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Review

An Insight from Rock Bolts and Potential Factors Influencing Their Durability and the Long-Term Stability of Deep Rock Tunnels

Wadslin Frenelus *, Hui Peng and Jingyu Zhang

Department of Hydraulic Engineering, College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang 443002, China
* Correspondence: wadslin@ctgu.edu.cn

Abstract: Selecting and designing the most suitable support systems are crucial for securing underground openings, limiting their deformation and ensuring their long-term stability. Indeed, the rock excavations imposed by the erection of deep tunnels generate various harmful effects such as stress perturbation, damage, fractures, rockbursts, convergence deformation, and so on. To combat such effects by helping the surrounding rocks of these structures to hold up, rock bolts are typically utilized as pioneer support systems. However, the latter must be efficient and sustainable to properly fulfil their vital roles. A thorough understanding of the existing rock bolt types or models and the relevant factors influencing their failure is highly required for appropriate selection, design and applications. It is observed that, despite numerous studies carried out, there is a lack of comprehensive reviews concerning the advances in such rock support systems. This paper provides an insight into the most pertinent rock bolt types or models and describes the potential factors influencing their failure. Additionally, it discusses the durability of rock bolts, which has a huge impact on the long-term stability of deep rock tunnels. Furthermore, the paper highlights some proposals for future trends.

Keywords: rock bolt types; rock bolt durability; rock bolt influence factors; deep rock tunnels; structural integrity; long-term stability of tunnels

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Citation: Frenelus, W.; Peng, H.; Zhang, J. An Insight from Rock Bolts and Potential Factors Influencing Their Durability and the Long-Term Stability of Deep Rock Tunnels. *Sustainability* **2022**, *14*, 10943. https://doi.org/10.3390/su141710943

Academic Editors: Van Qui Lai, Chayut Ngamkhanong, Ting Li and Suraparb Keawsawasvong

Received: 8 July 2022
Accepted: 30 August 2022
Published: 1 September 2022

1. Introduction

Ensuring the long-term stability of deep rock tunnels is a major issue, as it is influenced by many potential factors. In fact, when tunnels are excavated, there are perturbations of stresses which impose new balances of stresses. Due to the behavior of the natural rocks, surrounding rocks of tunnels always tend to converge on excavated areas. Accordingly, tunnel convergence is unavoidable and can be the most pronounced impact of rock excavations, and as revealed by Kontogianni et al. [1], it belongs to the process of deformation of tunnels. Moreover, tunnel convergence generally increases by the effects of excavation methods which are significant [2]. On top of that, the convergence deformation amplifies over time, and consequently affects the long-term stability of tunnels. Depending on the type of rocks and the degree of damage caused by the excavation methods, the convergence strain can be more and more notable. When tunnel deformation exceeds a certain tolerable limit, partial or total failure may occur prematurely. To control excessive deformations, maintain stability and thus ensure long-term service life of tunnels, rock bolts are generally used. Therefore, the proper selection, design and performance of rock bolts are key elements in maintaining the longevity of tunnels. Indeed, to prevent their failure, rock bolts constituents must have sufficient properties and be well adapted to the rock features and conditions [3]. It should be noted, as reported by Chappell [4], the properties of rock bolts and those of surrounding rocks govern the bolting.

Many tunnel breaks are provoked by inadequate or insufficient rock bolts. In fact, the latter broke when they ceased to perform their function of supporting the rocks surrounding the excavations, provoking the tunnels to rupture. For instance, numerous tragic accidents in North American mines are caused by the failure of rock bolts under different dynamic loadings [5]. It is related by Wang et al. [6] that the tensile failure of high strength rock bolts is frequent at great depth. Selecting and designing the most suitable rock bolts or rock support systems are therefore difficult tasks that require careful thought. Over the last decades, numerous studies have been devoted to the design of rock support systems in order to handle large deformation and stability of tunnels. For example, by studying grouted rock bolts, Indraratna and Kaiser [7] have showed that bolts are generally inserted into the elastic zones of surrounding rocks to minimize exorbitant deformations and thus controlling stresses in tunnels. Cai et al. [8] related that the rock bolt length is a potential factor influencing the stability of lined tunnels. They explained that the longer the rock bolts, the lower the shear stress around the anchors. Wang et al. [9] developed particular rock bolts to resist substantial deformations when subjected to high stress. These bolts are mainly made of smooth steel bars which are anchored and jointed conveniently. Li [10] studied the design principles of rock bolting and found that in weak rock masses, the resistance of rock bolts is essential, while strong rock masses necessitate rock bolts characterized by both high resistance and deformability capacity. In order for the deep surrounding rocks to withstand considerable deformation, Dai et al. [11] conceived a kind of rock bolts capable of manifesting constant energy absorption and also increasing stability. On their side, Yuan and Yang [12] investigated the interchange concept of rock support systems and ribs influence on high-deformation roadways. Their main finding is that there is a varied equilibrium law between rocks and rock bolts. Based on this, they proposed thick-board bolts to control large deformation in deep roadways. In spite of various research efforts, it still remains a challenging task to select and design the optimal rock bolts for deep rock tunnels. An ideal rock bolt is one that is able to strengthen durably the surrounding rocks of tunnels while deforming with them, reducing deformations of rocks and supporting the stresses and pressures exerted in them. Rock bolts are needed to prevent shear motion or the spread of fractures in the broken rock mass [9]. In fact, rocks and rock bolts systems should be incorporated [13,14]. In other words, the union of rocks and rock bolts should be seen as a new rock mass with enhanced properties [15]. It is thus very necessary to continually revise the tunnel support systems and in particular the rock bolts, since their failures are considerable and frequent at great depths [16].

This paper focuses on providing an insight into the most relevant rock bolts used to deal with strong deformations and stability of deep rock tunnels. Furthermore, it identifies and examines potential factors influencing rock bolt failure. Of particular importance, it can be utilized as a guide in the selection and design of appropriate rock support systems for deep tunnelling projects under various working conditions. It is important to note that the long-term life of deep tunnels requires proper stability performance which largely depends on the adequacy of their support systems. Therefore, this study is of utmost importance.

2. Workflow of the Research

Using reputable web platforms and following the guidelines proposed by Okoli and Schabram [17] and Machi et al. [18], an in-depth search and analysis of articles published in various scientific journals was performed. The whole methodological procedure considered as the workflow of this research is presented according to Machi et al. [18] through Figure 1.

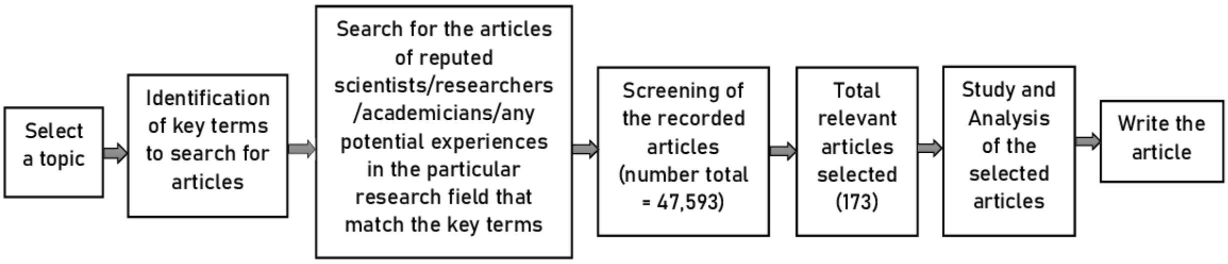


Figure 1. Research workflow.

The research was mainly conducted in various sources from publishers and search engines such as Elsevier, Springer, MDPI, Wiley, Hindawi, ASCE, Taylor and Francis and Google Scholar. For the search, a list of several keywords related to rock bolt types or models, rock bolt durability, rock bolt failure, characteristics of deep rocks and long-term stability of deep tunnels has been used. Lots of works have been identified and recorded. Thus, the recorded articles were categorized according to their fields, and only those which correspond to the fields of our study were retained. On the basis of their abstracts and main topics, a scan was carried out on the retained articles which were examined separately. According to the proposed objective, the articles have been reviewed various times in order to ensure a proper selection. Only those relating to the aim of our study were considered in the final selection. The 173 papers finally selected were deeply analyzed in order to produce this article. It is important to note that the search may have omitted some articles, but the number of examined papers is large enough for the analysis results to be satisfactory.

3. Definition and Classification of Rock Bolts

Although rock bolts have been used since 1913 for tunnel strengthening [19,20], and are becoming an essential need for contemporary support of rocks [21], there is no universal definition yet adopted for them. Consequently, several points of view are generally evoked. In order to improve understanding, Table 1 summarizes the main ones.

Table 1. Definition of rock bolts.

Researcher	Definition of Rock Bolts
Wu et al. [22]	Defined rock bolts as essential techniques used for dealing with the stability of surrounding rocks in deep roadways, and their anchorage pattern is crucial for that.
Kang et al. [3]	Defined rock bolts as kind of key support handling deformations and stability in mining operations.
Chen et al. [23]	Defined rock bolts as ligaments (bar or sprig) of rocks that are anchored in boreholes to consolidate rocks surrounding excavated areas.
Masoudi and Sharifzadeh [14]	Rock bolts are one of major components of rock mass support systems. In particular, their dynamic capacities must be sufficient enough to support tunnels when geological conditions are unfavorable.
Wei et al. [24]	Rock bolts are popular support procedures used in geotechnical engineering to strengthen underground openings and slope stability.
Ma et al. [25]	In civil and mining engineering, rock bolts are considered to be the first reinforcement techniques to fortify the contiguous and/or discontinuous rock mass.

Table 1. *Cont.*

Researcher	Definition of Rock Bolts
Yu et al. [26]	As crucial constituents of both traditional tunnelling and single-shell methods, rock bolts are inserted into rock masses where they are fastened by means of grout.
Martín et al. [27]	Rock bolts are bars installed in boreholes that are drilled into surrounding rocks or soils where fasteners facilitate their anchoring.
Osgui and Oreste [28]	Rock bolts are one of the most viable techniques for boosting the rock mass performance.
Kılıc et al. [29]	Rock bolts are techniques used in rock engineering to reinforce and stabilize mines and tunnels, and to unit any rock mass such as articulated, fractured, discontinued, and layered.
Garga and Wang [30]	In mining engineering especially, rock bolts are the predominant means of ground reinforcing for rock excavations.
Chappell [4]	Rock bolts are rocks reinforcement systems and considerably affect the rigidity of the rock masses.

Classification of rock bolts can be carried out under the basis of different points of view such as energy absorption ability, grout type, condition of grout application, rod material, prestressing conditions, etc. Other specific classification criteria are the most reported: anchoring mechanism [29,31,32], load transfer mechanism [8,13,16,19,21,31,33–36], performance [31,37,38], anchoring state [30,39–41], reinforcement mode [4,20,42,43]. Figure 2 illustrates a global classification of rock bolts (where CMC: Continuously Mechanically Coupled; CFC: Continuously Frictionally Coupled; DMFC: Discretely Mechanically or Frictionally Coupled; EA: Energy Absorbing).

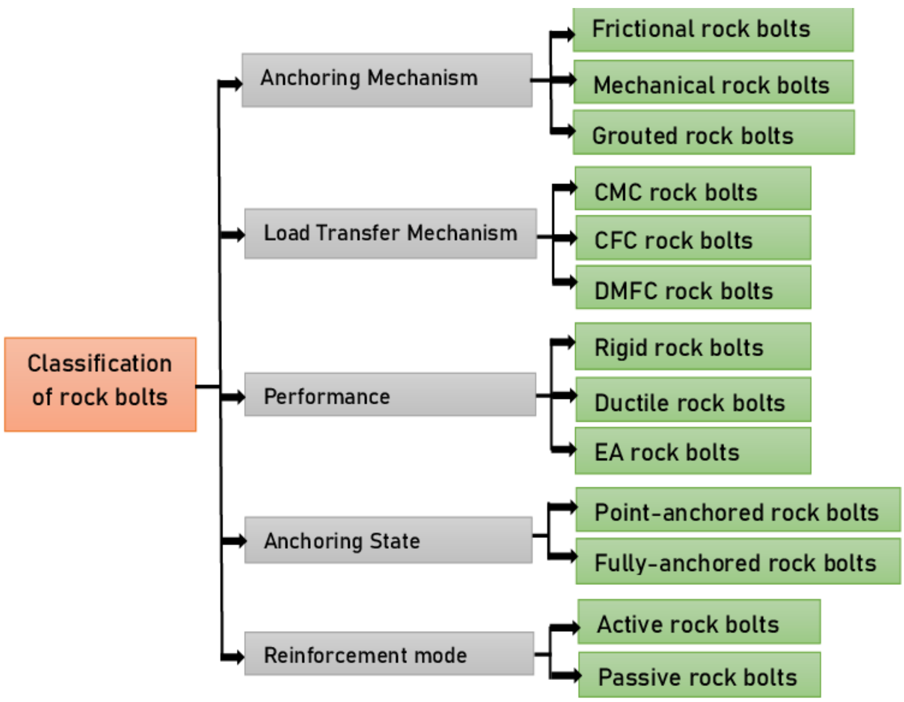


Figure 2. Classification of rock bolts.

Regardless of the category shown in Figure 2, rock bolts must have sufficient capacities and long-term performance to correctly fulfill their role. In fact, rock bolts should support the rocks surrounding the tunnels for the long term and minimize rock deformation as much as possible. Normally, the properties of bolted rocks should be reasonably and durably enhanced. In fact, the contributions of rock bolts should improve the whole properties of the concerned rock massifs [43]. Figure 3 shows a typical fully grouted rock bolt which is one of the most common rock bolt categories used in deep rock tunnels. It is presented as an illustration of the different parts of rock bolts that can be considered in the study of bolt durability. In reality, for any class of bolts, bolt components, rock properties, grout, rock-grout and bolt-grout interactions play a determining role in the effectiveness of rock bolts.

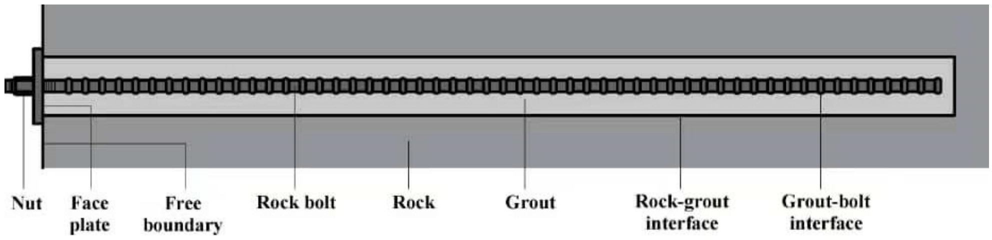


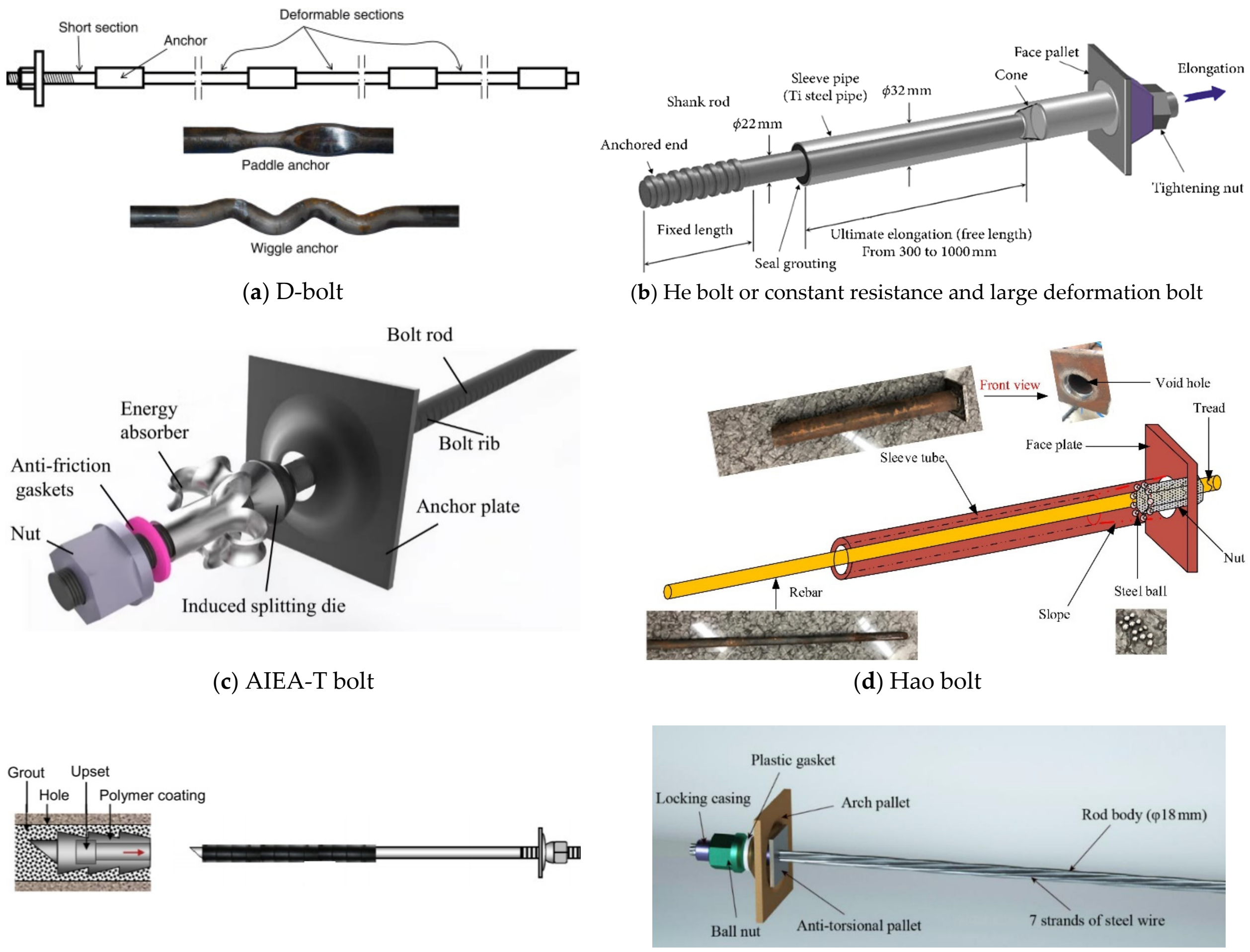
Figure 3. Typical fully-grouted rock bolt, reprinted from Lisjak et al. [21], Copyright ©2022, with permission from Elsevier, License No. 5344130686136.

4. Relevant Types or Models of Rock Bolts

Scholars and researchers have developed many types or models of rock bolts. Each of them has its particularities and limitations. Due to the many approaches and complex behaviors of rocks at great depth, it is generally difficult to select the most suitable type or models of rock bolts for a given tunnel. A thorough understanding of the characteristics of the different types or models of existing rock bolts is required for optimal selection and design. Figure 4 shows some of the developed rock bolts. It also indicates some evolutions regarding the development of different rock bolts. Indeed, the various rock bolts are designed with the objective of continuously improving their performance in order to ensure the safety and stability of underground excavations. In fact, the long-term stability of deep underground structures is always subject to continuous studies due to many factors upon which it depends. Note that one of the main functions of rock bolts is to act as sewing for cracks [43]. However, when rock bolts do not exert this role properly, cracks can widely propagate around the surrounding rocks and tunnels could rupture in the worst case. Indeed, by the expansion of fractures in the rocks located near the tunnels, ruptures frequently occur [44]. This is because the structural integrity of the tunnels are seriously attacked. For example, it was only after running for three years that the Xuecheng tunnel of China was taken out of service for repair due to the development of many fractures [45]. Proper and reliable rock bolts are thus essential to counteract the development of cracks in the rocks surrounding tunnels.

It is very important to review the existing rock bolts types or models in order to facilitate the selection and design of new rock bolts with increasing performance and better suited to different situations. Table 2 summarizes pertinent details of the relevant rock bolt types or models conceived for deep excavations under different rock mass conditions.

Bolt To improve understanding, where available, quantitative values are indicated for some characteristics of the most pertinent types or models of rock bolts under static and dynamic loads. Table 3 provides a summary.



(**a**) D-bolt (**b**) He bolt or constant resistance and large deformation bolt

(**c**) AIEA-T bolt (**d**) Hao bolt

(**e**) Yield-lok bolt (**f**) New Flexible bolt

Figure 4. Illustration of some types of existing rock bolts, reprinted from: (**a**) Li [31], with permission from Elsevier, License No. 5379281426329; (**b**) He et al. [46], with permission from Elsevier, License No. 5379291363971; (**c**) Dai et al. [47], with permission from Elsevier, License No. 5379301056708; (**d**) Hao et al. [48], with permission form Elsevier, License No. 5379310622062; (**e**) Wu and Oldsen [49]; (**f**) Xie et al. [50].

Table 2. Summary of relevant rock bolt types or models conceived for deep underground excavations.

Rolt Bolt Type or Model	Applicability	Main Components	Remarks	Verification	Study
Anti-scour bolt	Deep underground excavations under rockburst impact	Ribbed bar, tray, constant resistance energy absorption tool, singular nut	These rock bolts have robust robust mechanical properties and can withstand rockburst impacts.	Theoretical study and numerical simulation	Tang et al. [51]
Thick-board bolt	Deep roadway with different strata	Threaded steel bar (roof region) and round steel bar (rib region)	Constitutive support controlling huge deformations, can reduce rib deformation by up to 88.6%, and roof deformation by up to 83.7%.	Numerical study and fields experiments	Yuan and Yang [12]

Table 2. *Cont.*

Rolt Bolt Type or Model	Applicability	Main Components	Remarks	Verification	Study
Combined Improvement and Bonding (CIB) CIB-bolt	Deep tunnel (city wall gate shape) in soft rock	Hollow steel rod with packers, tensile mortar and urethane	CIB-bolt enhance the plasticized areas, delay deformations, have excellent anchoring, and are favorable when water is present in a given borehole.	Field experiments, laboratory tests and numerical simulations	Shimamoto and Yashiro [52]
Self-swelling Split-set bolt	Deep mines in highly stressed fractured rock mass	Split-set, bolt ring, Faceplate, montage of self-inflating cartridges or rollers	It offers better anchoring force and constant resistance when sliding. It behaves particularly well in rocky massifs where groundwater is frequent.	Laboratory and fields tests	Xu et al. [53]
New flexible bolt	Deep tunnels or mines in complex geological conditions and high stress	Shank with 7 strands of steel wire, lock box, spring, gasket, nut, arch pallet, anti-torsional pallet.	The new soft bolt can withstand huge deformations and provide the excavation security control.	Laboratory and field tests	Xie et al. [50]
J-bolt	Deep tunnels or mines under rockburst impact	Mixing, anchoring and straining modules, washer, nut and plate	J-bolt exhibit high performance under static and alternating dynamic loadings	Laboratory tests	Zhao et al. [54]
Deformation-controlled (DC)-bolt	Deep tunnel in poor ground conditions	Smooth bar, threaded bar, ring, end anchor	DC-bolt can exhibit large deformation up to 100 mm, and resist in extreme underground conditions.	Laboratory tests and simulations	Yokota et al. [55]
Hao bolt	Deep roadways and deep mines in severe ground conditions	Rebar, sleeve pipe with internal partial slope, steel ball circle	Hao bolt can exhibit great elongation under high in-situ stress and severe ground conditions.	Laboratory tests and numerical simulation	Hao et al. [48]
Rock bolt with Anchoring Synergistic Component (ASC)	Deep tunnels in complex geological conditions	High strength steel rebar and 60 mm length for ASC	ASC can improve the bolt anchoring system by increasing the anchoring force, elongation and average energy absorption up to 8.14%, 40.67% and 67.18%, respectively. It thus minimizes the possibility of resin outflux.	Numerical simulation and laboratory tests	Liu et al. [56]
Anti-impact and energy-absorbing tail (AIEA-T) rock bolt	Deep roadways in rock mass with dynamic disaster risks	Ductile bolt rod, anchor plate, splitting component, nut, Anchor shank Thread segment, Splitting die	Energy can be absorbed in the bolt tail, and the bolt can deal with large deformations, under static and dynamic loads.	Laboratory tests	Dai et al. [57]
Yieldable rock bolt	Stratified rock mass with tendency to huge deformations	Ribbed steel bar, nut, rod pin, and backing plate	Rock bolts should be as flexible as possible to withstand large deformations without failure.	Laboratory tests	Skrzypkowski et al. [58]

Table 2. *Cont.*

Rolt Bolt Type or Model	Applicability	Main Components	Remarks	Verification	Study
Self-Swelling Anchorage (SSA) bolt	Deep mines in relatively articulated rock mass	Threaded bar, gaskets, nuts, faceplate, self-swelling hollow rolls	Made up of 6 components and can be single-point or Multi-point anchoring. The anchoring performance of SSAB is boosted by itself-swelling roll.	Laboratory and field tests	Xu et al. [32]
Modified Cone Bolts (MCB)-Superbolt	Deep underground excavations in rockbursts-prone media.	Threaded, undulated, and smooth bar	They have high energy absorption and high deformation capacity during static and dynamic testing	Numerical simulation and laboratory tests	Cai et al. [59]
Versa-Superbolt	Deep underground excavations in rockbursts-prone media.	threaded, undulated, and smooth bar; Paddle anchors	They have high energy absorption and high deformation capacity during static and dynamic testing	Numerical simulation and laboratory tests	Cai et al. [59]
Tension and compression-coupled (TCC) yielding rock bolt	Deep tunnels in squeezing and burst-prone media	Smooth steel bar, 2 supplemental anchors	This type of rock bolt performs well under high stresses, exhibiting excellent response to coupled tensile-shear actions.	Laboratory tests	Wu et al. [60]
Rock bolt with splitting component	Deep roadway in high-stress media	Ribbed bar, energy absorber, anchor plate, induced splitting die, gaskets and nuts	Bolt for the splitting die allows better energy absorption efficiency.	Laboratory tests	Dai et al. [47]
PAR1 bolt	Deep tunnels in high stress and rockburst impact	Steel bar, five paddles at each end serving as anchors, plate and nut	PAR 1 bolt can be used to resist dynamic impacts loads in deep underground excavations	Laboratory tests	Knox et al. [61]
Durabar	Deep underground excavations	Smooth bar, wavy part, nut and face plate	The highest displacement of the bolt is governed by its distal end that contains a smooth tail	Laboratory tests	Cai and Kaiser [62]
Beam-element-based bolt	Deep tunnel in rock mass with joints and high slope	Round steel bar	Improved bolts of remarkable length and diameter resist both shear and tension, as well as bending deformation.	Numerical simulation	Wei et al. [24]
Glass fiber-reinforced polymer (GFRP) rock bolt	Deep subsea cavern under aggressive environment during mining	Bars polymers reinforced with special glass fibers	GFRP bolts can be intact or hollow and have high corrosion resistance. Their tensile-strength properties are notable even after long-term service.	Laboratory tests	Benmokrane et al. [63]
Dynamic Omega-Bolt	Deep tunnels in high stress rock mass releasing abrupt energy	Omega shape, additional steel component, upper and lower bushings	It is suitable for dynamic load conditions and can effectively support tunnels surrounding rocks. It can also absorb large elastic energy.	Laboratory tests	Scolari et al. [64]

Table 2. *Cont.*

Rolt Bolt Type or Model	Applicability	Main Components	Remarks	Verification	Study
CT-M22 rock bolt	Deep excavations of brittle rocks in high in-situ stress		This rock bolt is reliable to deal with spalling damage in deep brittle rocks, and ensure prevent tunnel roof failure.	Numerical analysis	Langford and Diederichs [65]
He bolt	Deep mines under complex geological conditions	Rebar, sleeve tube, front pallet and a clamping nut	He bolt has great ability to absorb dynamic load and present a very great elongation	Laboratory tests	He et al. [46]
Truss bolt	Deep roadways tunnels in severe ground conditions	Two inclined bolts with 2 anchors and one horizontal bar	Truss bolt can thwart the failure of the cutting roof of deep roadways under high pressures and stress.	Numerical modelling	Ghabraie et al. [66]
Wang bolt	Deep tunnels in squeezing and bursting rock mass	Smooth steel bar and anchor	It can absorb considerable energy and exhibit large elongation when subjected to excessive loads.	Laboratory tests	Wang et al. [9]
D-bolt	Deep underground excavations	Smooth steel bar with incorporated paddle and wiggle anchors	D-bolt has great deformability and elongation capacity	Laboratory and field tests	Li [31]
Cone bolt MCB33	Deep mines in burst-prone grounds	Smooth bar, threaded end, forged cone, plastic sleeve	Inserted into 33 mm diameter drill holes, this bolt can reduce the spread of damage generated by rockbursts impacts. The plastic sleeve serves as a durable release agent and makes it easier to stretch the bolt.	Laboratory tests	Cai et al. [67]
Yield-Lok bolt	Deep mines under rockburst impacts	Round steel bar, Polymer coating, upset head	Constant performance in convergence situations. High resistance to tensile and shear stresses.	Laboratory tests	Wu and Oldsen [49]
Hybrid bolt	Deep underground excavations	Hollow steel bar, polystyrene mold, Cement grout	This is a split set and rebar combined to provide higher strength	Laboratory tests	Player et al. [68]
Garford Bolt	Deep mines in rock masses with varied lithology and high seismic risk	Threaded mild steel solid bar, steel and polyethylene sleeve, dynamic section	Garford bolt is a dynamic rock bolt to deal with high seismic risk and unwanted movement of rocks.	Laboratory tests	Varden et al. [69]
Roofex rock bolt	Deep mines in severe rock mass conditions	Smooth bar, sliding element, sleeve, stop and mixing elements, faceplate and nut.	This bolt can improve the rigidity of the bolted rock mass and keep the yielding load constant when the elastic limit is reached to limit dynamic deformations.	Laboratory tests	Charette and Plouffe [70]
Ansell bolt	Deep tunnels subjected to rockbursts and high explosives	Smooth steel bar, rib-shaped anchor section, nut, curved circular disc	It can resist to rock bursting, high explosives and corrosion when fully grouted.	Laboratory tests an numerical	Ansell [71,72]

Table 2. *Cont.*

Rolt Bolt Type or Model	Applicability	Main Components	Remarks	Verification	Study
Swellex bolt	Deep underground excavations	Ductile metal, bent tube, circular tube	High pressure water is injected to inflate the bent tube into the circular tube. This bolt has a large bearing capacity, and it has a high frictional contact with the borehole.	Laboratory tests	Charette [73]

Table 3. Summary of quantitative values of some characteristics for the most relevant types or models of rock bolts.

Rock Bolt Types or Models	Characteristic Length (mm)	Rod Diameter (mm)	Elongation (Maximum or Mean) (mm)	Maximum Energy Absorbed (kJ or kJ/m)	Maximum or Mean Static Load (kN)	Maximum or Mean Dynamic Load (kN)	Study
Anti-scour bolt		22	>300	57.63	300	600	Tang et al. [51]
Thick-board bolt	2500	20			100		Yuan and Yang [12]
CIB-bolt	6000	70			200		Shimamoto and Yashiro [52]
Self-swelling Split-set bolt	2300	32	200	16.8	92		Xu et al. [53]
New flexible bolt	740–4080	18			340.33	347	Xie et al. [50]
J-bolt	1985–2229	21.85–34	143.7	46.5	>190	>250	Zhao et al. [54]
DC-bolt	3000		>100			320	Yokota et al. [55]
Hao bolt	700	22	300	123.28	120		Hao et al. [48]
Bolts with ASC	480	29	28.57	2483.53	129.15		Liu et al. [56]
AIEA-T bolt	2200	26		127	125–150	125–250	Dai et al. [57]
Yieldable bolt	1800	22	32.67		153.29		Skrzypkowski et al. [58]
SSA bolt	2200	20	133		235		Xu et al. [32]
MCB-Superbolt	2400	28.3	103	56.9	197	448	Cai et al. [59]
Versa-Superbolt	2400	32.3	345	70.4	270	530	Cai et al. [59]
TCC yielding rock bolt	2500–5000	22–26	386–754		200		Wu et al. [60]
Bolt with splitting component	2200	20–22	200	130	150	150	Dai et al. [47]
PAR1 bolt	2400	20	230	45.6		225	Knox et al. [61]
Durabar		16	600		100	100	Cai and Kaiser [62]
Beam-element-based bolt	6000–8000	32			303.8		Wei et al. [24]
GFRP Rock bolts	3500–5500	25–28					Benmokrane et al. [63]

Table 3. *Cont.*

Rock Bolt Types or Models	Characteristic Length (mm)	Rod Diameter (mm)	Elongation (Maximum or Mean) (mm)	Maximum Energy Absorbed (kJ or kJ/m)	Maximum or Mean Static Load (kN)	Maximum or Mean Dynamic Load (kN)	Study
Dynamic Omega-Bolt	3000	36–41	450	35	246	374.1	Scolari et al. [64]
CT-M22 bolt	3500				290		Langford and Diederichs [65]
He bolt	1600	22–25	1000	9.81	180	357.6	He et al. [46]
Truss bolt	2000–3000						Ghabraie et al. [66]
Wang bolt	510	22	130		250		Wang et al. [9]
Yield-Lok bolt		17.2–23	108	62	345	345	Oldsen and Roberts [74]
D-bolt	2700	20	63	74	180	250	Li [31]
Cone bolt MCB33		17.2	700	33	125		Cai et al. [67]
Hybrid bolt	2400	47			120	120	Player et al. [68]
Garford bolt		20	180	27–33		145	Varden et al. [69]
Roofex rock bolt		12.5		27	100	95	Charette and Plouffe [70]
Ansell bolt	2050	16–40	164				Ansell [71]
Swellex		25–39		18–29	200		Charette [73]

Considerations on the Rock Bolt Types or Models

Tables 2 and 3 show many rock bolts types or models designed to support deep excavations. It can be seen that scholars and researchers have made or being made countless efforts in the field of tunnel engineering. Although the types or models of the presented rock bolts can be used to support deep excavations, each one has its particularities. The selection and design of one type depends on the characteristics and conditions of the rocks surrounding the tunnels, as well as the tunneling conditions. However, it is observed that the burial depth of tunnels or mines are increasing more and more, where rock properties and conditions are increasingly complex [35]. This requires a continuous review of the rock bolt types in order to select and design the most suitable of rock bolts. Depending on the relevant exposure situations of the rocks surrounding the tunnels, the parameters of a selected or designed rock bolt type might need to be improved to properly ensure the long-term stability. For instance, to guarantee the stability of a deep soft rock roadway in the Hongmiao coal mine, China, improved rock bolts have been proposed, where the length, diameter, thread length, and the pulling capability of the rock bolts have been increased [75].

The support types or models shown in the aforesaid tables are mainly energy absorbing rock bolts and can be used for deep underground structures subject to high stresses, complex conditions and rockbursts. However, depending on the exposure conditions, improvements in the design of rock bolts are sometimes necessary. In South Africa, for instance, a yielding rock bolt was redesigned to better fulfill its function and attenuate the potential risk of rockfall in a hard rock mine [76]. In fact, deep underground structures can often experience extreme conditions under the coupling actions of many potential factors. Typically, deep rock engineering confronts high stress, high temperatures and high groundwater pressures. The coupling of such situations is very detrimental for the rocks surrounding the tunnels as well as the support systems. The extent of the damage provoked by such situations depends mainly on the resistance of rocks and that of the rock bolts. The weaker the resistance of the rocks, the stronger and more efficient the rock bolts must be to properly perform their support functions. For deep tunnels or caverns constructed in low strength rocks and exposed to strong dynamic conditions caused by earthquakes which usually generate considerable additional damage to the surrounding rocks, the exposure conditions are increasingly severe for rock bolts. The latter should be able to cope with very extreme situations in deep rock engineering.

It should be noted that in certain very extreme situations, the rock bolts must have very high dynamic performance to maintain the stability of the rock surrounding the tunnels. However, in such situations, it is very difficult for them to stabilize the tunnels by themselves, without other secondary supports. For instance, in the case of a fissured rock formation due to secondary faulting resulting from folding, faulting, and shear-like metamorphic changes, the rock bolts do not have the potential to stabilize the tunnels. It has been studied by Wang et al. [77] that main among the conditions causing underground instabilities include fractured rocks, incompetent lithologies and high tectonic stress. Indeed, while the rock bolts generally have both resistance and elongation limits, they are vulnerable under these very extreme conditions. When subjected to very extreme conditions, the rock bolts can become fatigued very quickly and cease to stabilize the tunnels due to their possible premature failure. In spite of that, shear loads can be carried by fully grouted rock bolts [78], but these may fail under the additional loads and deformations generated by folding, faulting, and shear-like metamorphic changes. These very extreme conditions require at least a secondary support system to assist the rock bolts in stabilizing the rocks surrounding the tunnels. Indeed, in complex loading and tunneling conditions, cable bolts are required to work together with the rock bolts [79]. However, in very extreme conditions, priority must be given to designing suitable support schemes in order to properly stabilize the tunnels and caverns.

In addition, it is important to mention that the existing rock bolt structures sometimes fail in deep soft ground tunneling where the mineral resources are generally explored. To ensure the long-term stability of openings in deep soft rock exposed to extreme conditions, appropriate support schemes should be determined as accurately as possible. Generally, cable bolt steel arches with additional reinforcements are usually offered. Additionally, based on the extent of the deformation in different parts of tunnels, different types of rock bolt models can be used. For example, to ensure the stability of an underground mine tunnel in USA where non-persistent faults exist, different rock bolts models and two grouted cable bolts models were used [80]. Table 4 summarizes key information of the most relevant support strategies developed to cope with very large deformations of soft rock tunnels and mines exposed to extreme conditions.

Table 4. Support systems proposed for deep soft rock engineering in extreme conditions.

Study	Deep Underground Structures	Location	Predominant Lithology of the Surrounding Rocks	Extreme Conditions of the Surrounding Rocks	Proposed Support Schemes
Deng et al. [81]	Dapingshan Tunnel	China	Argillaceous sandstone	High geostress, groundwater seepage, broken rocks due to syncline and faults.	Mixed hollow bolts, advance small catheter, foot-lock pipe, shotcrete, waterproof panel, secondary lining
Marinos et al. [82]	Przojna Padina Tunnel	Serbia	Flysch (repeated alternations of sandstone and siltstone)	High stress, presence of groundwater, folded, sheared and disturbed ground	Combination of shotcrete, bolts/anchors, steel arches, wire mesh
Xing et al. [83]	Tunnels in an underground mine	USA	Mudstone, limestone, basalts	Wide angle faults, high stress, Polylithic megclastic debris flows, fine-grained debris flows	Long swellex bolts, resin bolts, split sets, long cable bolts
Wang et al. [84]	Deep roadway in Xin'an coal mine	China	Mudstone, sandy mudstone, siltstone, and fine sandstone	Nonlinear large deformation, Strong water absorption	He bolt, steel mesh, floor hollow grouting cable, and steel fiber concrete
Xue et al. [85]	Deep roadway in Wangzhuang coal mine	China	Sandstones and sandy mudstones	Complex in situ stress, waterlogged, and weakened strength of rocks, large deformations	Grouted Bolt, Cable, Mesh, Shotcrete, Grouting
Perras et al. [86]	Niagara Tunnel	Canada	Limestone, sandstone, siltstone, shale, and mudstone.	High horizontal stresses, significant overbreak, sheared areas, high groundwater inflows	I-beam rings, waterproof membrane, swellex rock bolts, wire mesh, steel arch piece, and shotcrete

Table 4 shows some proposed support schemes aimed at stabilizing deep underground soft rock structures under complicated conditions. Nonetheless, depending on the level of complexity of the surrounding rocks, it is necessary to continuously improve the capacity of the rock bolts and that of the other components of the tunnel support systems. For example, the Kaiyang Phosphate Mine support scheme was changed to an improved scheme due to the high stress caused by increasing the mining depth [87]. Indeed, tunnel support structures must be ultra-efficient to deal with ultra-huge deformations [88]. For all support scheme, since rock bolts are generally the first support system components, they should be the most suitable possible. Nevertheless, it should be noted that when the surrounding fractured rocks undergo the very complicated conditions of great depths, i.e., high stresses, high groundwater pressures, high temperatures and mining disturbances, in addition to the presence of fault zones, stabilizing tunnels requires more efficient support systems [89]. In such situations, for instance, as recently analyzed by Chen et al. [89], more suitable combinations of supports such as concrete-filled tubular steel supports (CFST) and U-shaped steel supports might be more promising.

5. Potential Factors Influencing the Durability of Rock Bolts and the Long-Term Stability of Deep Rock Tunnels

5.1. Rock Strength

The strength of the rocks is one of the potential factors that can significantly affect the durability of rock bolts and the long-term stability of deep tunnels. In fact, rock bolts that are properly inserted into high strength rocks could have a long life and can contribute to the long-term stability of deep tunnels. Analogically, low rock strength could reduce the life of rock bolts if adequate measures are not taken correctly. Indeed, the performance of rock bolts is greatly influenced by the rock strength [90,91]. For example, as the strength of rocks increases, the extent of cross-strain of rock bolts decreases dramatically relative to the bolt diameter [91] (Figure 5).

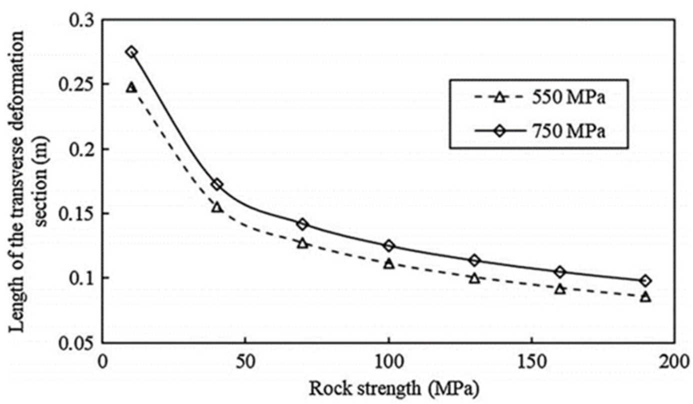


Figure 5. Effects of rock strength on the extent of bolt transverse strain, reprinted from Liu and Li [91], Copyright ©2022, with permission from ASCE, License ID 1245446-1.

The suitability of rock bolts refers to the appropriateness of the encountered rocks in deep excavations. That is, rock bolts must be capable to effectively support and compensate the failed and weakened zones of deep tunnelling over the long-term. In these inevitable zones, as revealed by Wu et al. [92], the relevant properties of rocks are durably deteriorated. In addition, in such zones, the transmissibility properties of rocks are intensified [93], and consequently cracks and fractures could be easily propagated in the surrounding rocks of tunnels [2]. Indeed, pressures and inflows of groundwater could be appeared into the openings. By these, rock resistance and shear are reduced [30,94]. This implies a risk of partial or total failure of the excavations. Thereby, the selected and designed rock bolts must effectively compensate for the loss of strength and shear of loose areas of the rocks around tunnels. When such zones are not properly reinforced, the convergence speed can be high over time and the lifetime of tunnels will be lessened. Rock bolts are thus needed to continuously replace the lost properties of rocks surrounding tunnels. The less resistant the host rocks, the more they are weakened after excavations, and the more the rock bolts must be adequate to secure and retain them. In case of articulated rock masses, for instance, Liu and Li [91] reported that the shear displacement of joint varies inversely with the resistance of the rocks. Likewise, the tensile strength of rock bolts is highly dependent on joint orientations of the mentioned rocks [95]. It is essential to determine the resistance of rocks which is generally strongly attenuated by its existing discontinuities [41,90,96,97], when selecting and designing rock bolts. It should thus be recognized that an accurate estimation of rock strength is highly necessary for the selection and the conception of the most appropriate rock bolts for deep tunnels.

To sum up, actual rock strength can be a guide for the proper selection and design of rock bolts. In particular, when the rocks show alternating deformations under the effect of dynamic disturbances, rock bolts can enter their post-elastic state more quickly and their durability can be reduced. Anchor bolts should be as suitable as possible to the point of effectively reinforcing the rocks encountered [98], in order to resist in any relevant situation they face. In fact, the strength of rock bolts should be greater than that of the rocks. The durability of rock bolts can be reduced when they are not appropriately designed based on the actual rock strength. That is, the weaker the rock strength, the greater the resistance of rock bolts. A minor error in assessing the actual rock strength can lead to the selection or design of inappropriate rock bolts. As such, the latter will be weakened too quickly in the exercise of its support function, and thereby its durability will be reduced, if their strength is lower than that of the rocks. Because the rock/bolt system must form a new material with increased properties [15], the strength of the bolts should however be compatible with that of the rocks. The strength of the bolts must still be greater than that of the rocks, but with a minimum of compatibility.

5.2. Consideration on Creep Behavior of Rocks

Several types of rocks undergo creep deformation at great depth. As the deep in-situ stresses are generally high, the speed of tunnel convergence can be increased by squeezing and bursting of rocks. By this way, tunnel convergence is considerably influenced by creep [99,100]. Creep, considered to be a huge consistent deformation, is almost inevitable due to the high in-situ stresses and difficult geological conditions at great depth [101,102]. More precisely, it is a pervasive character of all types of rocks subjected to long-term loads [88]. Therefore, the bolts used must be able to cope with creep deformations which could be enormous when they surpass the tolerable limit of the deformation for the surrounding rocks. Rock bolts must be strong and ductile enough to resist creep deformations [5]. Otherwise, they would fail if their capacities were not sufficient. Indeed, rock bolts can be broken by a sudden increase in the deformations of the rocks when the creep reaches its accelerated phase [103]. From an engineering point of view, all types of rocks surrounding the deep tunnels could have some degree of softening when the critical depth for softening is exceeded [85], in addition to the high in-situ stresses. As a result, large deformations are inexorable [44,47,104–109]. Moreover, such deformations are not linear and therefore cause perturbations that can affect the integrity of the supports and cause the tunnels to fail [109,110]. Under such conditions, rock bolts are required to restrict rocks creep strain, and hence convergence strain, so that tunnels are stable over the long term. It should be noted that one of the main reasons for failure of rock bolts at great depths is loss of bond, when tunnels present huge deformations. The rock bolts must accurately fill the boreholes in order to avoid any possible infiltration of groundwater inside the openings and also to prevent the evolution of creep deformation which is favored by the presence of water. More clearly, water drastically reduces the creep resistance of rocks and at the same time increases the rate of creep deformation [2]. It is thus endorsed that groundwater is one of the potential causes that trigger failures in deep rock excavations [36,38]. Although the rock bolts are not the only components of the tunnel support systems, being the first, they should limit the infiltration of groundwater into the boreholes as much as possible. This is of great concern since particularly high groundwater pressures and flows are frequent at great depths.

It should be noted that the hydrological aspects of the rocks surrounding the tunnels have considerable effects on the infiltration of groundwater into the bolting structures. Certain types of rocks are more prone to facilitate the groundwater creeping into the bolting. In fractured rocks, groundwater can easily seeps into the bolting through existing interstices if proper treatments are not considered. In such rock types, the aperture of fractures is a major factor that can govern groundwater flow. According to Rahimi et al. [111], the main groundwater channel in rock structures are fractures. Similarly, soluble rocks such as limestone can have increased permeability and cause groundwater infiltration problems in weakened areas of tunnels [111]. Groundwater flow is largely dependent on the type and condition of the rocks, as well as the level of groundwater abundance near the tunnels. Indeed, considerable inflows of groundwater can be triggered and could be maintained in the long-term in blocky rock masses; and moist conditions can be maintained in sheared or weakly faulted rocks [82]. In water-rich areas, the potential for groundwater infiltration may be greater and it varies depending on the characteristics of the rocks surrounding the tunnels. Uncontrollable groundwater inflows can be expected when the tunnels pass through karst areas [112], which are located close to water-rich zones. Since the presence of water greatly affects the creep of rocks and particularly accelerates creep life [88], it is extremely important to consider the hydrological aspects of rocks in the selection and design of rock bolts. It is important to note that when the rock strength is lower than the pore pressure, groundwater flow can be initiated [111].

Consequently, the bonding material should be minutely selected and installed in order to fully play its role in the long-term. In this context, referring to Wang et al. [108], double shell grouting can be employed to suitably incorporate rocks and bolts and thus produce a new rock mass with improved properties. In other words, as previously reported by Bernaud et al. [113], rocks and rock bolts should be worked as a homogenized medium with excellent adhesion. Accordingly, the rate of creep deformation of rocks can be limited, and the creep resistance of rocks can be improved. Thereby, rock bolts can perform their role over the long-term.

5.3. Bolting and Grouting Materials

Bolting and grouting materials play a crucial role in the long-term performance of rock bolts under high stresses. In fact, they strongly influence the bonding capacity of the anchoring system as well as the conduction of loads along the rock bolt length. As for the bolting material which is most often steel [72,114,115], the bolt shank is usually ribbed or smooth (Figures 6 and 7). The choice of ribbed or smooth bar depends especially on the geological conditions of host rocks. Nevertheless, at great depths where rocks are typically encountered in complex geologic conditions, ribbed bolts can provide better adhesion at the bolt-grout and rock-grout interfaces. In fact, the bondability of the ribbed bars which is ensued by the shear strength of the grout, is more marked than that of smooth bars [116]. Moreover, it has been tested by Chong et al. [117] that smooth bars are less resistant to pull loads than ribbed bars. Habitually, the tensile capacity of rock bolts is greater than that of shear. Specifically, the shear capacity of rock bolts is about 65% to 70% of their tensile capacity [118,119], and its peak value is set to 80% of the tensile strength [3]. It can thus be deduced from this that smooth bars are even less resistant to shearing. However, the spacing and height of the ribs must be carefully considered as they influence the performance of the ribbed bolts. As suggested by Cui et al. [120], ribs spacing must be as suitable as possible; but their height could be lower in rockburst-prone media. Failure of rock bolts can occur if they exhibit inadequate response under tensile and shear stresses. Indeed, the combined action of tensile and shear stresses leads to common failure of rock bolts [118]. For long-term resistance, rock bolts should be as suitable as possible. Based on that, ribbed steel bolts should be given priority. If all their components are optimized, they could secure and stabilize the rocks surrounding the tunnels in a sustainable manner.

Figure 6. Illustration of smooth bar [37].

Figure 7. Illustration of ribbed bar [121].

For its part, the grouting material which acts as an intermediary between bolts and rocks [121], must also be correctly selected and installed. In deep excavations where large deformations are frequent, rock bolts cannot be effective without grouting [108,122]. The properties and application of the grout material are of tremendous importance in ensuring the long-term performance of rock bolts. Indeed, the damaged zones of the surrounding rocks can become plastic and can thus better adapt to the strong deformations thanks to the grouting [122]. However, the grouting should be as appropriate as possible. It has been revealed by Luga and Periku [123] that unsuitable grouting is very disadvantageous as it reduces the bearing capacity of rock bolts. In fact, the elasticity of rock bolts can be affected by the compressive action of certain types of grout [72]. Therefore, the grouting choice should be carefully considered. Moreover, the interface of the joints-grout needs to be taken into account. Xing et al. [90] related that there is failure of joints when the shear capacity at the joints-grout interface is less than the shear force associated with the grout joint. It should be noted that most rock bolt failures are due to grout breakage and loss of adherence between rocks and grout [116,120,123,124]. Indeed, to avoid early failure, the end of the rock bolts must be highly considered due to its great importance, and it must be properly grouted [123].

5.4. Rock Bolt Corrosion

In the choice and design of rock bolts, the corrosion factor is of exceptional importance. Indeed, its impacts are considerable on the durability of rock bolts. Precisely, corrosion has been reported to have significant effects on the life of rock bolts and their unanchored length is more vulnerable [125]. In fact, in rocks surrounding deep tunnels, rock bolts often face aggressive environments such as high temperatures, high groundwater pressures, etc. Due to its chemical ingredients, groundwater is considered to be the main cause of corrosion when rock bolts are subjected to its flow [36,126]. Rock bolts can be exposed to different forms of corrosion such as uniform corrosion, pitting corrosion and stress corrosion [45] (Figure 8). Thereby, their risk of being corroded is high. Referring to Komurlu and Kesimal [127], the scratches caused by the installation of the bolts in the holes are also causes increasing their risk of corrosion. It is widely believed that in the event of corrosion, the strength and durability of rock bolts are greatly influenced and diminished [45,114,115,128–130]. For example, as studied by Aziz et al. [128], the strength of corroded rock bolts can drop sharply from 21% to 39% of their initial capacity. Depending on the evolution of the corrosion rate and the resistance of the bolts to deal with such damage, rapid or delayed failure can occur in corroded bolts. Indeed, rock bolts failure are due to corrosion to a large extent. For instance, it has been reported that in Australian mines, 29% of the rock bolts fail through corrosion [36,131]. Rock bolts selected and designed must be capable of exhibiting significant corrosion resistance in order to be durable. Their protective layer should be thick enough not to erode under the pressure of groundwater, and at the same time to minimize the effects of corrosion. Proper grouting should always be a priority, as it will minimize or prevent the flows of groundwater into underground openings [132]. In fact, when the protective layer does not resist the propagation of cracks, the bolts are corroded by the aggressive agents which infect them [130]. For example, due to their corrosion resistance, GFRP bolts are preferred over metal bolts which are very corrosive [133]. However, corrosion can attack all types of rock bolts and can therefore reduce their capacity in the short and long term [129]. In all situations, the risk of corrosion remains high in the rock bolts of deep tunnels built in generally anisotropic rocky environments. In fact, rock anisotropy is ubiquitous and manifests itself mainly in permeability [134]. Taking into account the directional variation in the permeability of rocks is a great advantage in improving the corrosion resistance of rock bolts.

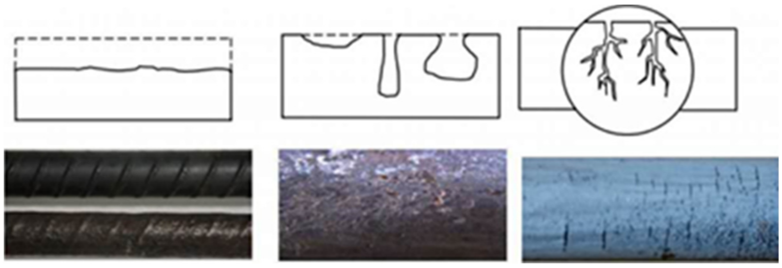


Figure 8. Illustration of corrosion in rock bolts, from left to right: uniform corrosion, pitting corrosion and stress corrosion, adapted from Xu and Gutierrez [45], Copyright ©2022, with permission from Elsevier, License No. 5344140552087.

5.5. Rock Bolt Length

Another potential factor affecting the longevity of bolted tunnels is the length of rock bolts. It is widely known that rock excavations lead to impacted zones. Among them, there are the excavation damaged zone (so-called loose zone) where the physical, mechanical and hydraulic properties of rocks are lastingly devalued [92]. Rock bolts length must be enough in order to secure and completely compensate for the loose areas of the excavations. In fact, rock bolts length should outrun the plastic zone of tunnels surrounding rocks [20,43,135,136]. More precisely, the length of the bolts should exceed the plastic zones by 2 or 3 m [136]. The plastic zone around tunnels can refer to the loose zone. In deep discontinuous rock masses where fractures can easily propagate, it turns out that the length of rock bolts must also exceed the fracture depth [137]. In order to limit the evolution of cracks in hinged rock mass, Feng et al. [138] numerically demonstrated that the length of the bolts must extend beyond the perimeter line of FAI = 0.8, as shown in Figure 9. FAI is the Failure Approach Index (FAI) that can reflect the extent of damage in the excavation damaged zone (EDZ) and can be such as 0.8 < FAI < 1, in conditions of high stress and huge time-dependent fractures [138].

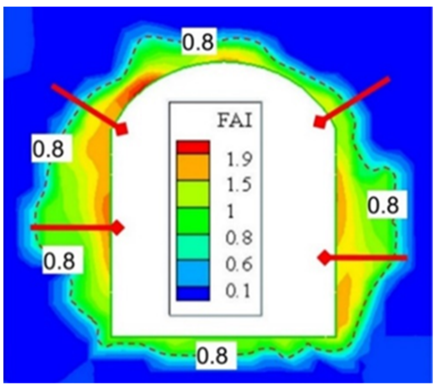


Figure 9. Length of rock bolts exceeding the perimeter line of FAI, reprinted from Feng et al. [138], Copyright ©2022, with permission from Springer Nature, License No. 5344180177286.

Rock bolt length must be minutely estimated. In fact, the insufficient bolt length leads to incomplete reinforcement of the loose zones of rocks surrounding the tunnels. The evolution of the deformations of unreinforced areas may exceed the deformation capacity of the bolts and their failure may thus have occurred. On the other hand, the increase in bolts length or too long bolts is not attractive for both technical and economic reasons. Technically, the extra length of bolts do not participate to the strengthening effect of the rock bolts [34,139,140]. Moreover, it is costly to use bolts which have additional lengths. Bolt length should be sufficient or exact to provide a good anchorage [139], and to be effective [88]. Thereby, a better compromise must be found in determining the proper length of rock bolts which guarantees both efficiency and economy [65,141].

Diverse propositions for estimating the length of rock bolts have been made. Table 5 summarizes some relevant of them.

Table 5. A summary of proposals for estimating the length of rock bolts.

Rock Bolt Length (L)	Equation Number	Parameters	Applicability	Investigators
$L = L_1 + L_2 + D$	(1)	L_1: exposed length of bolt shank; L_2: bolt length anchored in the non-cracked area D: maximum cracking depth.	Deep roadways in discontinuous hard rock subject to cracking and huge deformations	Zhao et al. [137]
$L = 2\,\mathrm{h}$	(2)	h: tunnel shape height	Deep tunnels in complicated rock mass	Gao et al. [142]
$L = 1.4 + 0.184B$	(3)	B: tunnel opening span	Tunnels in relatively jointed hard rock mass	Li [10]
$L \geq l + a$ $a \geq 1\ \mathrm{m}$	(4)	l: thickness of weak strata, a: anchorage length; In rocky media susceptible to bursting	Deep coal mines having formation of weak strata on the mining roof	Li [10]
$L \in [1\ \mathrm{m};\ 9\ \mathrm{m}]$			Deep caverns in active seismic areas	Zhou et al. [143]
$L = 0.6\,H$	(5)	H: Tunnel height	Deep tunnels in soft rock	Li et al. [144]
$L \leq 2\,R$	(6)	R: Tunnel radius	Tunnels in media assimilated as homogeneous	Bernaud et al. [113]
$L = (0.02CMRR \quad +1.54) \times \log(H) + \left(\frac{100-CMRR}{100}\right)^{1.5}$ with $CMRR = 21.6 + 11.5\ logH$	(7)	H: overburden depth of mines (ft); $CMRR$: coal mine roof rating L: rock bolt length (ft)	Deep coal mines exposed to high humidity	Mark et al. [145]

It is important to point out that determining the optimal rock bolts length for a particular rock bolts types or models is not obvious as it depends on the actual rocks properties which remain complex. In the majority of cases, using a unique rock bolts length may not be able to conveniently reinforce the overall surrounding rocks of deep tunnels. In fact, as revealed by Barton and Quadros [134], rocks anisotropy is very popular. Accordingly, the loose or plastic areas of a given rock surrounding the tunnels vary from direction to direction. For both safety and economy reasons, referring to Hatzor et al. [146], the best sizing of the bolts length is that in which the anisotropic character of the rocks is taken into account.

5.6. Elongation of Rock Bolts

Another important factor to consider when selecting and designing the right bolts is the elongation of rock bolts. Generally, bolt elongation can provoke a decrease in bolt tension [39] and generate a risk of failure of rock bolts. The risk of failure is usually increased by the combined effects of bolt elongation and anchor slippage, primarily under high dynamic loads and complex geological conditions. Hence, rock bolts have to display considerable elongation for several reasons. One is that decreasing the tension in the bolts will not significantly affect the overall performance of the rock bolt system. On the other hand, this will make it possible to maintain the structural integrity of the systems rocks-bolts in an acceptable manner so that they resist in the long term. Moreover, the high elongation capacity of bolt is also important to avoid the failure of rock bolt [48]. In fact, as related by Yan et al. [16], great elongation bolts systematically contribute to improving the stability of rock massifs. The reduction in the span of the plastic area of the rocks surrounding the tunnels is another crucial benefit of high-elongation rock bolts [16]. Note that low elongation of rock bolts generally results in instability in the bolting. According to Dai et al. [11], poor elongation of bolts can cause tail breakage of bolt in deep tunnels. Rock bolts failure can occur untimely owing to poor elongation ability [6]. Consequently, the most suitable rock bolts should be capable of exhibiting large elongation in order to cope with large deformations in deep tunnels. In addition, when such rock bolts strongly elongate, they should not be damaged and their integrity should not be attacked. Figure 10 illustrates the elongation of rock bolts.

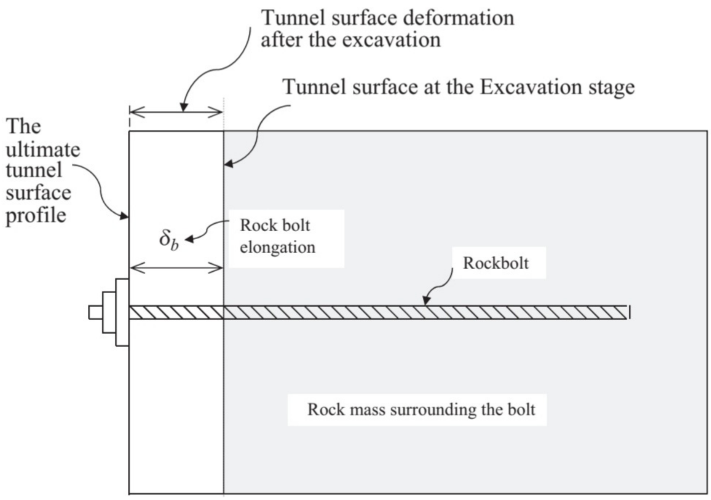


Figure 10. Illustration of rock bolt elongation, reprinted from Ranjbarnia et al. [147], Copyright ©2022, with permission from ASCE, License ID 1245450-1.

5.7. Number of Bolts and Their Spacing

The number of bolts and their spacing are important factors to emphasize in controlling the rock bolts failure and thus the long-term stability of tunnels. Indeed, the number of bolts in tunnels must be enough to duly fortify the surrounding rocks and prevent any exorbitant deformation. Bolts spacing is another factor affecting rock bolts performance in deep tunnels. Small bolt spacing is necessary to reduce the risk of rock bursting in deep tunnels [148]. It has been experienced by Boon et al. [99] that plasticization begins in the rocks surrounding the tunnels by increasing the bolt spacing. When the plastic areas which depends on the rock mass properties [7], evolve over time and become too large, the bolts can fail. The bolt spacing must therefore be optimal and by this way the required bolt density will be typical. For soft rock, as studied by Li et al. [144], the optimum density should be 1 rock bolt per square meter. Wu et al. [34] shown that the rock mass is stabilized when the bolts space is reduced and the bolts density increases. This is because deformations in tunnels are reduced by reducing the bolt spacing [11]. When the number of bolts are exact in accordance with the reinforcement requirements of the surrounding rocks, the bolts spacing can be considered optimal. It has been demonstrated by Wang et al. [149] that the number of crushed bolt connections can be significantly reduced when increasing the number of bolts from 4 to 12. As reported by Basarir [150], the quantity of bolts depends also on the rock mass quality. The poorer the quality of the encountered rocks, the greater the number of bolts should be and therefore the smaller their spacing should be, to increase the reinforcements. For tunnels in articulated rock mass subject to strong stresses and expansion of the excavation damaged zone (EDZ), the rock bolts spacing of 1.2 m is rational [138]. Figure 11 shows the effects of rock bolts spacing on the extent or depth of the EDZ.

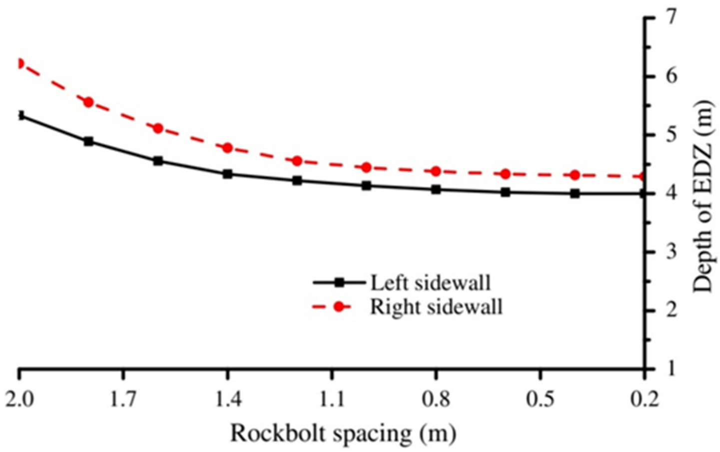


Figure 11. Effects of Rock Bolt Spacing on the Extent of Excavation Damaged Zones of Rock Surrounding Tunnels, reprinted from Feng et al. [138], Copyright ©2022, with permission from Springer Nature, License No. 5344180177286.

Propositions have been carried out to calculate the bolt spacing under different ground conditions. Table 6 reports the main ones.

Table 6. Determination of bolt spacing in deep tunnels.

Rock Bolt Spacing (b)	Equation Number	Parameters	Applicability	Investigators
$b = \sqrt{\left(\frac{P_0}{P}\right)}$	(8)	P_0: Bolt tensile failure stress; P: anchoring force	Deep roadways in different strata	Yuan and Yang [12]
$b \in [0.15L_s;\ 0.20L_s]$		L_s: Half-span of tunnel shape	Deep tunnels in complicated rock mass	Gao et al. [142]
$b = \sqrt{\left(\frac{T}{P_e}\right)}$	(9)	T: Working load of rock bolts; P_e: Support pressure	Deep caverns in rocky media with varying characteristics	Behnia and Seifabad [136]
$b = \sqrt{\frac{1}{FS}\frac{2E_{ab}}{t\rho V^2}}$	(10)	FS: factor of safety; E_{ab}: energy absorption of each bolt; V: ejection speed; t: thickness of the interaction zone; ρ: rock density	Deep tunnels or mines in rocky conditions prone to bursting	Li [10]
$b < \frac{1}{2}L$	(11)	L: length of the bolts	Deep caverns in active seismic areas	Zhou et al. [143]

Note that the insufficiency of rock bolts in tunnels is considered a nocuous condition. When the quantity of rock bolts is not enough in the surrounding rock of tunnels, deformations can evolve faster and bolts that are more spaced will have to carry more loads increasing their risk of failure. Bolts that have the ability to deform greatly with surrounding rocks may resist. However, their integrity can be adversely affected, and their durability can be reduced, as they will tire more quickly by enduring considerable effects of the convergence of natural rocks around tunnels. When the deformational capacity of rock bolts is severely reduced under such conditions, their failure is imminent.

5.8. Orientation of Rock Bolts

The orientation of the bolts is also a potential factor that needs to be given a lot of attention when studying the durability of bolted tunnels. In fact, the performance of rock bolts does not only depend on the above-mentioned factors, but also on bolt orientation. The latter must be properly taken into account when installing the bolts. As experimented by Kang et al. [151], the failure of the end of a bolt depends largely on the angle at which the bolt is installed. Rock bolts must offer great resistance to withstand the shear stresses that are prevalent especially at depth. However, this resistance is considerably influenced by bolt orientation [91,123,151]. A large angle of inclination results in a decrease in the shear strength of the bolts [151]. At great depths, bolts are usually subjected to dynamic shear loading as rockbursts are common. In this situation, for best shear performance and limited deformation, an inclination angle of 45° is proposed by Li et al. [121] for rock bolt installation. However, it has been demonstrated by Li et al. [152] that the inclination of rock bolts relative to the shear surface should be between 55° and 75° in order to be most effective in dealing with shear stresses. According to them, beyond this range, there is a risk that the rock bolts will bend and fail. The best bolt orientation is required both for static and dynamic shear loads. Through joints and weak areas, the strength of bolted rocks augments with the contribution of that of rock bolts [153]. To prevent them from breaking, the bolts must be properly oriented inside the rocks surrounding the tunnels. This is of considerable importance even if the types of bolts selected and designed are the most suitable. It must be pointed out that bolts can generally bear less shear loads than axial loads under different loading conditions [119]. Indeed, all the components of a bolt can be optimal, but if the installation angle is not quite suitable, its shear strength will be low and its shear displacement will be considerable, especially in discontinuous rock masses. In such situations, rock bolt failure could occur under shear load. Figure 12 shows a comparison of shear resistance and shear displacement of a bolt for different angles, according to Li et al. [152].

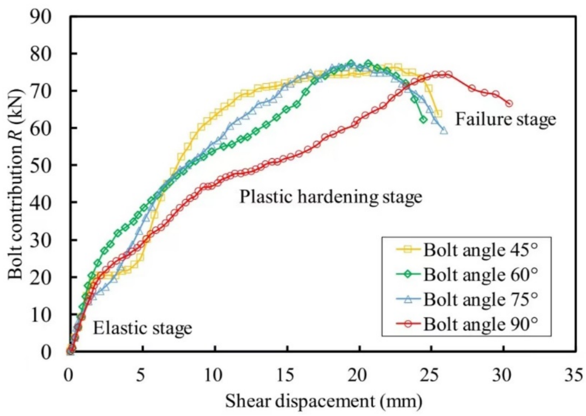


Figure 12. Comparison of shear resistance and shear displacement for different installation angle of rock bolt, reprinted from Li et al. [152], Copyright ©2022, with permission from Elsevier, License No. 5344141390457.

The correct installation angle is also required for the best energy absorption of the bolts. It has been studied by Li et al. [121] that rock bolts should not be installed horizontally, because in this position they absorb little energy compared to tilted bolts under the same conditions (Figure 13). In addition to all of this, in order to adequately limit the convergence of the surrounding rocks, rock bolts should be installed as early as possible during and/or after the tunneling period. To avoid breaking the roof of the surrounding rocks, installation at the right time should be favored [97].

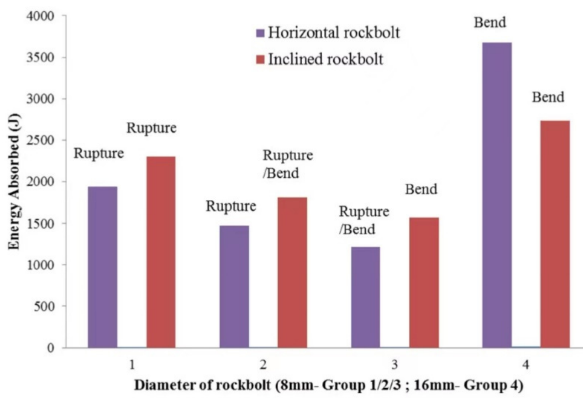


Figure 13. Comparison of absorbed energy between horizontal and inclined rock bolt, reprinted from Li et al. [121], Copyright ©2022, with permission from Springer Nature, License No. 5344181297068.

5.9. Anchorage System

Since anchorage is considered the most important component of rock bolts, its effectiveness determines the durability of the bolting. In fact, the performance of the bolting depends very much on the efficiency of the anchoring system (Figure 14). The latter usually consists of different components such as borehole, bolts and grout. More clearly, as reported by Kılıc et al. [29], the anchoring system of rock bolts is generally constituted by solid or hollow steel bars which can be inserted into the rock mass in a stretched or unstretched manner. During and after the insertion of rock bolts, the generated anchoring force can be reduced by the quality of all the aforementioned constituents [56]. Moreover, as related by Jiang et al. [154], under high stresses causing damage to expand, the anchoring force can be lessened to the point of provoking the rock bolts to break. The resistance of the anchoring force depends on various factors such as the bolts components and the bearing capacity of surrounding rocks. When these factors are not conveniently addressed, failure of rock bolts can occur. For example, the diameter of the bolts is one of the factors affecting the capacity of the anchoring system. The tensile and shear capacities of the anchoring system increase with increasing bolt diameter [155]. Crack evolution can be mitigated at the bolt-rock interface by the increased shear resistance that large diameter bolts can provide [156]. Owing to the alteration of surrounding rocks properties after tunnelling, the emplacement of bolt anchorage must be effectuated adequately. According to Dong and Wang [157], the steady elastic zone should be the zone to situate the anchorage (Figure 15). Normally, the anchorage system finds its full capacity when the end of the bolt reaches the elastic zone [158]. The plastic zones cannot support the anchoring system because the alteration of the properties of the rock is perennial there. In the stable elastic zones [88], the anchoring system must be properly installed to avoid failure due to rupture that could occur at the resin-bolt (grout-bolt) and rock-resin (rock-grout) interfaces.

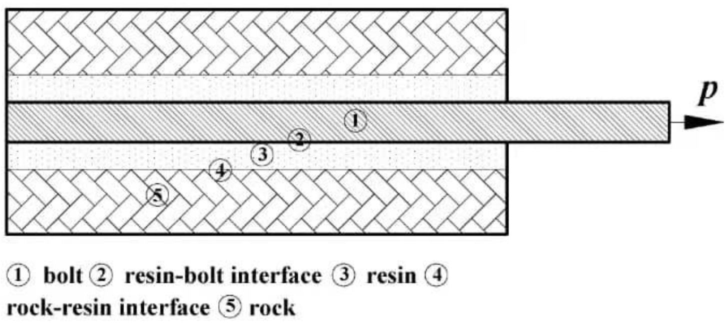


Figure 14. Illustration of a typical anchoring system (adapted from [157], Copyright ©2022, with permission from Springer Nature, License No. 5344190800114.

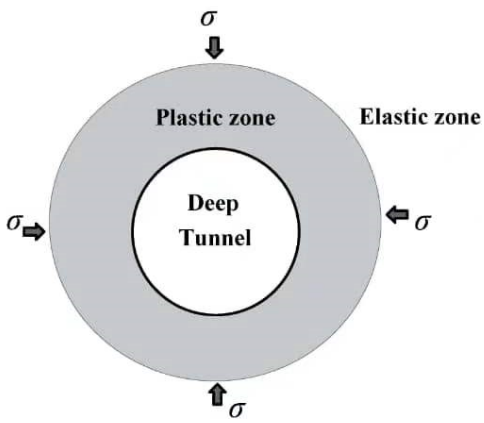


Figure 15. Illustration of zones generated after rock excavations for circular tunnels.

Furthermore, the anchoring system should be strong enough to prevent sliding and loss of tensile strength. In fact, the sliding of anchorage generally can also lead to a decrease in bolt tension which endangers the bolting stability [39]. According to Mark et al. [159], in order for rock bolts to better perform their anchoring function, their anchoring capacity must be greater than the bolt capacity developed in the design. In fact, the performance of the anchoring system is influenced by the anchoring length which should be estimated carefully. Moreover, rock bolts can perform their roles properly when they have a reliable anchoring system which can be improved by adequate grouting [106,122]. A lack of anchoring length can result in loss of fasteners and can then lead to anchor bolt failure [117]. Specifically, as proposed by Chang et al. [160], 1.54 m anchorage length is suitable for any type of rock bolts in deep quadrilateral mines. Nevertheless, an unanchored length can also be assigned to the rock bolts. The unanchored length of a rock bolt can allow it to fully play its role of reinforcement [149,160]. Figure 16 illustrates the anchorage and unanchored length of rock bolts.

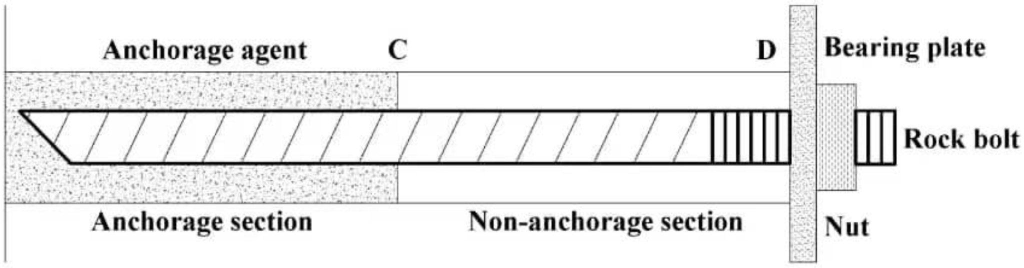


Figure 16. Illustration of anchored and unanchored length of rock bolt, adapted from Chang et al., 2021 [160].

The greatest load that a rock bolt can withstand must be estimated correctly to ensure its long-term functioning. It has been proposed by Peng and Tang [39] that creep experiments can be used to determine the maximum load of that rock bolts can bear. Such tests are generally necessary to accurately estimate the optimum load capacity of materials to be subjected to long-term loads. This is of great importance to ensure long-term performance of the anchoring system. Note that pull tests are widely used to study the capacity of the rock bolt anchoring system [42].

6. Geological Formation and Suggestions of Rock Bolts

The geological formation plays a major role in tunneling aspects. As such, the selection and design of the rock bolts is generally made according to the type of geological formation encountered in the route of the tunnels. Rock mass requirements for supports are also considered in rock bolt selection and design. Different rock types can be encountered in tunneling. The lower the resistance of the rocks, the more they need high-performance supports. The suggestions of rock bolts for different geological formation can be based on different approaches or considerations. Among them, classical or empirical approaches such as Rock Mass Rating (RMR), Barton's Q-systems (Figure 17) are generally employed. In the RMR system, the rock mass quality is put forward to estimate the length and spacing of rock bolts. However, in such system where the rock mass quality is divided into five classes ranging from very good to very poor, the guidelines are mainly provided for horseshoe-shaped tunnels 10 m wide, and the rock bolts are fully grouted and have a diameter of 20 mm [161]. Note that the RMR system values range from 0 to 100, where point bolting is suggested for RMR > 85.

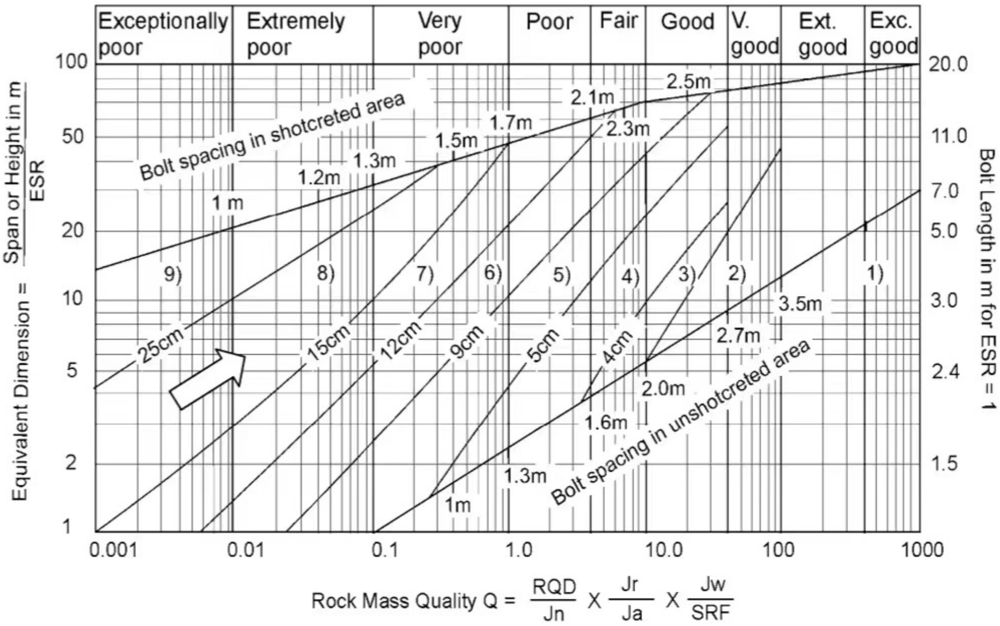


Figure 17. Chart of the Q-systems of rock support (From Barton [162], Copyright©2022, with permission from Elsevier, License No. 5378160017237).

The Q system, with rock mass quality ranging from exceptionally good to exceptionally poor, is established to aid in the empirical design of rock support systems in tunnels. According to Barton [162], when using the Q system, not only must the rock conditions encountered be mastered, but attention must be paid to two main situations: the presence of massive rocks, the existence of failure induced by stress. The rock mass quality (*Q*) is determined as follows [162]:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \quad (12)$$

where *RQD* indicates rock quality designation; J_n is the rating for the number of joint sets; J_r is the least favorable roughness ranking of sets of joints or filled discontinuities; J_a is the rating of the degree of weathering or clay filling of the least favorable set of joints or filled discontinuity; ESR is Excavation Support Ratio.

Q-system is widely used in the determination of rock bolt supports in tunnels and caverns. The class and condition of the rock mass and the Q-value are the main factors considered in determining the associated rock bolt supports. In an exceptionally poor rock mass where the Q value is exceptionally low, rock bolt supports must be heavily evaluated on a case-by-case basis. For example, as reported by Høien et al. [163], an exceptionally poor rock mass can have a Q value of less than 0.01.

According to Skrzypkowski [98], geomechanical tests can be performed to determine the quality of rocks encountered on the roof of mining tunnels, and the results can serve as a basis for selecting appropriate rock bolt supports. Table 7 shows some suggestions of rock bolts taking into account the roof rock classification of Olkusz-Pomorzany Zinc and Lead ore mines in Poland.

Table 7. Selection of suitable rock bolts-based roof rock classification (Skrzypkowski [98]).

Class of Roof	Description	Compressive Strength (MPa)	Rock Mass Weakening Coefficient	Types of Excavations	Types of Rock Bolts Support Systems
I	Very hard rock	≥70	>0.9	Rectangular or trapezoidal	Rock bolts or without support
II	Strong stratified rock	50–70	0.7–0.9	Rectangular or trapezoidal	Expansion or point resin rock bolts
III	Fragile stratified rock	30–50	0.5–0.7	Flat or oval roof	Expansion or point resin rock bolts
IV	Weak rock	20–30	0.4–0.55	Oval roof	Point resin or full column resin rock bolt and steel lagging
V	Very weak rock	<20	<0.4	Oval roof	Arch yielding support

Furthermore, Length of the roof rock bolts ≥1.6 m; Basic net bolting diagram: 1 m × 1 m or 1.2 m × 1.2 m; The side walls of excavations longer than 4.5 m are bolted and in which the first row is made 4.5 m from the floor; Length of side walls rock bolt ≥ 1 m [98].

The rock bolts must be able to withstand both static and dynamic loads. The latter are frequent at great depths. Factors such as ground demands and support capacity should be considered when designing safe support systems [14]. Table 8 present suggestions for suitable support systems based on ground demand and support capacity according to Masoudi and Sharifzadeh [14].

Table 8. Support selection based on demand and capacity according to Masoudi and Sharifzadeh [14] (Copyright©2022, with permission from Elsevier, License No. 5378160668877).

Ground Demand		Reinforcement Selection	
Surface Displacement (mm)	Energy (kJ/m^2)	Recommended Reinforcement	Capacities Category
<50	<5	Expansion shell rockbolt, Resin/cement steel rebar	Low/stiff
50–100	5–15	Split set, Swellex, Roofex, Yield-Lok	Medium
100–200	15–25	Swellex, D-Bolt, Conebolt, Roofex, Yield-Lok	High
200–300	25–35	Roofex, Conebolt, Garford	Very high
>300	>35	Conebolt, Garford	Extremely high

Despite these propositions, it should be noted that further efforts are still needed to select the optimal rock bolt type for a given tunnel or cavern based on the geological conditions. Careful identification of the geological conditions is very important. Additionally, the relevant rock and rock mass properties are of paramount importance in the optimal selection and design of rock bolts. Regardless the method employed for the selection and design of rock bolts, long-term monitoring is necessary to track the real-time structural conditions of the rock bolts structures in order to make adequate decisions about tunnel maintenance in a timely manner.

7. Discussion

This paper illuminates pertinent types or models of the developed rock bolts and the potential factors influencing their failure in deep tunnels. Most of the rock bolts presented in this paper are yielding or energy-absorbing, which are typically offered in complex underground situations. The main characteristics of these rock bolts are shown in

Tables 1 and 2. Many of these rock bolts are developed on the basis of numerical analysis and laboratory tests. Few of them have been verified by field experiments. Numerous experiments and controls in the field are therefore necessary to ensure the real static and dynamic capacities of the rock bolts. The dynamic capacity of rock bolts is required to deal with dynamic conditions that are frequent in deep excavations. As related by Hadjigeorgiou and Potvin [164], dynamic design of rock support is usually appreciated to a certain extent. Nevertheless, although it remains a difficult task, there is a great need to accurately estimate the static and dynamic properties of rock bolts. An example of a dynamic impact which can seriously weaken the strength of the bolts is the action of an earthquake [51]. In fact, depending of the total length of the tunnels and their position, they can be exposed to natural earthquakes. Moreover, deep hard rocks are also exposed to frequent seismic event due to the triggering of rockbursts at great depth. Rockbursts are dynamic catastrophes that the rocks surrounding deep excavations have to deal with [48]. Tunnels can even fail completely if their support systems do not have the capacity to withstand the damage and energies caused by rockbursts [165]. In that context, rock bolts should be anti-seismic especially those supporting deep tunnels in discontinuous rock mass. It has been related by Zhou et al. [143] that rock bolts parameters should be optimized to resist earthquake damage. In other words, rock bolts must be selected and designed based on their ability to handle extraordinary quantities of energy which can reach 10^6 kJ [35]. Thereby, rock bolts should be able to develop extremely high performance to cope with extreme rocky environments, even when paired with different components of a given support scheme. It can be understood that when rock bolts operate in such environments, their durability is reduced, especially when realistic geological and geotechnical characteristics are lacking in their design steps. However, such characteristics are generally difficult to determine with precision due to numerous technical and economic constraints.

Much effort is already being made by the scientific community in the development of various types or models of rock bolts which have to face severe situations in deep underground excavations. Despite this, due to the complex characteristics of deep rocks, there is a great need for continual review of rock bolt types or models for reasons of safety and stability. Indeed, rock bolts which demonstrate good performances with respect to the tensile and shear stresses have at the same time uncertain behaviors in situations of torsion. In addition to the tensile characteristics, as reported by Sainsbury et al. [118], it is suggested that the shear and torsional constituents be taken into account in evaluating the strength of rock bolts. The resistance of rock bolts should be a combination of tensile, shear and torsion components [118]. In fact, the torsional capacity of rock bolts cannot be neglected. When installing the bolts and when tightening, they are usually subjected to torsion mainly in their nuts [151]. Additionally, torsion can trigger in rock bolts by gap movement around tunnel face [118]. Rock bolts with low torsional capacity are vulnerable. Indeed, selecting and designing rock bolts without considering their torsional strength is risky. If the torsional capacity of the rock bolts is not sufficient, their breakage may occur. Moreover, torsion can degenerate important characteristics of rock bolts such as tensile capacity and elongation. These properties are drastically reduced by up to 77% to 86% when considerable torque is exerted [3].

At great depth, rock bolts are indispensable for tunnels built in all types of rock massifs. In fact, even high-quality rock massifs require a reasonable amount of rock bolts to strengthen the surrounding rocks of tunnels. This is due to the complex deep rock conditions which are characterized, by high in-situ stresses, high temperatures and high water pressures [47,57,96,109,166,167]. In such conditions, tunnel failure is predominantly due to stress [59]. In addition, at such a depth, degeneration and damage to rocks properties caused by excavation persist over time, and rockbursts are unavoidable [2]. Since the effects of rockbursts are generally very risky, it is therefore necessary to use rock bolts capable of withstanding them [59]. It is of paramount importance to select and design the most suitable rock bolts to ensure the long-term stability of deep tunnels and mines. This is because that the integrity of tunnels largely depends on the integrity of rock bolts [114]. It is incontestable that the loss of integrity of rock bolts leads to the loss of structural integrity of the tunnels. As such, when the durableness of rock bolts is reduced, the service life of the tunnels is also reduced, and failure may occur at any time.

From an engineering point of view and due to the presence of high stresses at great depths, a certain degree of softening can be attributed to rocks, regardless of their types. For this reason, excessive deformations are generally common at great depth and rock bolts have to deal with them. In fact, some soft rocks often stabilize after visibly deforming [168], and rock bolts should support them in the long-term, otherwise tunnel failure can happen without delay. Colossal deformations of rocks have been observed in deep tunnels in such rock type. For example, 2000 mm deformation has been measured during excavation of a diversion tunnel in Sichuan Province, China [168]. In addition, 2403 mm has been measured in Muzhailing tunnel, Gansu Province, China [169]. After excavation, a deformation of 1244 mm was assessed in the rib of Huahong coal mine, Shanxi Province of China [170]. Thus, these situations serve to emphasize that the rock bolts must be reliable and able to properly support large deformations. It should be noted that at great depth, substantial deformations of rocks can persist in the long term and that the maintenances are difficult [107], rock bolts must function effectively to ensure safety and to avoid premature failure of the tunnels. Indeed, rock bolts with low deformation capacity or insufficient elongation capacity should not be used for deep tunnels. In reality, all parameters of rock bolts must be carefully determined. Dimensions and spacing which are design parameters of rock bolts [41], should be estimated with the greatest possible care. They must reflect as much as possible the actual geological and geotechnical conditions of the host rocks of tunnels.

As related by Hadjigeorgiou and Potvin [164], the level of requirement on the rock support is very high for deep tunnels subjected to strong in-situ stresses. Accordingly, the rock bolts should be as suitable as possible in order to meet the different requirements of reinforcement and stability of the surrounding rock mass. This should be seen as an extremely high priority. This is because the safety and durability of tunnels greatly depend on the conditions of rock bolts [133]. Normally, the demands of deep rock massifs can be expressed in terms of energy, surface displacement and pressure [14,33]. For illustration, Figure 18 shows the range of the global quantitative values of such demands. The rock bolts should be ideal in order to withstand considerable loads and enormous deformations without failing (Figure 19). Technically and economically, estimating rock demands is mandatory in order to design adaptable rock bolts [171], which should work in the long term. In fact, bolted tunnels are typically designed to be operational for 100 years [167]. Referring to Wang et al. [169], it is therefore imperative to increase the capacity limits of energy-absorbing rock bolts.

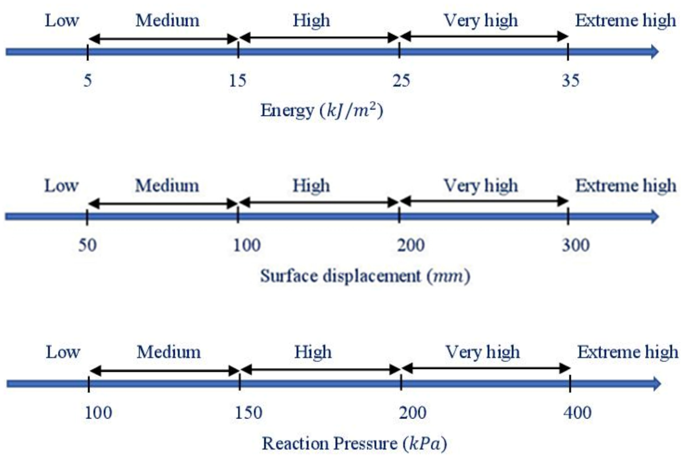


Figure 18. Ground demand in terms of energy, surface displacement and pressure, adapted from [14,33].

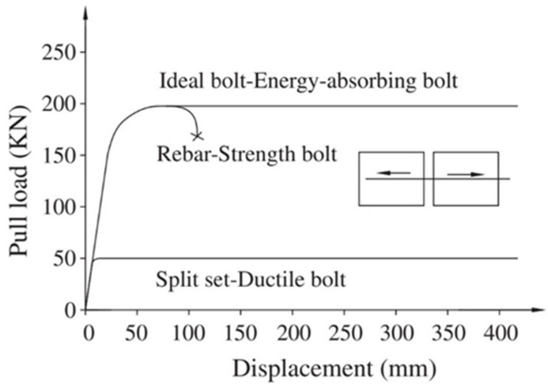


Figure 19. Concept of ideal rock bolt, reprinted from Wang et al. [9], Copyright ©2022, with permission from Elsevier, License No. 5344210042511.

Since rock bolt failure is very common in deep tunnels where rock deformations are often excessive [16], it is of the utmost interest to choose, design and install the most suitable type and the most efficient. This should be counted at a paramount importance level, as according to Aziz et al. [172], the efficiency of rock bolts changes with the modification of field conditions. In fact, safety and stability issues can be avoided in rock support systems with appropriate and unfractured rock bolts [173,174]. Accordingly, to effectively and durably limit the deformation of deep surrounding rocks, high-performance rock bolts are required [175].

From the determination of the actual static and dynamic strength of deep surrounding rocks, the following steps illustrate the importance of selecting, designing and applying the most appropriate rock bolts for the long-term stability of deep tunnels (Figure 20).

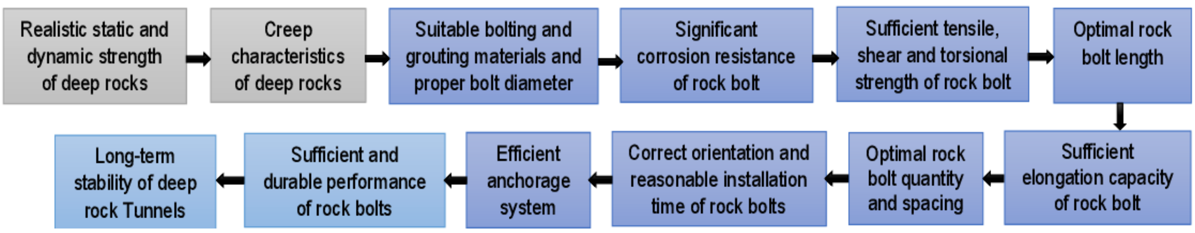


Figure 20. Steps leading to the design of rock bolts that can have sufficient and durable performance and therefore the ability to properly ensure the long-term stability of deep rock tunnels.

8. Conclusions and Future Trends

8.1. Conclusions

Throughout this article, an insight of the most relevant rock bolt types or models and the potential factors affecting their performance has been presented. Its importance lies in the fact that the long-term stability of deep tunnels largely depends on the suitability and the long-term performance of their rock bolts. The main conclusions are as follows:

1. Various aspects and conditions have profound influences on the lasting viability of rock bolts. The most marked are the complex behaviors of rocks and the excavation situations which condition the reliability of rock bolts. The lasting performance of rock bolts is thus governed by several potential factors, as discussed in this paper. When they are not properly considered, such factors are the major causes of rock bolt failure and instability in deep underground engineering. The long-term performance of rock bolts is therefore required for the long-term stability of deep tunnels.
2. Since realistic deep rock characteristics remain difficult to accurately determine, it is difficult to optimize rock bolt selection and design. Moreover, for technical and economic reasons, simplified assumptions are generally adopted in both numerical analyzes and laboratory tests. Indeed, for instance, numerous data are ordinarily

required to achieve precision in numerical analyzes. However, since the required time to obtain them is so huge, they are usually limited. Consequently, long-term monitoring is required to monitor changes in deep rock behavior and rock bolt performance. Thus, the structural integrity of the tunnels will be assessed in a timely manner and any premature failure can be prevented.

3. Among the existing rock bolts presented, the selection of a type for a given tunnel can be made in conformity with the similarities of applicability (Tables 1–3) and the level of reliability towards the potential factors. It must be recognized that comparisons in the same situations are necessary to determine which type of rock bolt is most appropriate for a given deep tunnel.
4. Although considerable research has already been carried out in this area, it can be argued that much effort is still needed. Above all, the greater the embedding depth of the tunnels, the more the behavior of the surrounding rocks is complicated and difficult to estimate with precision. This is therefore the main reason why researchers have invented many types of rock bolts for different situations. By considering the potential influencing factors herein elucidated, newest types or models of rock bolts can be developed to better support the surrounding rock of tunnels or mines located at greater depths.
5. It is important that research in this domain be more useful from a scientific, technical and economic point of view. Accordingly, a key task is to accumulate accurate and legitimate historical data for diverse types or models of rock bolts in order to conceive verified databases for better utilizations. Thus, the selection and design of new rock bolts will be safer and fairer, and therefore the most efficient possible.

8.2. Future Trends

In spite that numerous studies have attained a lot of progress in developing rock bolts to support the surrounding rocks of deep rock tunnels, there is still a need to develop new reliable rock bolts to accurately support the long-term life of deep underground structures. The following points may therefore constitute trends for future research:

- Since the performance of rock bolts is influenced by many potential factors, it is of great consideration to study the durability of rock bolts from a multi-criteria analysis under different realistic in-situ stresses.
- Currently, most rock bolt designs and studies are based on tensile and shear experiments. It is of great interest to evaluate the performance of rock bolts subjected to combined actions of tensile, shear and torsion for deep tunnels under complex geological conditions. Under such conditions, the strength of rock bolts can be assessed more accurately and their failure can be better predicted.
- Given that in deep underground engineering, high groundwater pressures and flows are frequent, it is of essential to study the comprehensive characteristics of various types of rock bolts subjected simultaneously to aggressive groundwater and different modes of solicitations.

Author Contributions: Conceptualization, W.F.; methodology, W.F.; software, W.F.; validation, H.P.; formal analysis, J.Z.; investigation, W.F.; resources, W.F.; data curation, W.F.; writing—original draft preparation, W.F.; writing—review and editing, W.F.; visualization, J.Z.; supervision, H.P.; project administration, H.P.; funding acquisition, H.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the China Scholarship Council, grant number 2019GBJ008203.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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