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A New Criterion on Designing an Effective Cable Bolt Length Subject to Static Loading in Underground Excavations

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Abstract

A simple probability analysis failure criterion for cable bolts in underground excavation is described. The criterion was developed using static loading tests of mechanical anchors (38 tons, 18 mm diameter cable, 2 m length and six strands), and Finite Element Method. Three static loading tests were performed, thereafter, an underground excavation was simulated with several wedges wherein the effectiveness of the bolt was tested in varying spacing, while other parameters remaining constant. A simple probability criterion was therefore developed to bridge the gap on identifying effective bolt length and total effective length of the bolts within the excavation in varying strata control (change in angle of the strata and change in thickness of the strata). The criterion is suitable for predicting the effective bolt length, predicting the total effective bolts length within the excavation provided the orientation and thickness of strata in known and also suitable to classify the excavation as over/under supported. Two practical applications and examples of the criterion are described. These are firstly, identifying of and secondly, predicting the effective bolt length and total effective length of the bolts in strata with varying orientation and thickness in both hanging and side walls.

Keywords: • Mechanical anchor • Probabilistic criterion • Laboratory tests • Numerical simulation • Safety factor

Introduction

Underground mining usually creates excavations of varying sizes in the surrounding rock mass. However, the rock mass itself is never homogenous, because it can be of varying rock strength and can be traversed by geological disturbances as well as subjected to changing stress fields. During mining activities, the developed excavations need support to maintain the stability of the excavations. Failure to support them can result in the collapse of the excavations on varying scales, causing injuries to miners as well as disruptions to mining, which in turn can affect the mine's productivity. The safety and life of such excavations can be maximised if properly designed mining layouts are in place accompanied by the use of correct support systems. Some excavations like tunnels are planned for long time usage and therefore require effective support.

As mining progresses towards ultra-deep mining levels, the stress levels increase rapidly, compromising the stability of the tunnels and excavation intersections. Tunnels driven into highly stressed ground typically suffer from stress-induced damage [1]. Stress-induced damage can form from either creation of new fractures or reactivation of existing fractures in the rock mass. As a result of these challenges, rock support systems of underground excavations have changed significantly over the past decades due to improved technologies, experience gained and rock support requirements for different rock masses. The number of rock reinforcement systems has also been developed and evidence to perform very deep level hard rock mining is abundant. Some of the known studies that have outlined the behaviour of rock bolts in mining practices include [2,3]. The above-mentioned authors have introduced numerous rock bolts of different length and energy absorption as well as other parameters. Nonetheless, the understanding of rock bolts behaviour has been based on laboratory, field tests, analytical methods as well as numerical analysis [4-22] Although the methods indicate that the bolts would perform very well, there have been numerous studies which have reported bolts that have failed dramatically. Nevertheless, the assessments of the failure are most concentrated on the bolt performance rather than on the rock strata onto which it was installed as well as the period within which the bolt was installed.

As a matter of fact, there have been several scholars who strived to address some of the limitations posed by the previously developed bolts. Some of the encouraging studies include those conducted by authors in [23-29]. The previous studies mentioned above were intended to present newly developed rockbolts or cable bolts or modify the existing bolts. Although there has been such extensive work, it is very complex to develop a rock reinforcement system which is perfectly applicable in all ground condition. Due to the fact that there is no perfect rockbolt or cable bolt already existing within the field of study, this provides the motivation to continuously develop and test new cable or rock bolts to ensure the safety of employees and to reduce damages at the vicinity of the mining tunnels.

Despite the existence of numerous studies that have documented the new development in effective rock bolts for underground working, these rock bolts have been reported to perform very well under laboratory, field tests and numerical simulations. These bolts are also evidenced to fail rapidly in most underground excavations. This situation has always challenged geoscientists and rock engineers on whether there is any rock bolt which truly works or not. The proposed study is intended to develop a probability analysis criterion that can quantify the effectiveness of the installed roof bolts, to outline the knowledge gap regarding the common factors that influence the ineffectiveness of roof bolts. The criterion provides the ability to classify an excavation either as an over or under supported excavation.

Short review on Mechanical cable anchor

The Mechanical anchor system is an active reinforcement system, used to stabilise large single blocks or wedges formed on the hanging wall and sidewalls of underground excavations. This reinforcement system tends to provide effective reinforcement of the excavation walls where normal rock bolts are inadequate due to their short embedment lengths. They can be used in a wide range of hole diameters from 25 mm to over 60 mm. Various steel diameters can be used to suite the required strengths . Mechanical bolts do

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have certain limitations in that if the correct torque is not applied on installation, an inadequate load will be achieved. The load is also lost through ground vibration caused by blasting or other rock movement, rock burst or strain burst. If scaling occurs around the collar of the support hole, load is also lost. As a result, full column grout mechanical anchors have been introduced to eliminate some of the limitations associated with mechanical anchors.

The design of the support system in the mining industry and geotechnical fields has being well established and documented in many studies. However, the major focus is always to ensure that the developed support system has the ability to perform all functions of the support system at the vicinity of the excavations [29] is the known first study to propose the common functions of the support system at the vicinity of the excavations where the authors indicated that there are three functions of the support system which are to; hold, retain and reinforce. Few decades later, Cai Ming, et al. [28] revisited the above mentioned functions and found out that there are four functions rather than three functions. In their study, a function called "connect" was then introduced. Functions such as to hold, retain and reinforce can be observed or tested in the field, while the most important function which is to connect cannot be tested yet. However, although other functions of the bolts are achieved, the last function usually plays a major role. As such, to address some of the limitations associated with support failure, the proposed criterion will include the ability to classify the bolt as fully connected or partially connected. The detailed methodology of the paper is outlined below.

Approaches

The methodologies followed in this study includes, laboratory tests (static loading tests), numerical simulation (Finite Element Method), development of the criterion and case studies on the application of the methods, as well as validating the criterion. The detailed procedure of the laboratory static loading test and numerical details are indicated in the following subsections below.

Static pull tests procedure

The tests were conducted in accordance with the following procedure:

- The anchors are in turn installed vertically between the platens using a suitable dye to provide an anchoring surface for the barrels and wedges on the top position, as shown in Figure 1.
- One of the cable ends is well gripped with a wedge that is fitted into the hollow side of a steel dye, with no evident slippage, whereas the other cable end is fitted with a barrel and wedge assembly inside a clevis.
- A pre-load of between 5 kN and 10 kN is applied to eliminate any slack in the assembly.
- The anchors are then gradually loaded at a rate of 30 mm/min until tensile failure is achieved.

Numerical simulation procedure

In order to understand the best situation in which the bolt can be installed, numerical simulation with a varying spacing of the bolt was performed. The numerical simulation consisted of several input parameters as indicated in Table 1. Nonetheless, the simulation was also used to validate the effectiveness of the bolts in the varying orientation of the bolt installation. It is important to indicate that the simulation was largely focusing on simulating Factor of Safety (FoS) of wedges revolving around the excavation. Three joint sets were used to simulate underground excavation at a deep level with high stress. A stereonet of the simulated excavation is shown in Figure 2. A horseshoe arch was used as a simulating arch since most of the deep level mines usually follow such a pattern, meanwhile, the dimension of the excavation is indicated in Table 1. Note that the bolt parameters used are those presented in static analysis of the mechanical anchor, it is crucial to indicate that three bolt tests presented in this study are representative of more than 20 tests.

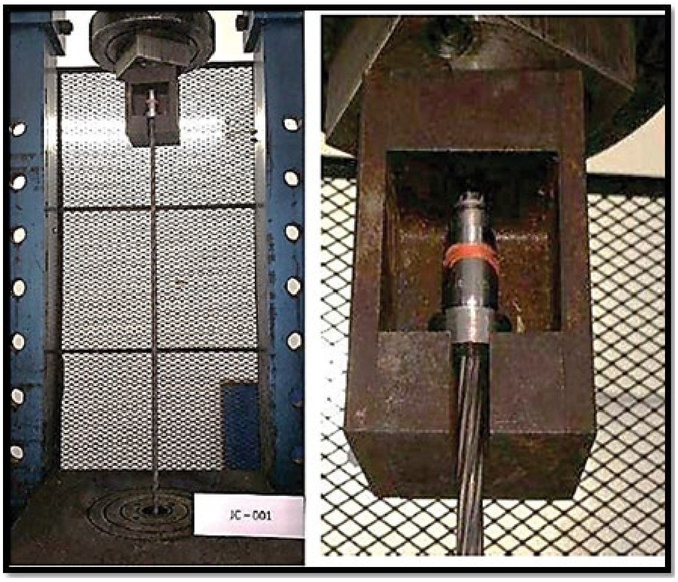


Figure 1. A mechanical anchor of 1.5 m, 18 mm diameter steel cable with 18 ton AMS barrel anchor assembly inserted into a testing machine before test with a barrel and wedge assembly on the top platen.

Table 1. Input parameters used for simulation.

Excavation Dimensions		Joints Properties			Bolts spacing			Principal stress	
		Joint sets	Dip (º)	Dip Direction (º)		In plane (m)	Out of plane (m)		Magnitude (MPa)
Height (m)	5.7	Joint 1	70	37	Stage 1	1	1		
					Stage 2	1.5	1.5	σ_1	89
Width (m)	5	Joint 2	85	101	Stage 3	2	2	σ_2	47
Type of Arch	Horse Shoe	Joint 3	48	262	Stage 4	2.5	2.5	σ_3	27

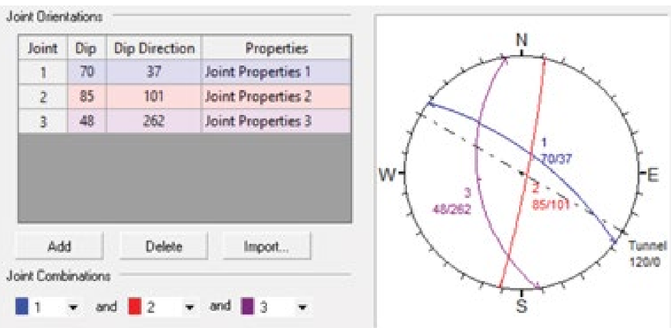


Figure 2. Stereonet of the simulated underground situation using Unwedge (Finite Element Method).

Results and Discussion

Static pull tests

Figure 3a represents the first tensile test results conducted on the 38 tons Mechanical Anchor, indicating that the cable bolts start to show a sign of yielding at an approximate load of 344.1 kN, where a deformation of approximately 47 mm was recorded. As these performances were followed they gradually increased yielding of the cable bolts ranging between 345.0 kN and 379 kN with the recorded deformation ranging from 48 mm to 78 mm. It was clearly noted that immediately after the gradual increase in yielding, a peak load of 380.4 kN was achieved with the deformation of approximately 79 mm. From the result and observational point, it was noted that the bolt performed much better than it was expected, reaching its peak load between 350 and 360 kN. The first yielding point was achieved after few strands had been broken and later the yielding continued to improve as other strands followed or broke with the peak load being achieved after the middle strand broke. During this test, it was noted that the cable had the ability to withstand the maximum stress of about 1495 MPa at its peak load.

The second tests were then performed and the results are shown in Figure 3b. It is clear from Figure 3b that the initial yielding load was recorded at approximately 342 kN with a deformation of approximately 41 mm. From the curves, it is also clear that at an applied load of 200 kN a slight fail of the cable was experienced, it is assumed that such a slight fail might be due to one strand collapsing or being broken. Furthermore, the cable did not show an extensive increase in yielding as compared to the first one; instead the bolt immediately reaches its peak load after a shallow increase in yielding. A maximum load of 357.5 was then achieved with a deformation of about 48 mm. When comparing the first test with the second one, it is clear that the second bolt could not resist much load as it could not provide extensive deformation as the first bolt did. Arguably, such abnormality could be due to the slipping of the cable manufacturing error. Furthermore, the second test also presents very reasonable results that at some point the bolt could perform less as per the specification but a reasonable state.

The previous results led to conducting of another test to further understand the performance of the bolt. Figure 4 shows the results obtained from the last test. The results of the test show that the bolt showed some level of yielding at the load of 342 kN with the deformation of approximately 42 mm. Soon after achieving its yielding point, a gradual increase on the yielding load was achieved with a deformation ranging from 43 mm to 66 mm. It is also clear that immediately after the gradual increase; a peak load was then achieved at 375.5 kN with a deformation of approximately 69 mm. From the three results stated above, it can be noted that the first and second tests are very close to each other and have shown that the developed 38 tons' Mechanical anchor has the ability to withstand a tensile load of approximately 380 kN with a deformation of approximately 79 mm.

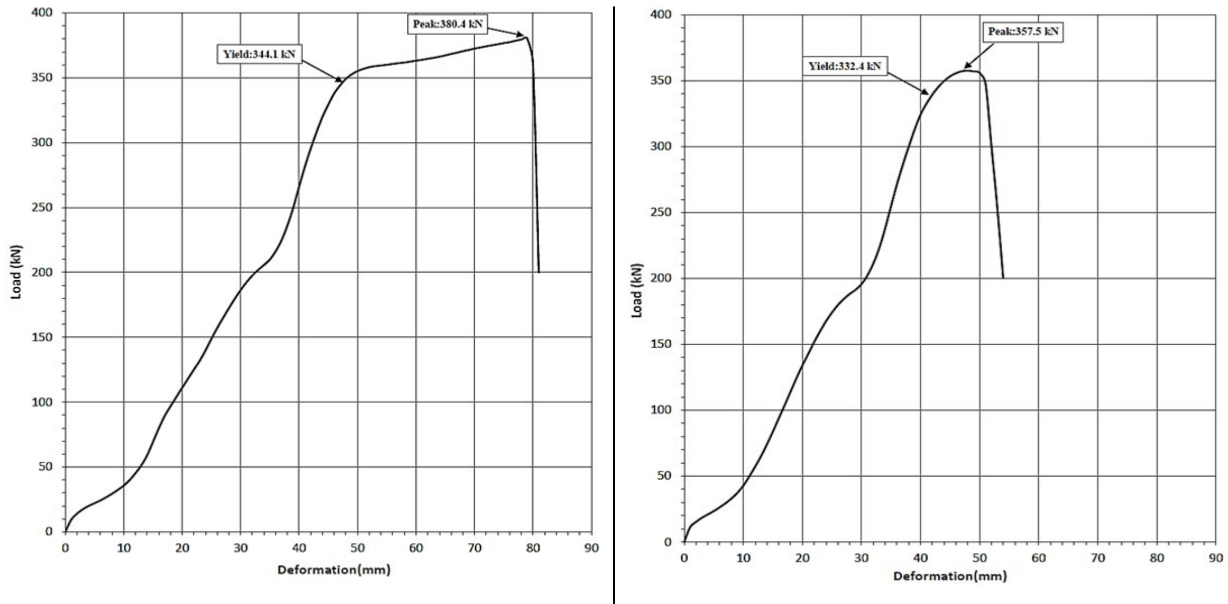
The calculations indicate that at least a minimum deformation of 43 mm can be achieved when the bolt achieves its yielding load and approximately 65 mm can be expected to occur before the bolt can totally fail. A minimum of 1405 MPa (stress) was achieved through the tests with the maximum stress of 1495 MPa; this gives an impression that the newly developed Mechanical anchor has the ability to perform very well in high stressed ground conditions. In summary the results of the study have shown that mechanical anchors can withstand a minimum load of 332.4 kN with a displacement of 47 mm and a maximum load of 380 kN with a displacement of 79 mm, with a reasonable standard deviation.

Performance of 38-tons mechanical in deep underground excavation

A basement excavation with three wedges was simulated and the stability of the wedges was assessed based on their Safety Factor (FS). In short, a plane excavation without a support system (support and reinforcement) was simulated where it was noted that the roof wedge had a FS of 1.180, which clearly means that the wedge was not stable and was expected to fail provided the conditions (tensile movement) were met (Figure 5). In other words, such excavation will require a support system to ensure the stability of the wedge created on the hanging wall. Meanwhile other wedges were simulated to be stable wherein the upper right and lower left wedges were simulated to be at the FS of 9.031 and 23.052 respectively. The simulation was to generate the underground situation and to perform trails in which the bolts could be more effective in providing stable walls. Nevertheless, the simulated roof wedge was denoted to fail through falling of wedge mode, meanwhile other wedges were expected to fail through sliding along joints 1 and 2 (Table 3).

Further steps on testing the performance of the bolts were conducted where the cable bolts with the above discussed capacity were installed along the excavation with spacing of 1 m by 1 m in plane and out of plane. Therefore, the FS of the excavation was assessed where it was observed that after the installation of the support system the FS rapidly increased from 1.180 to 7.702 on the roof wedge. Meanwhile other wedges also showed a rapid increase in FS, specifically the lower left wedge which increased to 44.259, while the upper left wedge increased to 11.421 (Figure 6 and Table 4).

Further simulation was done to understand bolts that are expected to fail through tensile failure as the study was more interested in static loading. The results of the simulation have shown that a majority of the bolts installed within the wedges were expected to fail under tensile mode, while the rest of the bolts remained stable. Owing to that, the number of bolts simulated to fail under tensile loading was determining by the size of the wedge and spacing of the bolts. Of course, the roof wedge was noted to present few bolts that could fail under tensile failure, specifically about five cable bolts were simulated to fail under tensile failure. In the meantime, the lower left wedge presented more bolts to fail under tensile as compared to the roof wedge, where approximately 11 bolts were expected to fail through tensile failure mode. Lastly, the upper right wedge had more bolts than the rest of the wedges, in which 17 bolts were expected to fail under tensile mode (Figure 7). In summary, the estimation of failure mode along the wedges is partial believed to be controlled by the spacing and size of the wedge. Nevertheless, the FS of each wedge appeared



(a) First static loading (b) Second static loading

Figure 3. (a & b) Static loading tests results of a mechanical anchor (38 tons, 18 mm, and 6 strands).

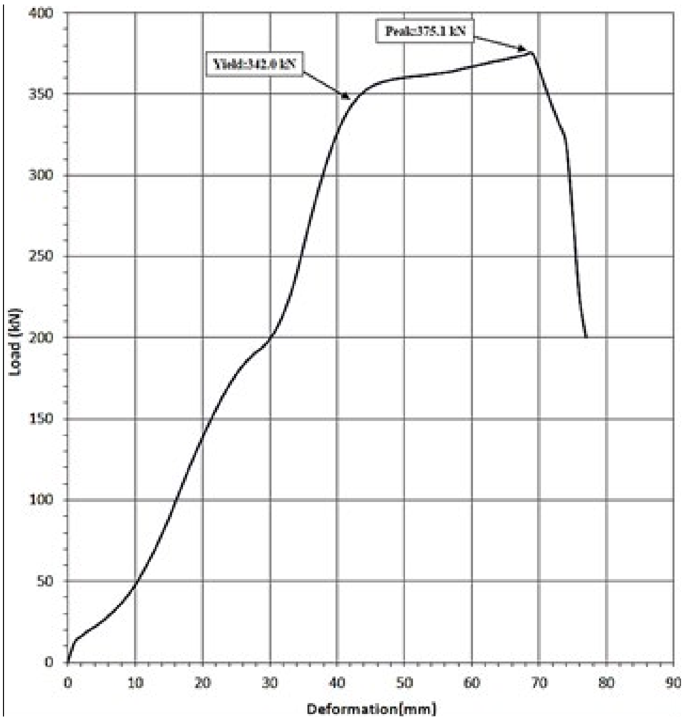


Figure 4. Third static loading test results of a Mechanical anchor (38 tons, 18 mm, and 6 strands).

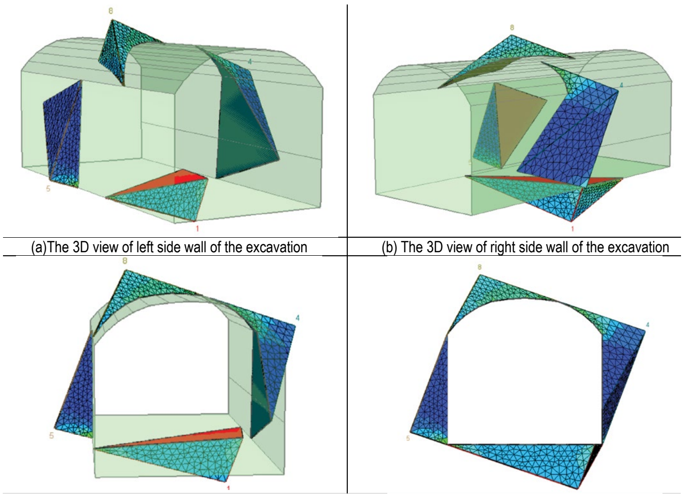


Figure 5. (a-d) Simulated FS of an excavation in a deep level environment, with three significant wedges denoted on the hanging wall and sidewall. Note that the footwall wedge is not of interest in this study.

to have a significant contribution this concentration of fail among the wedges, in which it appears that the higher the FS, the higher the number of bolt distribution that could fail under tensile fail mode.

Further simulation was performed with change in spacing of the bolts. However, it was denoted that when the spacing increases from 1.5 to 2.5 in plane and out of plane, the FS also gradually reduced progressively. The results of the simulation give an impression that indeed spacing of the bolts contributes largely to the stability of the excavation. Specifically, the FS of the roof wedge gradually reduced from 2.830 to 2.533 as the bolts' spacing reduced; meanwhile the other wedges also presented similar results. On the other hand, the number or bolts expected to fail under tensile failure mode were also gradually reduced with a decrease in the bolt spacing. However, this decrease was only noticed along the sidewall wedges while the roof wedges presented two bolts throughout. Therefore, the argument is that, if the spacing increases, the roof wedge would eventually be left with only one bolt which could fail under tensile failure. Detailed results of this discussion are shown below in Figures 8 and 9 as well as Tables 5-7.

Table 2. Static loading tests results.

Test number	Yield load (kN)	Deformation at Yield load (mm)	Maximum Deformation at Yield load (mm)	Peak load (kN)	Stress (MPa)
1	344.1	47	79	380	1495
2	332.4	41	48	357.5	1405
3	342.0	42	69	357.5	1474
Mean	339.5	43	65	371.0	1458
Standard Dev	6.2	3	16	12.0	47
Maximum	344.1	47	79	380.4	1495
Minimum	332.4	41	48	357.5	1405

Table 3. Simulated results of an excavation in a deep level hard rock mining environment without support system installed.

Criteria	Roof Wedge (8)	Upper Right Wedge	Lower Left Wedge
Factor of Safety	1.180	9.031	23.052
Weight of the wedge (MN)	0.055	0.262	0.0164
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

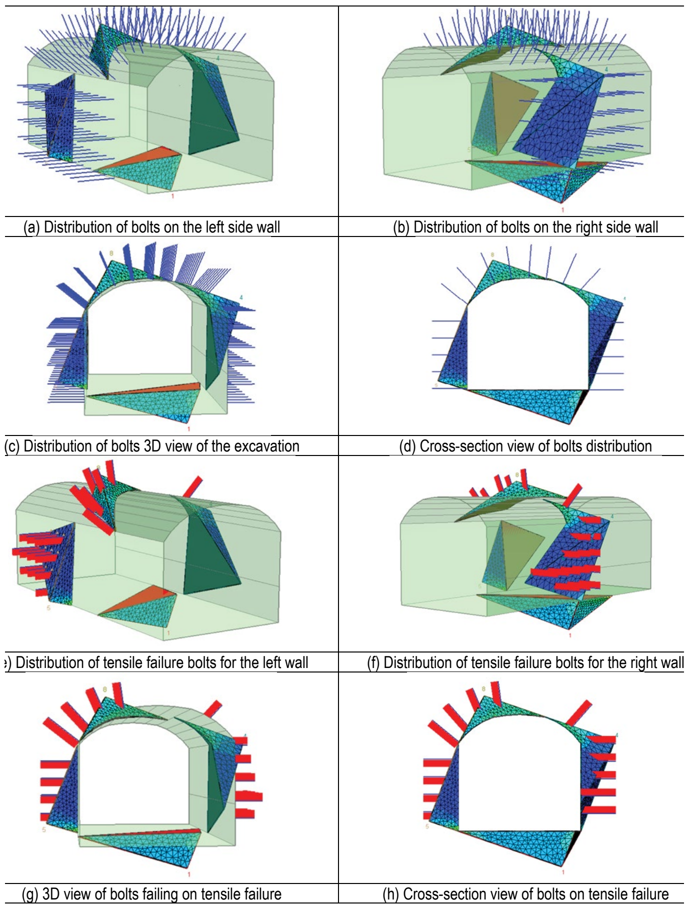


Figure 6. (a-d) Distribution of cable bolts installed at the spacing of 1 m by 1 m in plane and out of plane respectively, along the desired excavation and (e-h): Distribution of cable bolts that could fail through tensile failure mode along the simulated wedges in the excavation with 1 m by 1 m spacing.

In summary one would say that the tested bolts appeared to be suitable in large excavations as they could withstand a static load of about 380 kN. However, the results shown above are the common procedure used to evaluate the tensile performance of bolts in underground situations. Although this method appeared to produce very effective bolts, if the bolts are not installed accordingly based on the orientation and thickness of the strata, they could fail rapidly, which could lead to one questioning the effectiveness of the method.

Table 4. Simulated results of an excavation in a deep level hard rock mining environment with support system installed at the spacing of 1 m by 1 m in plane and out of plane respectively.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	7.702	44.259	11.421
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

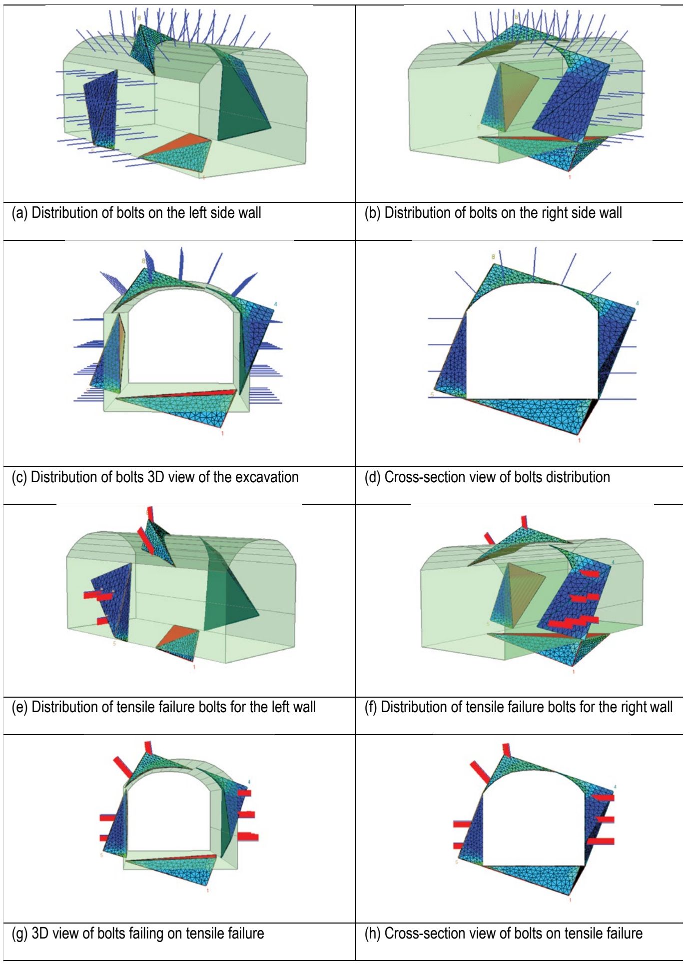


Figure 7. (a-d) Distribution of cable bolts installed at the spacing of 1.5 m by 1.5 m in plane and out of plane respectively, along the desired excavation and (e-h): Distribution of cable bolts that could fail through tensile failure mode along the simulated wedges in the excavation with 1.5 m by 1.5 m spacing.

As a result, failure to understand the composition and orientation in which the bolts should be installed across the excavation has led many authors to develop new bolts without taking a close look at what makes the bolts to fail. Indeed, it is possible for one to quickly perform pull tests, static tests, drop tests and torque tests of the bolts and totally forget about the orientation and thickness of the strata onto which the bolts have to be installed.

This gives an impression that although many authors have correctly reported that there is no perfect bolt, the performance of the bolts may be compromised because most bolts are normally installed at the opening section of the excavation regardless of the orientation and thickness of the strata. In such cases, not all functions of the bolts are well active and if one function is not achieved, such bolts do not deserve to be classified as well installed bolts. This knowledge gap leads to the suggestion about the probabilistic analysis failure criterion of the bolts which, mostly focus on assessing the connecting function of the bolts by looking into the effective length of the installed bolts. A detailed description of the proposed criterion and its application examples are presented below.

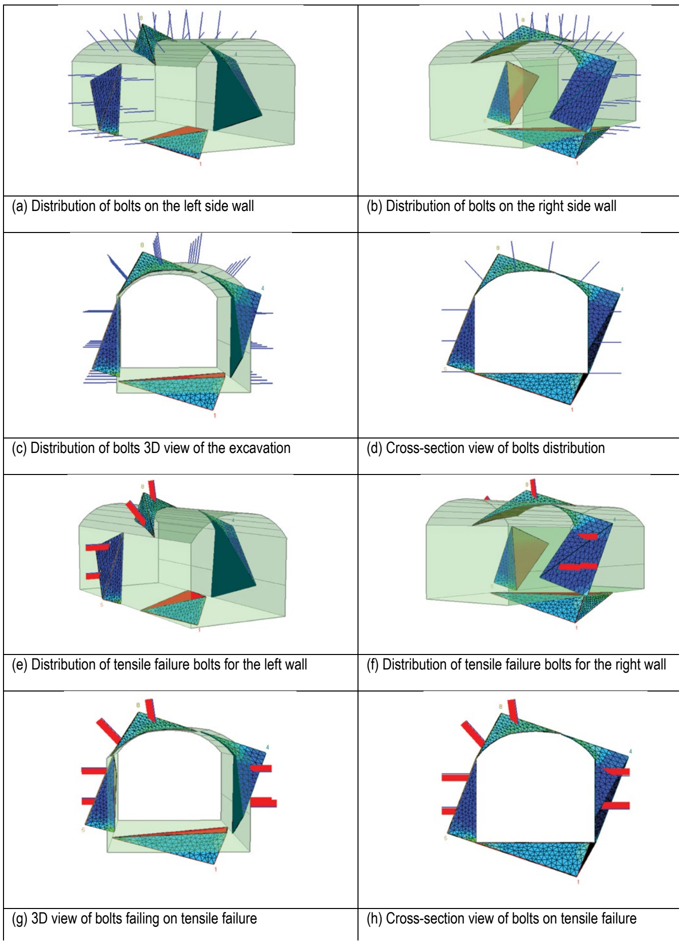


Figure 8. (a-d) Distribution of cable bolts installed at the spacing of 2 m by 2 m in plane and out of plane respectively, along the desired excavation and (e-h) Distribution of cable bolts that could fail through tensile failure mode along the simulated wedges in the excavation with 2 m by 2 m spacing.

Probability analysis failure criterion

The proposed probabilistic analysis failure criterion is mostly applicable in layered strata of varying orientation and thickness. This criterion is mostly intended to bridge the gap of quantifying the effectiveness of the last function of reinforcement system which is to connect. In this study, to connect or the connection of the reinforcement system is defined as the suitable length of the rock bolts connecting two layers. However, the connection is further defined as adequately connected or poorly connected based on the length of the bolt connecting the two layers. It is therefore noted that at least 50% of the bolts should be within another layer of the strata and should be classified as adequately connected. A simple probabilistic criterion is therefore proposed as follows:

$$C_e = \frac{£_{el}}{£_{Tl}} C_{sl} \quad (1)$$

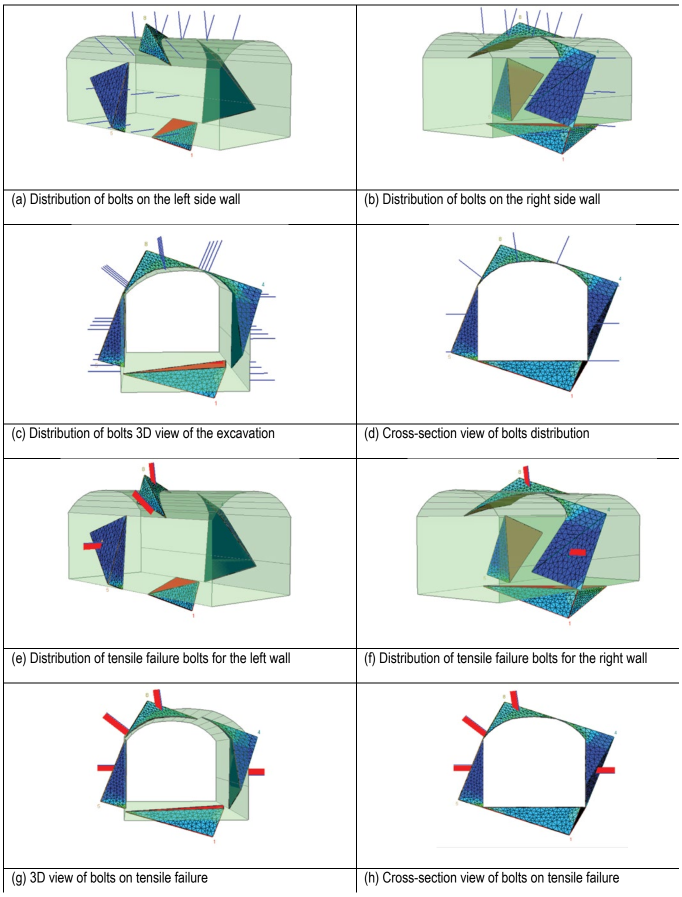
Where C_e is the effective static load of the bolt, $£_{el}$ is the effective length of the bolt, $£_{Tl}$ is the total expected effective length of the bolt, and C_{sl} is the total static loading of the bolt.

Therefore, the total percentage of the effective bolts can be calculated by using equation 1 as the basic solution, and the equation will be as follows:

$$C_{e(\%)} = \frac{Ce}{C_{sl}} x100\% \quad (2)$$

Where $C_{e(\%)}$ is the total percentage of the effective bolt length?

Nevertheless, this brings us to the question of how one could determine the bolt effective length. It has been discovered that if the orientation and the thickness of the strata is known, therefore the sine rule can be used to identify



(a) Distribution of bolts on the left side wall (b) Distribution of bolts on the right side wall (c) Distribution of bolts 3D view of the excavation (d) Cross-section view of bolts distribution (e) Distribution of tensile failure bolts for the left wall (f) Distribution of tensile failure bolts for the right wall (g) 3D view of bolts on tensile failure (h) Cross-section view of bolts on tensile failure

Figure 9. (a-d) Distribution of cable bolts installed at the spacing of 2.5 m by 2.5 m in plane and out of plane respectively, along the desired excavation and (e-h): Distribution of cable bolts that could fail through tensile failure mode along the simulated wedges in the excavation with 2.5 m by 2.5 m spacing.

Table 5. Simulated results of an excavation in a deep level hard rock mining environment with cable bolts spacing at 1.5 m by 1.5 m in plane and out of plane

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	2.830	28.836	9.868
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

Table 6. Simulated results of an excavation in a deep level hard rock mining environment with cable bolts spacing at 2 m by 2 in plane and out of plane.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	2.830	28.836	9.868
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

Table 7. Simulated results of an excavation in a deep level hard rock mining environment with cable bolts spacing at 2.5 m by 2.5 m in plane and out of plane.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	2.533	26.908	9.449
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

the effective length. In Figure 5 below, it is indicated how one can identify effective length through the use of sine rule wherein two angles and one side is known, hence the effective length can be identified by subtracting the length identified on the y –axis from the total length of the bolts.

$$\frac{a}{Sin\ A} = \frac{b}{Sin\ B} = \frac{c}{Sin\ C} \tag{3}$$

Therefore, in order to calculate the total effective length of the bolts within a ring or excavation the following equation can be obtained as follows:

$$C_{total} = \frac{\sum C_e(C_{e1} + C_{e2} + C_{e3} \ldots C_{en})}{\sum £_{rl\ /\ el}} x100\% \tag{4}$$

Where C_{total} is the total percentage of the effective bolts length within the excavation or ring, $\sum £_{rl/el}$ is the total length of bolts per ring or excavation, $C_{e1} + C_{e2} + C_{e3} \cdots C_{en}$ effect length of bolts from each bolt.

It is crucial to indicate that the above mentioned criterion cannot operate without an understanding of the strata. However, the criterion works very well with the updated geological block model since it provides the operator with the orientation and thickness of the strata. Therefore, it can be argued that this criterion has the ability to provide rock engineers with an effective reinforcement angle of installation and the length of the reinforcement required to perform to its capacity. As a result, it can be deduced that if this criterion could be used, the support design could improve underground mining, subsequently leading to most ground incidents being reduced rapidly. Although there is no perfect reinforcement system currently, the performance of the recent reinforcement system could be improved if the criterion intended to assess the performance of bolts are implemented correctly. In the meantime, the application of the criterion discussed below using simulated situations.

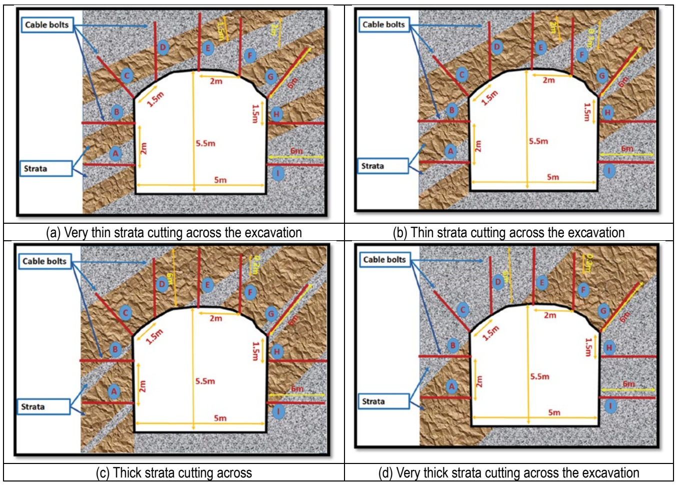
Nevertheless, for the criterion to be reasonable in determining the effectiveness of the bolts, it is assumed that a bolt which anchors through more than two layers is classified as fully effective, while those that are within two layers have to go through the equation. Moreover, the length between the two layers should be equal, although in some cases this may not be possible because the thickness of the layers is not always equal. As mentioned in the title of the paper that the criterion is a probabilistic analysis types, therefore the above assumptions cannot be avoided.

Application of the criterion in varying thickness of strata

A simulated underground situation was used for the application of the criterion, which was applied in a ring of installed cable bolts. The application of the criterion was to assess the effectiveness of the installed rock bolts in excavations which had different strata orientations. The bolts were simulated to be installed using the concept of normal to opening section, as shown in Figures 10a & 10b. This concept was selected because in most underground excavations the installation of rock bolts usually follows it. Therefore, it was found significant to create a common real practice situation.

Nonetheless, the thickness of the strata was changed four times. From the results of the simulated excavations, the first excavation consisted of multiple strata layers that cut across the excavation with varying strata thickness. As shown in the diagram above, cable bolts can also be installed using the normal practice, however the purpose is to apply the probabilistic analysis failure of the excavation based on the effective length of the bolts. Based on the analysis (Figure 11), the calculated effective length of the ring was approximately 94%. In simple terms, the ring is categorized as stable or has an acceptable total effective length of the bolts. The analysis shows that the installed bolts covered the connecting function of the bolt. It is important to indicate that, this result highlights that the ring had a fully connected number of strata. However, it is crucial to verify other functions of the bolts such as to hold, retain and reinforce.

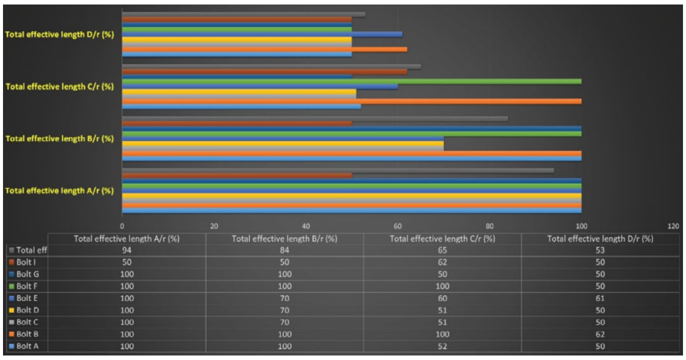
In the meantime, similar analysis was performed for the same excavation with a change of strata thickness (Figure 10d). In this case, the strata thickness was a bit thicker compared to the previous one (Figure 10c). Nevertheless, the results of the analysis show that the effective length within the ring gradually dropped, from 94% to 84%. One could partially deduce that the increase in strata thickness has an influence in the effective length of the bolts and the stability of the excavation. In simple terms, the length of the bolt within the



(a) Very thin strata cutting across the excavation (b) Thin strata cutting across the excavation

(c) Thick strata cutting across (d) Very thick strata cutting across the excavation

Figure 10. Simulated underground excavation with varying strata thickness.



	Total effective length A/r (%)	Total effective length B/r (%)	Total effective length C/r (%)	Total effective length D/r (%)
Total eff	94	84	65	53
Bolt I	50	50	62	50
Bolt G	100	100	50	50
Bolt F	100	100	100	50
Bolt E	100	70	60	61
Bolt D	100	70	51	50
Bolt C	100	70	51	50
Bolt B	100	100	100	62
Bolt A	100	100	52	50

Figure 11. Calculated effective length of the bolts using the simulated examples in conditions of varying thickness of strata.

second or first strata was observed to be limited as compared to the first case. Therefore, one could argue that the connecting function of the bolt was compromised a bit as compared to previous the case (Figures 10c & 10d).

Further analysis was performed with the increase in thickness of the strata. The results of the analysis showed that the increase in strata thickness contributed largely to the total effective length of the installed bolts. In simple terms, the percentage of the effective bolts length dropped from 84% to 65% (Figures 10 and 11). Meanwhile, the results obtained from the analysis revealed that the installed ring of the excavation was not effective, implying that it was expected that the bolts would not be able to perform as per their capability. Therefore, a gradual failure was expected along the ring in which tensile failure was very prone to happen. Furthermore, as the thickness of the strata increased, one could partially deduce that if the length of the increase in bolts remains the same, not all functions of the bolts could be achieved, especially the connecting function of the bolt. Therefore, this criterion can easily provide guidance on the length of the bolt as well as the angle of the installation required to maintain the stability of the walls.

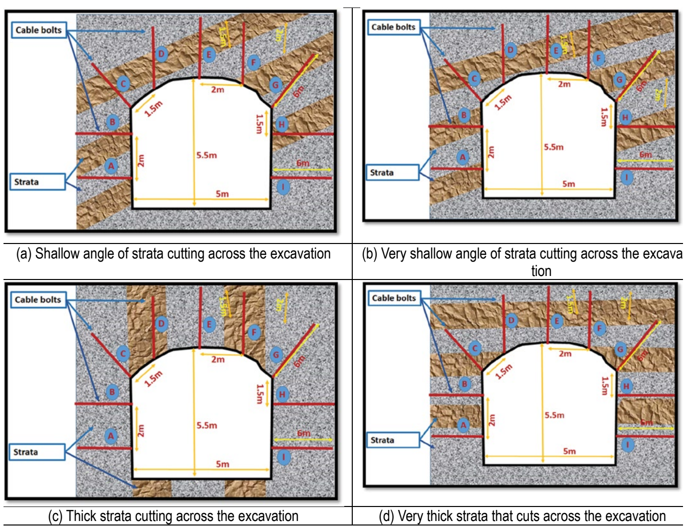
In summary, one could deduce that indeed the change in strata thickness has extensive influence on the performance of the bolts. However, literature assessed the performance of the bolts through revisiting the three functions of the bolts which are to retain, hold and reinforce. These assessments were performed through observation and testing in the form of pull tests, and torque tests. However, the last function about connecting could not be tested or assessed because it is mostly based on the bolt connecting layers of the strata. The proposed criterion appears to have the ability to assess such important functions of the bolts. As such, this method is called the probabilistic analysis of failure, which entails that it is based on the probability of failure.

Application of the criterion in varying orientations of the strata

The second application of the criterion was based on change in orientation of the strata. The purpose of this simulation was to understand if the criterion can be able to provide the probability of effective bolt length in a situation where the strata thickness remains constant with change in orientation. The result of the trail has shown that an excavation with strata striking at a shallow angle (angle less than 45 degrees) will probable result into about 95% of the effective length along the ring of the cable bolt (Figures 12a-12d and 13). This result is mostly controlled by the fact that most strata are thin and therefore the bolt has the ability to connect more than two strata, as a result, the criterion gives the bolts 100% effective bolts length, since they would have achieved the function of connecting. In Figure 12b, the angle of strata has changed, the analysis has shown a slight reduction of the percentage of the effective length of the bolts along the ring. However, the effective length of the bolts was estimated to be high due to the fact that the conditions are slightly similar to the first case.

Furthermore, a rapid change in strata orientation was implemented where the strata angle was placed at 90 degrees. The results of the analysis revealed that the probabilistic analysis of failure along the ring of the excavation was 50%. This result clearly shows that all the installed bolts were expected to underperform due to the premature connecting function of the installed bolts. From (Figure 12c), one could have deduced that all bolts had anchorage with one strata, therefore the function of connecting in this case was compromised. However, in really cases, most mines apply similar strategies of installing their reinforcement system regardless of the orientation of the strata. As a result, most falls of the ground have been reported where the support system was installed perfectly, but many causes of such falls are always blamed on the manufacturing companies of the bolt while the common failure cause is not really investigated. Therefore, the support system can be designed to withstand a certain load, but if all the functions of the bolts are not achieved the reinforcement system should not be expected to perform as per the design. Hence, the proposed criterion has the ability to provide a solution in which the bolt could be installed to increase the effectiveness of the bolts. The bolts' effectiveness is always assessed by the criterion and as usual, this criterion outlines the probabilistic analysis failure of the installed bolts.

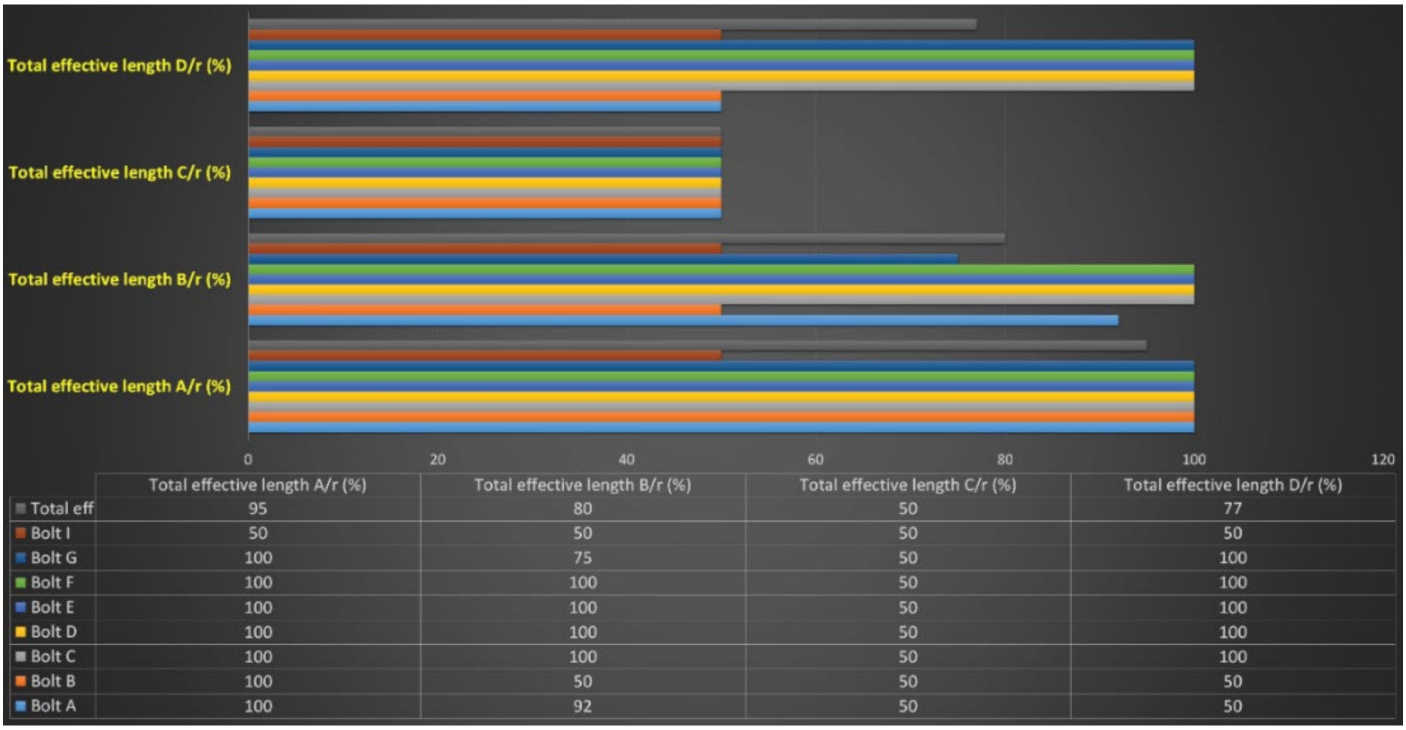
Nonetheless, the orientation of the strata was also changed to become flat or be at zero degree. The results of the analysis have shown that the total effective length of the bolts along the ring improved from 50% to 89%. In the meantime, one could have deduced that the percentage changed due to the fact that the bolts were able to connect from several strata. Nevertheless, all the bolts installed along the side walls were affected when in terms of connecting, however, this challenge has never been considered in underground situations. As already indicated, the installation of the bolts is based on the concept of normal to the opening section. A close look was also considered where it was observed that if the orientation of the sidewall bolts is changed the total effective length across the ring will probably change or improve. However, this gives an impression that most bolt failures in such situations were due to the



(a) Shallow angle of strata cutting across the excavation (b) Very shallow angle of strata cutting across the excava tion

(c) Thick strata cutting across the excavation (d) Very thick strata that cuts across the excavation

Figure 12. Simulated underground excavation with varying orientations.



	Total effective length A/r (%)	Total effective length B/r (%)	Total effective length C/r (%)	Total effective length D/r (%)
Total eff	95	80	50	77
Bolt I	50	50	50	50
Bolt G	100	75	50	100
Bolt F	100	100	50	100
Bolt E	100	100	50	100
Bolt D	100	100	50	100
Bolt C	100	100	50	100
Bolt B	100	50	50	50
Bolt A	100	92	50	50

Figure 13. Calculated effective length of the bolts using the simulated examples in conditions of varying orientations of the strata.

fact that the last function of the bolt was not performed at all. Therefore, it should be expected that the bolts' performance is compromised.

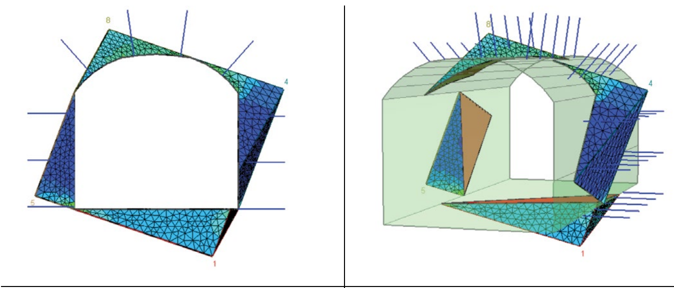
Validating the criterion using finite element method

In validating the criterion using numerical simulation, unwedges software was utilized. However, the purpose of the simulation was to look into the effect on changes in the angle of installation on the Safety Factor of the wedge which was developed. In order to produce a meaningful comparison, the simulation was firstly based on simulating the basement or reference point. Therefore, a basement excavation was simulated and three major wedges were created on the hanging wall and sidewall of the excavation. The focus of this section was to validate that the effect of change in the angle of bolts to the Safe Factor of the wedge, from which the results could be used to validate the purpose of the development of the probabilistic analysis failure criterion.

Nonetheless, the first simulation was used as the basement through normal to the opening section criteria. The simulation has revealed that the roof wedge has a Safety Factor (FoS) of 2.830, in which the wedge is considered stable, owing to the fact that the lower left wedge was simulated at 26.908, meanwhile the last wedge at the upper right was noted to be at 9.449. Both sidewall wedges were simulated to be failing through sliding along joint 1 and 2, meanwhile the roof wedge was simulated to failure due to a falling wedge. This result shows that all created wedges can be stable after being supported by cable anchors at a spacing of 2 m by 2 m square meters (Figures 14a & 14b). Nevertheless, further simulations where the bolts are installed at a shallow angle of 15 degrees are discussed below.

As outlined above, the simulation was progressed to an excavation with bolts installed at 15 degrees and the results of the simulation has shown a 50% decline of the FS on the roof wedge, in which the FS reduced from 2.830 to 1.180. However, this gives an impression that when the angle of the bolts is installed at 15 degrees, the stability of the wedge is compromised and as such the wedge is expected to fail although there are roof bolts installed. This result relates to the finding on the effective length of the bolts based on strata orientation and thickness. Nonetheless, other wedges also experienced a decrease in FS although their decrease was minimal (Table 9 and Figures 15a & 15b).

Furthermore, the angle of installation was therefore increased to 45 degrees, where it was observed that the FS of the roof wedge also increased although the increase was minimal. However, other wedges were observed to remain constant. This result initiated further simulations to identify the actual behavior of the wedge as the angle of installation increased (Figures 15c & 15d and Table 10). An angle of 70 degrees was therefore implemented and it was noted that the FS on the roof wedge kept on improving. In this case, the FS simulation was even more than that of normal to open section type of installation.



(a) Cross-section view of the supported excavation (b) 3D view of the supported excavation

Figure 14. Simulated underground excavation with installed bolts using the normal to opening section.

Table 9. Simulated results of the wedge with the excavation supported by bolts installed at 15 degrees.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	2.830	26.908	9.449
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

Therefore, this result proves the point that not every excavation should be supported based on the normal to opening section criterion of support design. It is clear that even if the two excavations were compared using the proposed probabilistic analysis method, the results were going to look similar based on the orientation of the strata and the angle of bolts installation (Figures 15e & 15f and Table 11). In the meantime, the last simulation was performed at the bolt angle of 90 degrees, where the results of the simulation showed that the FS of the roof wedge had become 3.667 which were the highest in all simulations. This result could mean that for the roof to be more stable the block should

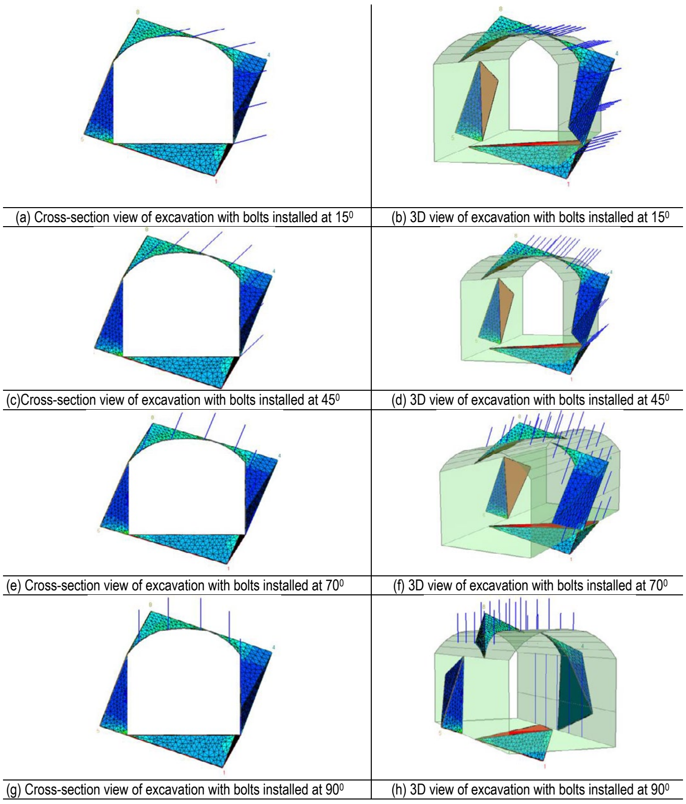


Figure 15. Simulated underground excavation with installed bolts using varying cable bolting.

be supported with roof bolts installed at an angle of 90 degrees (Figures 15g & 15h and Table 12). As indicated above, the purpose of this section was to validate the significance and relevance of the proposed criterion. Indeed, cable bolts which had been installed based on common practice (normal to opening section) did not always perform all their functions as they were not installed to full capacity. In simple terms, it can be argued that, installation procedures had much more influence on failure of the roof bolts in many occasions where the strata orientation and thickness were not taken into consideration. Therefore, the proposed criterion comes with the possibility to verify and understand the best orientation in which the support system could be installed and whether the criterion can work with other sophisticated methods.

Comparison with existing results

The literature body reveals that there have been numerous support design methods, some of which are designed by precedent rules, rock mass classifications, 95 percentiles and Rules of thumb. In this section a close look into the previous method compared with the present proposal was done in an attempt to bridge the gap or avoid repetition of what has been documented already.

In short, the first method of support design/reinforcement design which has been extensively applied in many studies is the Design by Precedent Rules. The precedent rules were developed by Lang through the use of back analysis of reinforcement which were implemented and found to be effective in civil engineering structures in the late 1950s. It is evidenced from the literature that the precedent rules do not incorporate the rock mass quality and stress regimes related to the excavation. Arguably, the method does not provide an element or criterion that could be utilized to measure the connecting function of the bolts or the effective length of the bolts, which is the focus of this study. In short, the method could be summarized by the following Equations 5, 6 and 7 below.

$$L_{Min} = \text{The Largest of } 2s,\ 2b,\ \frac{B}{2}\ (B < 6m) \tag{5}$$

$$L_{Min} = \text{The Largest of } 2s,\ 2b,\ \frac{B}{4}\ (B > 18m),\ +\frac{H}{5}(H > 18m) \tag{6}$$

Table 10. Simulated results of the wedge with the excavation supported by bolts installed at 45 degrees.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	1.835	23.052	9.824
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 & 2

Table 11. Simulated results of the wedge with the excavation supported by bolts installed at 75 degrees.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	3.240	23.052	9.819
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 &2	Sliding on Joints 1 &2

Table 12. Simulated results of the wedge with the excavation supported by bolts installed at 90 degrees.

Criteria	Roof Wedge (8)	Lower Left Wedge	Upper Right Wedge
Factor of Safety	3.669	23.052	9.031
Weight of the wedge (MN)	0.055	0.0164	0.262
Mode of failure	Falling Wedge	Sliding on Joints 1 & 2	Sliding on Joints 1 &2

$$S_{\max} = \text{The Smallest of } \frac{L}{2} or 1.5b \tag{7}$$

Where L is the bolt length, S is the bolt spacing, b is the mean block width, B and H are the excavation width and height, respectively

Although this method has been popular, there are other encouraging studies which have been proposed to estimate the length of the bolts, in which some form the back bone of the Precedent methods while others were intended to modified the precedent rules [30-32]. In summary, the proposed bolt length by the above-mentioned scholars are presented in Equations 8, 9, 10, 11 and 12 below respectively;

$$L = 0.3B \tag{8}$$

$$L = 1.829 + 0.0131B^2, \geq 3b \tag{9}$$

$$L = 0.25\ to\ 0.30B \tag{10}$$

$$L = 0.35B \tag{11}$$

$$L \quad 0.1\ to\ 0.5\ H \tag{12}$$

Furthermore, studies on bolts length have been reported in large numbers due to the fact that the above-mentioned methods were presenting limitations. Therefore, studies such as those by Coates and Cochrane, Farmer and Shelton, USACE Laubscher, and Choquet and Hadjigeorgiou [33-35] strove to bridge the gap. The encouraging result that summarizes the above-mentioned input was discussed by Choquet and Hadjigeorgiou [34] who outlined that predictions of reinforcement lengths from the above-mentioned studies present reasonable results but complicated expressions are not required nevertheless, a new reinforcement system has been rapidly designed and yet these reinforcements have been failing in most areas. Meanwhile the effect effective length of the bolts related to the connecting function of the bolts was not assessed in most cases or there was no criterion to assess it. Thus, the present study was mainly intended to address this aspect.

Furthermore, the design by Rock Mass Classification based on the Q system has been also reported to be utilized in many studies. Nevertheless, the pioneers of this method indicated some cardinal note that the method "should be used with caution, particularly in regard to some of the design expressions that have been developed". This note was based on the factor that the method was originally developed with the use of a database of civil engineering tunnels at a shallow depth. Nevertheless, several scholars [36,37] have striven to improve the methods, with the recent update by Hoek and Diederichs [38]. In summary, the methods still could not have outlined or suggested criteria to determine the effective bolt lengths relative to the connecting function of the bolts. In the meantime, other methods such as 95 percentiles have been developed but the method is purely dependent on the historical database of the Fall of Ground thickness. Meanwhile the rules of thumb have been there but they are based on the size of the excavation, meaning that the methods were not intended to address the connecting function of the bolts through the determination of the effective length of the bolts. In summary, this study does not replace the previous methods, but rather complements them in that they are useful in the determination of other functions of the bolts. However, it appears that the great encouraging work conducted from the past has ignored the quantification of the connecting function of the bolts through the determination of effective bolt length. The current study appears to present new knowledge that bridges the gap which has been there for many decades. Nonetheless, it is not expected that the proposed method could solve every problem in the world, nor is it perfect, but it is a method which could be further developed using other sophisticated methods.

Conclusion

The experimental investigations on the performance of the 38 tons Mechanical Anchor of 18 mm diameter, 4.5 m length with six strands has shown that the bolt has the ability to withstand the initial minimum yielding load of 332.4 kN with a displacement of 47 mm and a maximum peak load of 380 kN with a displacement of 79 mm. The laboratory tests were found to differ with the desired performance of the bolts as per manufacturing specifications. Nevertheless, some tests have shown a slightly different performance of the bolts as compared to the desired performance. It can then have concluded that the slight difference can be due to slipping or manufacturing error when designing different strands.

In order to understand the actual performance of the bolts in some real situations, an underground situation was simulated using Finite Element Method (Unwedge). The purpose of the simulation was to identify best bolt spacing that could be used to stabilise the excavation. Likewise, the common support installation principles were followed where it was noted that when the bolts are spaced at 1 m by 1 m in plane and out plane respectively, the Safety Factor among the wedges increases, meanwhile the stability of the excavation increases as well. A further step was undertaken to identify the distribution of tensile failure of bolts along wedges as the spacing of the bolts vary. The model has revealed that the number of bolts that fail under tensile failure mode reduces with an increase in bolt spacing. Although the performance of the bolts appeared to be excellent, the common change that concerns geoscientists and rock mechanic engineers is that, every now and then new bolts have been installed but still fail rapidly. This question has posed a serious challenge to the study prompting the researcher to further suggest a probabilistic analysis of failure of the cables based on the effective lengths of the installed bolts with varying orientation and thickness of strata. The developed criterion has the ability to evaluate one of the important functions of the bolts which has been ignored in many studies. However, it appears that three functions of the bolt have been well established in terms of assessment while connecting them remains unestablished.

The developed criterion has proven that indeed if the understanding of strata orientation and thickness is not well established, the performance of the installed bolts cannot be justified because there is one missing function of the bolts. Furthermore, the criterion also revealed that it is possible to identify the total effective lengths of the installed bolts along the ring. As a result, one could easily deduce if the ring is over supported or under supported. In the meantime, the criterion emphasises the view that the installation of the bolts should be based on the strata conditions (orientation and thickness). This clearly means that the excavation might not be supported by bolts of the same length or bolts that are installed at the same orientation to ensure the stability of the excavation. It is believed that this criterion can reduce rapid failure of well performing bolts (based on their laboratory, numerical and underground tests (pull tests and torque tests). Furthermore, it is important to indicate that so far the criterion seems to be more suitable in layered rock mass. However, further investigation is in progress to develop a specific criterion that could be suitable for any rock mass composition and implementation of other sophisticated methods to improve the criterion.

Conflicting of Interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication. Furthermore, there has been no financial support given to influence the outcome of this work.

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The author would like to say rest in peace to all mine workers who lost their life as a result of rockburst accidents.

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