The effect of different rock mass properties on deformation distribution detected with intelligent rock bolts in underground mining

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ABSTRACT: Significant changes in stress distribution are caused by the mining excavation process, which could lead to instabilities. The conventional approach involves the installation of rock bolts along with other support measures. Technological advancement enables upgrading these bolts with low-cost sensors for measuring deformation and monitoring the overall bolt condition. The objective of this study is to show the potential of such intelligent rock bolts. To achieve this, we analyzed deformation readings obtained from simulated intelligent bolts in a simplified mining scenario, considering the effects of joint spacing, orientation, and the K factor. We used Itasca's Software 3DEC to simulate data acquisition based on standard measurement bolts which are already available but differ in measurement capacity from the new development proposed here. This approach has the potential to identify deformation patterns associated with specific failure mechanisms related to different geological structures.

Keywords: Intelligent rock bolts, numerical modelling, deformation measurement, discontinuities.

1 INTRODUCTION

A rock bolt's primary function is stabilizing the rock mass and increasing safety around the excavation (Hoek et al. 1995). There are different anchoring types of bolt systems mechanical, grouted, or frictional (Hoek and Brown 1980). One of the issues with grouted rebar bolts is the possibility of failing without leaving visible signs, due to the residual strength of the grout. To overcome that, sensors can be installed along the bolt. The basic information that could be gained is whether the bolt has failed or not. However, to use an intelligent bolt to its full potential, there is a need to investigate possible long-term applications stemming from the deployment of numerous sensors/bolts in a mine. An intelligent rock bolt system could have many possibilities; one is to measure deformation along the tendon in real time. This would enable fast response in case of bolt failure. With many intelligent bolts installed throughout the mine, possible geotechnical instabilities could be assessed more precisely, and safety measures applied accordingly. For implementation on a bigger scale, intelligent bolts must be affordable, precise enough, and able to measure deformation along the tendon and transmit data in real time. This system is currently under development and not available on a big scale.

This paper aims at presenting a theoretical base for future development, i.e. availability of intelligent rock bolts on large quantities. For that, numerical modelling is used to present and describe the intelligent rock bolt concept. It also serves to illustrate a potential scenario for how bolt readings could be used to identify discontinuities. The result of the simulation is deformation data of the intelligent rock bolt – as it would be read on a real bolt. The model was simplified to focus on a single effect at a time – all of the properties aside from the joint orientation, K factor and joint spacing were kept constant. Although it is well known that the orientation of discontinuities affects the rock mass's strength (Hoek 2000), this paper has a different approach by asking whether movement of joints could be detected with intelligent rock bolts and used to back analyze discontinuity orientation.

2 INTELLIGENT ROCK BOLTS

Regular rock bolts are not providing any sort of measurement feedback. However, sensors can be installed to create "intelligent rock bolts" – a novel solution that can reinforce the rock mass, measure rock support system condition, and communicate that information to the central unit at the same time. Connecting measurement data and geological background could provide a better picture of the situation around the underground excavation (Nöger et al. 2021).

Intelligent bolts can be equipped with various sensors for measuring strain, temperature and humidity. After installation, this system requires data preparation, visualization and analysis. The precision of measurement and other possible additional information depends on the type of sensor device and the chosen measuring-support system (Song et al. 2017). When a sensor deforms, it automatically sends data to the central unit where it gets visualized to infer the condition of the rock mass in combination with a more thorough analysis. The maximum deformation of the rock bolt itself depends on its material, the coupling of the bolt with the grout-rock mass, and the type of bolt. The actual deformation it encounters depends on the rock mass and position in the profile. Choosing an appropriate type of bolting system and its position is important because depending on the chosen bolting system it will deform differently. Bolt deformation under shear stress is influenced by the inclination of the discontinuity. For example, bolt has higher capacity at an angle (bolt-discontinuity) of 45° than an angle of 90° (Lin et al. 2020).

3 NUMERICAL MODEL SETUP

Since currently there is a lack of data from the intelligent rock bolts, we use numerical modelling of the jointed rock mass to generate data for our simulation. It can provide a more detailed analysis than empirical and analytical methods, and it is more convenient to include various parameters in the calculation. However, numerical model of rock mass is not perfectly imitating reality and it requires the problem to be simplified. The main problem when modelling the rock mass is limited input parameters. For this paper, we simulated only one profile of the mine drift to focus on the concept of the intelligent rock bolt on a theoretical basis and show the end product of intelligent rock bolt with possible implementation scenarios. There is also a possibility of simulations that focuses on the modelling of the specific area, using the confidence level, as the technology advances and with that adding more precise input parameters (Shapka-Fels and Elmo 2022), which in this case is the next step once a significant amount of real intelligent rock bolts are installed in mining sites and measurements are available for calibration and comparison.

Most of the parameters are kept constant throughout the process in order to simplify the problem. The idea of how to better understand the data gathered from the simulated intelligent rock bolts is to analyze one factor at a time and observe changes in deformation readings. This will enable observing the influence of different factors on the overall deformation pattern in the profile. Table 1 shows the variable parameters used for simulations. The model resembles a layered rock mass with distinct bedding planes. Discrete element method (DEM) was used as a numerical modelling approach where discrete blocks are applied to represent the discontinuous material. Block rotation and large displacements along discontinuities are allowed; discontinuities are regarded as block boundary conditions. When meshing into finite difference zones (based on constitutive and joint models), blocks can behave rigidly or deformably. A joint structure from the geologic mapping can be easily incorporated into the model (Zhao 2017). This kind of model was first introduced by Peter Cundall in 1971 and later developed by Cundall and Strack in 1979, furthermore by the company Itasca and applied in software UDEC and 3DEC (Itasca Consulting Group, Inc.).

Table 1. Variable parameters are used for simulating different conditions.

Variable Parameter		Used values
Joint orientation	[°]	15, 30, 45, 60, 75
K factor*	[-]	0.5, 1.0, 1.5, 2.0
Spacing between joints	[m]	1.5, 3.5, 4.5
*ratio of the horizontal effective stress, σ'h, to the vertical effective stress, σ'v		

Table 2 shows the rock mass properties used. The associated material can be compared to competent limestone with inclined bedding planes (Yang et al. 2019). Generally, the exact knowledge of rock mass properties is not so significant in this study because the focus of this paper is on deformation trends and not on the exact values.

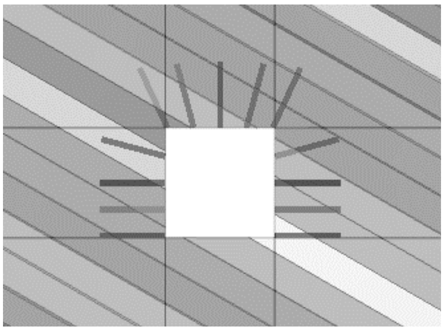

Figure 1. Numerical model showing the general setup with installed rock bolts and joints.

One profile contains 13 bolts in a position shown in Figure 1. Premade hybrid bolt code offered by the software 3DEC was used as structural support, provided with the command ‘sel hybrid command’ as a combination of reinforcement system bolts and bonding agent-grout. It contains dowels that are represented by a spring to provide resisting force to slipping. Every bolt contains 31 measuring points with specific coordinates, the software is tracking the movement of every point. In this case, we recorded starting position of every bolt and the last position after excavation.

Table 2. Constant parameters are used for simulating rock mass conditions.

Constant Parameter		Used values
Youngs modulus (rock mass)	[GPa]	70
Poisson ratio (rock mass)	[-]	0.3
Cohesion (joints)	[MPa]	0.5
Friction angle (joints)	[°]	35

4 RESULTS AND DISCUSSION

This chapter shows results of the numerical modelling explained previously, including joint orientations shown in Table 1 and parameters shown in Table 2. The primary goal of the simulation was to generate a dataset similar to those transmitted by real intelligent rock bolts. The anisotropic rock mass chosen for this purpose is directed by the dominating discontinuities with variations of angle, K factor, and spacing between joints. For simplification purposes and to observe only joint movements, the fracturing of the rock mass was not considered. Rock mass was represented by the elastic material and joints by Mohr-Coulomb failure criterion.

Figure 2 a) shows a profile with cumulative displacements of the bolt along the tendon; different colors represent bolt deformations from different joint angles, the K factor in this graph is 2.0 and the spacing between joints is 1.5 m. All sidewall bolts clearly show deformations that can be interpreted as being a joint intersecting the individual bolts associated with a significant deformation increase in the spot nearby the joint. From these readings we could already assume where the joints around this excavation are, and their approximate orientation. Another thing that can be seen from these deformations is that deformation of the joint close to 60° angle is higher compared to other presented angles. That can be explained by the angle between the bolt and the joint itself, the same effect is investigated in the laboratory by Lin et al. (2020). Figure 2 b) shows the deformation of the middle roof bolt. The red color represents the bolt from the simulation with 45° joints and cyan 30°. There are clear peaks where joints are intersecting the bolt, in the case of 30° two joints are crossing the bolt, and in the 45°, there is only one. When these peaks in the profile are connected angle and position of the joint can be assumed.

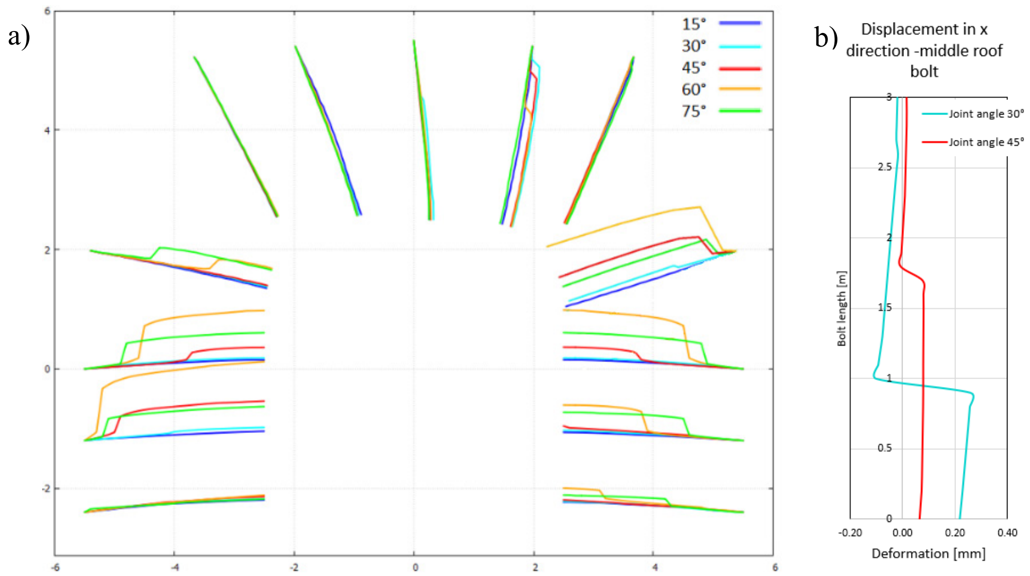

Figure 2. a) cumulative displacement along the bolt in the profile for the joint orientations 15°, 30°, 45°, 60° and 75°, and b) x-displacement of the middle roof bolt with the joint orientation of 30° (cyan) and 45° (red), both graphs have K factor 2.0 and spacing 1.5 m.

4.1 Influence of the discontinuity orientation on the deformation readings

This chapter shows the influence of different joint angles on the strain along the bolt. Figure 3 shows joint orientations of a) 45° and b) 60° with K factor 1.0, dotted grey backgrounds represent the simulated joints, and the overlays represent the strain along the bolt (green line) and initial position of bolts (black line). Here we can see where the joints are, only by observing peaks in the strain displayed along the bolt and determine the joint orientation by observing these graphs and interpreting patterns among adjacent bolts. To explore the influence of the joint orientation on the deformation readings and strain along the bolt we were changing the orientations of the joints and plotted out readings from the bolts. The strain printed along the bolt clearly shows peaks around the joint bolt intersections. From these peaks, joint orientation and position can be approximated.

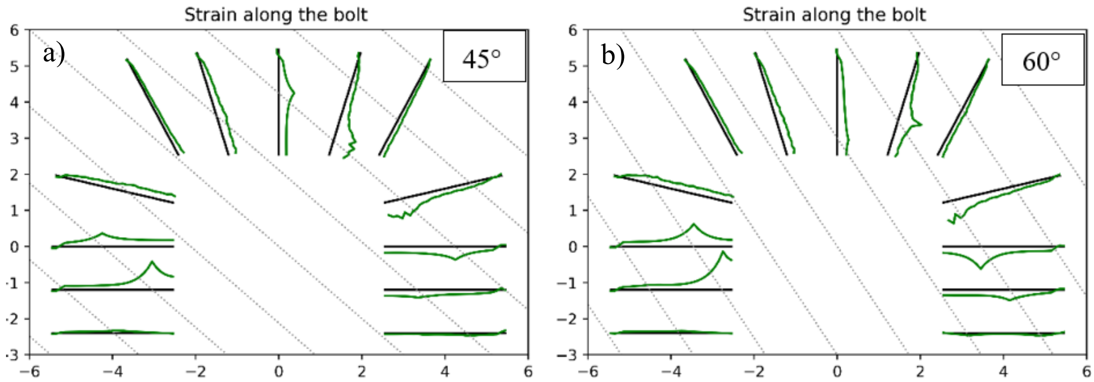

Figure 3. Strain along the bolt in the profile from different joint orientations, K factor 1.0, join spacing 1.5 m, a) strain along the bolt with 45° joint angle, and b) strain along the bolt with 60° joint angle.

4.2 Influence of the K factor on the deformation readings

This chapter shows how the K factor affects strain along the bolt in the excavation profile. For the K factor of 0.5 strain is smaller and peaks in the places of joints are not as clear, as they are in other cases where K is 1.0, or more. To explore the influence of the K factor on the deformation readings and strain along the bolt we simulated mentioned conditions and plotted out readings from the bolts. Figure 4 a) shows strain along the bolt when the K factor is 0.5 (green) and 1.5 (blue) and b) shows the displacement of the middle roof bolt when the K factor is 0.5 and 1.5, respectively. Both graphs show significant change near the joint.

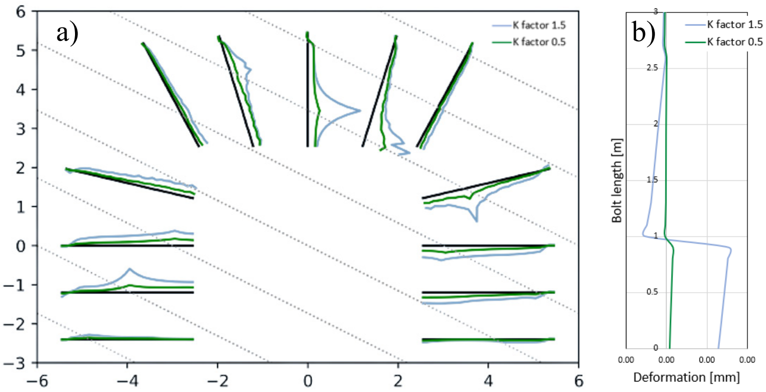

Figure 4. a) Influence of the change in K factor on the deformation readings with 30° joint in the whole profile displayed with strain, and b) deformation of the middle roof bolt, spacing between joints is 1.5m.

4.3 Influence of different spacing on the deformation readings

Considering spacing, the scale effect is a very important factor. Smaller spacings (1.5m and 3.0m in the simulations, respectively) show significant peaks in strain. However, 4.5m spacing cannot be detected with this bolt length anymore. The strain printed along the bolt shows that spacing between the joints cannot always be assumed, especially in cases where joints have spacings larger than the bolt length. Usually, the deformation of the joint closest to the excavation is higher than that of the ones deeper in the rock mass. This makes detection of the spacing between joints more difficult. However, it could be done by observing deformations of all bolts in the whole profile and with assumptions that joints are continuous and persistent. In our observations, a spacing of 1.5m showed the most apparent results in term of detecting joint spacing, because of the more favorable scale.

5 CONCLUSION

Intelligent rock bolts are a valuable tool for monitoring and increasing the stability of underground excavations. This paper shows the concept of the intelligent rock bolt and its potential application. However, these are simplified conditions in a virtual environment with known and limited input parameters. That will not always be the case with the results from the intelligent rock bolts deployed in a real mining environment. This study is a first step towards exploring the effect of certain rock mass parameters on the measurement data generated by intelligent rock bolts. The next step would be determining how to improve the corresponding estimations in terms of support and stability of the excavations. The results presented show that observing peaks in the deformation or strain gained from intelligent bolt joints could theoretically be observed, and by connecting them in one profile orientation can be revealed. The K factor influences the magnitude of deformations and patterns in the profile. The spacing between joints could be determined only if sufficient intersections with bolts are available for reliable interpretation of joint continuity. Otherwise, it could be approximated from the overall profile measurements. In the end, intelligent bolts will give some more insight into the rock mass that could potentially increase the safety of the mine, by providing more detailed input parameters for mine planning and geomechanical assessment. For more precise and realistic results there is a need for further testing and investigation. A big advantage would be the installation of real intelligent rock bolts on site to do more analysis of the data in comparison to the realistic environment and in that way, results of simulations could be verified. This paper showed the concept of intelligent bolts and their future potential. With more technological advancement there will be a possibility to precisely locate instabilities and possibly even predict them.

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