Zhu et al., 2017; Wu S. G. et al., 2018; Wu X. et al., 2018; Tao et al., 2018; Mak et al., 2019; Tang et al., 2019; Gao et al., 2021).

Type	Examples	Advantages	Disadvantages	Practical Cases
The Prestressed Anchors	Large anchor cables The tension–compression dispersive anchor cable Sand consolidated anchorage prestressed bolt Self-reinforced anchor bolt The frame supporting structure with prestressed anchors	1. Active supporting technology 2. High load-bearing capacity 3. Almost the unique option of the excavation high-steep slope 4. Strong ability to control ground deformation 5. Rapid and simple installation 6. Relatively inexpensive	1. Presence of prestress loss 2. Susceptible to corrosion	The Lianziya rock mass Tang et al. (2019) A rock slope in Chongqing Wu et al. (2018a) Fengtian hydropower station Qin et al. (2007) An expressway cutting slope located in Zhengzhou city of China Wu et al. (2005) Lanzhou Xiaxiyuan Fund Development Building Dong et al. (2010)
The non-prestressed Anchors	Hollow grouted bolt Self-drilling anchor GFRP anchor	1. Most commonly used anchor bolts 2. Relatively excellent corrosion resistance 3. Can be used for permanent reinforcement engineering 4. Crucial support technology for joint rock slope	1. Passive supporting technology 2. Relatively weak ability to control ground deformation 3. Relatively expensive 4. Necessary to wait for the setting time if using cement	K60 + 535-K60 + 585 of road S246 in Xin'an county, Luoyang City, Henan ProvinceWang et al. (2008) One Western modem artificially accumulated slag platform Chen et al. (2014) A field project in Hong Kong (Xu and Yin, 2016)
	Yielding anchor CRLD bolt	1. Provides both high load capacity and a certain amount of yield energy absorption	1. Relatively expensive 2. Susceptible to corrosion 3. Not widely used	The left bank of Jinping Hydropower Station Zhu et al. (2017) Tonglushan ancient copper mine relics Tao et al. (2018)

et al., 2018; Tao et al., 2018; Mak et al., 2019; Tang et al., 2019; Gao et al., 2021).

3 ANCHOR BOLT DEVELOPMENT IN THE PAST THREE DECADES

Before 2000s, anchor support technology was mostly exploited for the reinforcement and prevention of high-steep rock slopes of hydropower stations, open-pit mines, and highways (Zhang, 1995; Han et al., 1996; Li and Zhao, 1997). With the vigorous construction of the Three Gorges Project, the complex geological conditions in the Three Gorges area have given rise to numerous research needs and significant research on slope reinforcement, including excavation and reinforcement design, planar finite element calculations, stability analysis, field tests, and the establishment of the constitutive model for the high-steep rock slopes of the Three Gorges locks (Zhu and Zhang, 1996; Xu and Yang, 1997; Zhang and Zhu, 1997; Gao and Yang, 1998; Xu, 2000; Zhu and Cheng, 2000). Between 2000 and 2012, the research hotspots were the development of new anchor bolts and the study of the mechanical effects of anchorage. The development of load-dispersed anchors (cables), repeated grouting techniques, hollow-grouted anchors, and under-reamed anchors has occurred rapidly (Cheng, 2005). For the study of mechanical properties and the support effect of anchorage, numerical simulation and mechanical tests are mainly used (Zhang and Chen, 2003; Lin et al., 2005; Li et al., 2012). Inheriting previous developments, more complex problems were discovered during the project since 2012. When excavating slopes in areas of high *in situ* stress or extremely soft rock, ordinary anchors (cables) can no longer meet the needs of deformation in these areas, and the development of yield-absorbing anchors has become a significant research topic (Zhu et al., 2017).

In **Table 2**, we summarize the anchor bolts adopted by Chinese engineers in dealing with different slopes and the performances of practical engineering.

4 RESEARCH METHODS OF ANCHOR BOLTS

In terms of a performance study of anchor bolts, mechanical test, numerical simulation, and non-destructive test are three common research methods. Conventional mechanical tests generally include tensile test (Chang et al., 2017), pull-out test (Teymen and Kılıç, 2018; Xu et al., 2018), shear test (Li et al., 2019), shaking table test (Su et al., 2021), the drop hammer test, and the Split Hopkinson Pressure Bar test (Wu et al., 2019; Wang et al., 2022). Those tests include comparatively accurate mechanical properties such as tensile strength, elongation, and shear strength. However, the conventional mechanical tests are mostly laboratory tests, which are difficult to be applied in practical engineering situations and relatively expensive (Li et al., 2019).

The emergence of numerical simulation technology was welcomed by scholars due to its high precision, economy, and repeatability. By setting different working conditions, numerical simulation technology can calculate the parameters of anchor bolts in various working conditions (Chen and Li, 2022). Numerical analysis methods can be divided into continuous analysis methods and discontinuous analysis methods.

TABLE 2 | Summary of the anchor bolts used as support for different kinds of slopes and their performance (Wang et al., 2008; Tang et al., 2012; Zhou et al., 2013; Nie et al., 2014a; Tao et al., 2015; Zhu et al., 2017; Bai et al., 2018; Xiang et al., 2022).

Anchor bolt	Slope type		Environment			Performances			
	Soil slope	Rock slope	Corrosion	Freezing–thawing cycle	High in-situ stress slope	Charge	Deformation	Environmentally friendly	Combined with monitor
Prestressed anchor bolt/cable	△	○	□	□	△	L	L	L	N
Compression dispersion anchor	—	○	□	×	△	H	L	L	N
Frame support anchor	○	△	□	○	—	H	L	L	N
Hollow grouted bolt	○	○	○	□	—	L	L	L	N
Fully grouted bolt	○	○	○	□	△	L	L	L	Y
GFRP anchor	○	○	○	—	—	L	L	H	Y
Yielding anchor	△	○	□	○	○	H	H	L	N
CRLD bolt	△	○	□	○	○	H	H	L	Y

○ suitable, △ useful, — to be investigated, × unsuitable.
H, high; L, low; Y, yes; N, no.

Apparently, the finite element method (FEM) is the most preferred numerical method because of its applicability for solving mechanical problems (Soparat and Nanakorn, 2008). Advances in computer arithmetic have driven advances in discontinuous analysis methods (Yokota et al., 2019b). The discrete element method (DEM) can model jointed rock masses by using UDEC (Gao and Kang, 2016). The discontinuous deformation analysis (DDA) can efficiently simulate the crack formation and evolution (Yokota et al., 2019a).

It is difficult to obtain the installation defects and progressive damage to the installed anchor bolts. The installation defects and progressive damage are significant factors. Unlike the first two research methods, a non-destructive test (NDT) can carry out a quality inspection and assessment of the installed anchor bolts. For instance, in the aspect of bonding quality inspection of fully grouted bolts, vibration methods and wave propagation methods are two commonly used methods (Zima and Rucka, 2017; Bačić et al., 2020). Liu L. et al. (2022) proposed a new stress wave reflection NDT method using a two-sensor acquisition. Liu L. L. et al. (2022) presented an effective means of detecting internal defects based on an ultrasonic waveguide and an improved empirical mode decomposition method. Nevertheless, it is difficult to obtain the mechanical parameters of the installed anchors, such as the actual bearing capacity, which needs to be addressed.

5 DISCUSSION AND FUTURE PERSPECTIVES

5.1 Energy-Absorbing Anchor Bolts

The ideal anchor provides both high load capacity and a certain amount of yield energy absorption (Chunlin Li, 2010). The earliest concept of energy-absorbing anchors was introduced in South Africa in the late 20th century and was applied in South African coal mines (Li et al., 2014). The currently available energy-absorbing anchors mainly achieve the purpose of absorbing energy through the yielding structure (Wu X. et al., 2018), such as the Garford bolt (Varden, 2009), Roofex (Charette and Plouffe, 2007), the CRLD bolt (He et al., 2014), etc. However, there are relatively few innovative studies on rod material. The team of He successfully developed a new type of anchor steel rebar with a negative Poisson's ratio effect (Gu et al., 2022). The new-type NPR anchor steel can balance the contradiction between high strength and high ductility of metal materials and realize the large deformation and energy-absorbing characteristics of anchor bolts from the material nature (Tao et al., 2022). According to the recent results of the drop hammer test and Split Hopkinson Pressure Bar Test, the elongation and energy-absorbing capacity of the constant resistance energy-absorbing material are superior to those of the common materials (Wang et al., 2022). The successful development of NPR anchor steel proves that the effect of ideal anchor bolts can also be achieved through the innovation of rod materials and that the combination of a reasonable yield-absorbing structure can maximize its yield-absorbing effect.

5.2 Nonmetal Anchor Bolts

Metal anchors are often corroded by water seeping through cracks in the rock or by solutions containing chloride and sulfate ions (Gamboa and Atrens, 2003; Villalba and Atrens, 2009; Karalis et al., 2012; Kang et al., 2013). Investigations of anchor bolt failures have shown that the life of anchor bolts is principally controlled by corrosion, which influences the exposed free length (Jiang et al., 2014), while nonmetallic anchors based on fiber-reinforced polymer bars can overcome this drawback (Xu and Yin, 2016). In recent years, there have been many studies on the performance of glass fiber–reinforced polymer (GFRP) materials (Dutta and Hui, 2000; Yeung et al., 2007; Yu et al., 2007; Keller et al., 2008; Li C. et al., 2017). It is believed that GFRP materials and high-pressure grouting technology are sufficient to substitute steel reinforcement (Yeung et al., 2007). After glass fiber–reinforced polymer (GFRP), carbon fiber–reinforced polymer (CFRP), and aramid fiber composite–reinforced polymer (AFRP) are known, basalt fiber composite–reinforced polymer (BFRP) has arisen the interest of scholars (Lu and Xian, 2018; Wang X. et al., 2019; Bai et al., 2020). Compared to carbon fiber, basalt fiber is cheaper and simpler to manufacture (Larrinaga et al., 2014); compared to glass fiber, the mechanical performance is similar or even better (Fiore et al., 2015). Basalt fiber has excellent modulus, high strength and temperature resistance, non-toxic, natural, stable, easy to process, eco-friendly, and relatively cheap (Lopresto et al., 2011; Wei et al., 2011; Borhan, 2012). Compared with ordinary steel anchor bolts in laboratory shear test, the peak shear strength of the BFRP anchor rod is relatively low, while the residual shear strength and the ductility are relatively high, and the anchoring effect of the jointed rock body anchored by BFRP anchors is affected by the anchoring angle, and the shear strength is relatively higher when the anchoring angle is less than 60° (Zhang et al., 2022). The BFRP rebar was mostly exploited in reinforced concrete structures, and nowadays, it is increasingly applied in slope reinforcement engineering due to its excellent performance and progress of the process (Wu et al., 2021). Combined with the practical engineering needs, it is of extraordinary significance to design and manufacture new anchor bolts with mature properties, which is a research hot spot (Alraie et al., 2021).

5.3 Ecological Slope Protection

Research on ecological slope protection technology has been a significant research topic, which can ensure the required strength and is more eco-friendly. Ecological slope protection and carbon reduction can be achieved by reducing the use of steel and integrating ecology and anchoring technologies. FRP material has great potential to replace steel and is environmentally friendly. FRP anchors have high tensile strength and strong corrosion resistance but insufficient shear strength (Guo et al., 2018). How to improve the shear strength of FRP anchors is a critical issue. The plant root system not only retains soil and water but also has been proven to be effective in strengthening slopes (Lin et al., 2010; Ma'ruf, 2012; Cao et al., 2018). Integrating anchoring technology with the ecological environment is another direction to achieving low-carbon anchoring. This could attain the balance between ecological performance and mechanical performance (Su et al., 2021). Su et al. (2018) proposed new style of ecological slope protection using "Anchor + Hinged Block", which realized a better reinforcement and seismic performance. In addition, as a new-type material that has both biocompatibility and engineering function, it has not been studied; for instance, the feasibility of vegetation growing recycled concrete for grouting (Wang F. et al., 2019). In the context of global efforts to achieve carbon neutrality, these low-carbon and eco-friendly slope anchoring technologies will certainly become a vital part of slope support technology in the future.

6 CONCLUSION

In China, the anchor support technology for slope engineering is pretty mature. A reasonable anchoring scheme according to the actual slope conditions needs to be selected in order to maximize the support capacity of anchors and ensure engineering quality and safety.

1) In this mini-review, we introduce geotechnical anchors for slope engineering and their research methods, briefly describe the history of anchor development, and summarize the anchor bolts used to support different kinds of the slopes and their performances. This serves as a reference for engineers to quickly select applicable anchor bolts according to the actual engineering conditions. Meanwhile, we highlight the potential future perspectives for developments in the field.
2) In terms of improving the anchor support capacity, there are more improvements to the anchor structure but less development and use of new materials. FRP material has great potential to replace steel and is environmentally friendly; however, shear strength is insufficient. Finally, it is difficult to obtain the mechanical property parameters of the installed anchors by the existing research methods.
3) Nowadays, engineering geological conditions are becoming more complex and the ecological environment is more fragile, such as Sichuan—Tibet railway. The improvement of anchoring technology should be based on the actual engineering situation. In the context of global efforts to achieve carbon neutrality, scholars should strengthen the research on the integration of ecological slope protection and anchor support technology, which will contribute to the goal of carbon neutrality.

AUTHOR CONTRIBUTIONS

YD, HL, and LH were responsible for the work concept or design; HL were responsible for literature collection; YD and HL were responsible for drafting the manuscript; YD, HL, and SDC were responsible for making important revisions to the manuscript; YD and HL were responsible for approving the final version of the manuscript for publication.

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