Rock Reinforcement Data for Analysis and Design

John Hadjigeorgiou(✉)

University of Toronto, Toronto, ON, Canada
John.Hadjigeorgiou@utoronto.ca

Abstract. This paper discusses the challenges of selecting representative ground support data to investigate the influence of reinforcement in design of underground excavations in hard rock. This is presented with reference to a limit equilibrium rigid wedge analysis. The case is made that the use of "typical" or "default" values introduces a significant degree of uncertainty which may not be always acknowledged. This is highlighted with reference to friction stabilizer data. The choice of reinforcement input data can have a significant impact on the interpretation of the results in any numerical analyses.

Keywords: Rock Reinforcement · Data Quality · UnWedge

1 Introduction

1.1 Ground Support Benchmarking

The design of ground support for underground excavations in rock employs a range of analytical, empirical, and numerical methods. In mining, however, the design of ground support evolves from a preliminary/initial design based on field observations. In this context the initial design can provide a reference point for subsequent modifications. The design process, and the resulting ground support guidelines, are typically documented in the mine's Ground Control Management Plan (GCMP).

A review of 92 GCMPs by Potvin and Hadjigeorgiou [1], mainly from Australia and Canada, indicated that close to 75% of the mines had used the Q-system by Barton et al. [2] to characterize the rock mass and the empirical ground guidelines for tunnels proposed by Grimstad and Barton [3] to develop an initial design. A review of the actual design recommendations revealed that there were significant inconsistencies between the recommendations and what was used, Potvin & Hadjigeorgiou [3, 4]. A major reason for this discrepancy is that the Grimstad and Barton [3] ground support recommendations were based on civil tunneling case studies, large scatter of bolting patterns, strong bias towards the use of fibre reinforced shotcrete as surface support, etc. To overcome these limitations Potvin and Hadjigeorgiou [4] used the database from the 93 GCMPs of underground mines to develop preliminary ground support guidelines, at the feasibility and implementation stages. The Potvin Hadjigeorgiou recommendations

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 146–155, 2023.
https://doi.org/10.2991/978-94-6463-258-3_15

are only applicable for mining drives for defined as “normal” ground conditions that exclude seismically active mines or squeezing rock conditions.

Another observation from the Potvin and Hadjigeorgiou benchmarking study was that 56% of the GCMPs also referred to the use of the UnWedge limit equilibrium software [5] at some point for ground support design. A closer scrutiny of how UnWedge is used was the motivation for this discussion paper. The focus of this work is on the selection of reinforcement data and not on determining the structural regime (joint sets, mechanical properties of joints, etc.). The quality of ground support input data has not received the same level of attention as for geomechanical data.

This paper is an attempt to highlight some issues in the selection of ground support input data, specifically as related to reinforcement. This paper highlights some issues specific to the selection rock reinforcement data required for an UnWedge type of analysis [5]. It is the author’s experience that quite often the choice of non-representative reinforcement input data can potentially lead to misleading results.

1.2 Underground Wedge Analysis

Irrespective of the design method used, confidence in the results is clearly a function of whether the failure mechanisms can be adequately captured by the analysis tools. Lorig and Varona [6] recommended a number of appropriate analysis methods for each mode of tunnel instability. For structurally controlled instability they suggested that limit equilibrium techniques (e.g., UnWedge) are appropriate analytical tools.

The choice of UnWedge can be justified for structurally defined wedge analysis if the inherent limitations and assumptions are understood. The inherent assumptions are well defined in the supporting documentation [5]. In addition, the software facilitates both sensitivity and probabilistic analyses. As in all numerical tools, the analysis and interpretation are controlled by the quality of the input data. In a limit equilibrium model geomechanical data are critical in defining the demand, while ground support data are important in establishing the capacity part of the limit equilibrium equation.

The behavior of reinforcement and surface support elements can be determined using laboratory and/or in situ tests. Although laboratory tests can provide more repeatable results, they do not capture the in-situ behavior of the installed ground support in different ground conditions. Although it is possible to investigate different loading mechanisms the majority of ground support data is obtained from axial tests in the laboratory and in the field.

2 Rock Reinforcement in UnWedge

2.1 Reinforcement Mechanisms

Unwedge is an easy-to-use numerical analysis tool that is widely employed in underground mines. It can be used to gain a better understanding of the interaction of critical parameters such as excavation size, relative orientation with respect to geological structure, and the influence of material properties etc. Its inherent assumptions and limitations are well documented [5].

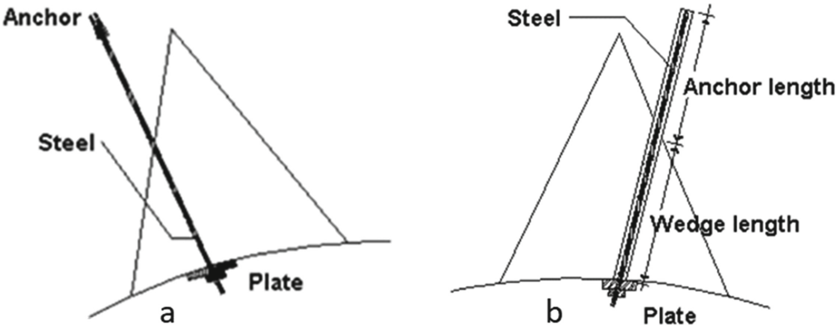

Fig. 1. Representation of reinforcement mechanisms in UnWedge, [5]

The introduction of reinforcement elements in Unwedge is very well documented. There are two distinct representations, Fig. 1. The first model assumes a point anchoring mechanism and the second one relies on the mobilization of the bonding strength of the bolt. A distinction is made between wedge length, i.e., the part of the rockbolt within the structurally defined wedge, and the anchor length which is part of the rockbolt beyond the wedge. This is equivalent to the embedment length bond described by Potvin and Hadjigeorgiou [7] necessary to anchor the loosened material in good ground. In the anchor length configuration, (e.g., grouted rebars, friction stabilizers, cable bolts, and expandable rockbolts) the bond capacity per unit length is often the critical parameter in the design rather than the nominal capacity of the bar itself. These reinforcement mechanisms are well captured in UnWedge.

2.2 Reinforcement Options and Characteristics

The last thirty years have seen the development of several new rockbolts capable of greater energy absorbing capacity. These are often referred to as yielding rockbolts. The discussion in this paper is limited to conventional rockbolts where the emphasis is on capacity as opposed to greater deformation capacity.

The rockbolt types and the required input parameters in UnWedge are reproduced in Table 1. Although the software interface refers to “Split Set” and “Swellex” rockbolts these are proprietary names for rockbolts from two suppliers. Since the expiration of the respective patents these rockbolt types are now available from a large group of suppliers. Swellex is one example of what are commonly referred to as expandable rockbolts. Other products in the same category include Omega bolts, Python, etc. Similarly, Split Set are usually grouped under friction rock stabilizers, and they are also available by multiple suppliers. Although it is still common to refer all expandable rockbolts as “Swellex” this fails to recognize that there are significant variations in different products.

Cable bolts are also available in plain strand and modified geometry with significantly different behavior. Grouted dowel, typically referred to rebars, are also available from multiple suppliers under a range of products, steel grade, diameter, etc.

Although it is often assumed that all rockbolts in the same category have similar properties this is not always the case. There can be significant variations in steel quality as well as bolt configuration that can influence the performance of the rockbolts.

Table 1. Reinforcement options and characteristics in UnWedge

Reinforcement	Anchor Capacity	Plate Nut thread capacity	Steel Tensile capacity	Bond Strength	Bond Length
Mechanically Anchored	X	X	X		
Grouted Dowel		X	X	X	X
Cable Bolt		X	X	X	X
Split Set		X	X	X	X
Swellex		X	X	X	X

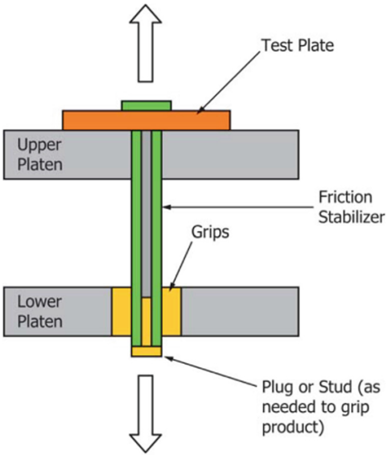

Fig. 2. Generalized test apparatus for friction stabilizers

2.3 Rock Reinforcement Tests

It is expected that the mechanical characteristics of reinforcement elements and accessories are established following established procedures, e.g., the ASTM Designation F432-19 [8]. These guidelines also provide compliance requirements which may be part of a company's QA/QC.

Typically, laboratory tests are undertaken for all rockbolt types. For example, Fig. 2 reproduces the testing configuration for friction stabilizer. Figure 3 is an example of a test to establish the capacity of a steel plate. In-situ pull tests are used to establish the bonding strength of grouted reinforcement, friction stabilizers and expandable rockbolts (Fig. 4).

2.4 Selection of Reinforcement Data

The responsibility for selecting meaningful input data rests with the person conducting the analysis and not with the software supplier. It is also implied that the limitations in

Fig. 3. Steel plate load test

Fig. 4. In situ rockbolt pull test set-up

the quality of reinforcement data are understood, to appreciate the level of confidence in the results of any analysis.

Specific to the use of rock reinforcement, the UnWedge software provides three options to the user. The first option is the use of "default" values while the second option provides access to data from one supplier, and the third option is user defined data. It is strongly recommended that the user relies on data from laboratory and field tests. A review of these data will allow the user to identify consistency of results, variations in performance in different ground conditions, QA/QC etc. In any case it is a QA/QC requirement that a defined number of pull tests are undertaken at each mine site.

Based on interactions with multiple mines in Canada and Australia, review of consulting reports, feasibility studies, etc., it is the author's experience that many users employ "default" values to represent the capacity and strength of ground support elements in UnWedge. When challenged, this is rationalized by comments such as these are "typical values", "good enough", "industry standards", "it is only a preliminary analysis" and "we do not have better data". It is the author's opinion that none of these responses are justified for any meaningful analysis. Of further concern is the observation that the reinforcement data, used in "preliminary" analyses, tend to become the site "standard". This can have significant implications on the perceived performance of ground support in fall of ground investigations.

A smaller number of the users consulted indicated that they use "typical supplier data". Again, it is important to establish whether the supplier data is "typical" or a "minimum value". It is also recognized that there are variations in how different suppliers report data. Establishing the mechanical properties of a rockbolt are often part of the QA/QC at the manufacturing plant. It is generally a straightforward process to establish whether the provided rockbolts meet the compliance criteria of the supplier or the mining company. However, unless there are site specific pull tests it is difficult to determine the confidence in provided "bonding strength" as it is a function of ground conditions. This can vary considerably between competent rock and poor rock masses.

Table 2 reproduces the default rock reinforcement values accessible within UnWedge as of February 2023. Anchor and tensile capacity are reported in metric tonnes and bond strength in tonnes/m. For ease of comparison with supplier data, the default values (tonnes, tonnes/m) are converted to kN and kN/m and reproduced in Table 3. The generic terms are used in Table 3, e.g., expandable as opposed to Swellex bolts. A comprehensive review of the characteristics of each reinforcement type is outside the scope of this paper. This is readily available in Potvin and Hadjigeorgiou [7]. The following high-level comments are provided to illustrate the need for caution in the use of default values.

The capacity of mechanically anchored rockbolts is controlled by the ground conditions and the shell type. Correct placement and adequate tensioning are necessary to meet the design requirements. Bolts installed at an angle less than 80° results in a significant loss of tension. Mechanically anchored rockbolts are susceptible to loss of tension due to blasting vibrations. Consequently, it is critical to undertake pull tests to establish the capacity of anchored mechanical rockbolts.

Table 2. Default reinforcement values in UnWedge reported in metric tonnes

Reinforcement	Anchor Capacity (tonnes)	Tensile Capacity (tonnes)	Plate Capacity (tonnes)	Bond Strength (tonnes/m)
Mechanically Anchored	10	10	10	-
Grouted Dowel	-	25	10	35
Cable Bolt	-	20	10	35
Split Set	-	10	0	3
Swellex	-	10	0	12

Table 3. Default reinforcement values in UnWedge reported in kN

Reinforcement	Anchor Capacity (kN)	Tensile Capacity (kN)	Plate Capacity (kN)	Bond Strength (kN/m)
Mechanically Anchored	98.07	98.07	98.07	-
Grouted Rebar	-	245.11	98.07	343.23
Cable Bolt	-	196.13	98.07	343.23
Friction stabilizer	-	98.07	0	29.41
Expandable	-	98.07	0	117.68

Grouted rebar rockbolts are available in different diameters and steel grade. This invariably has a direct impact on their reported capacity. A further consideration is the difference in material properties between the yield and tensile strength of the solid rebar and the threaded rebar. For example, for a given steel grade the tensile capacity can be as much as 20% lower for the threads as opposed to the body. Arguably the bonding strength may be similar assuming that there is good mixing. In the absence of on-site pull tests, it is difficult to establish the bonding strength of the cement or resin grouted rockbolts.

There are fundamentally two basic configurations in cable bolts. Simple strand and modified geometry. Assuming consistent quality control, modified geometry cable bolts will provide higher capacity. The use of typical data may arguably be defensible, as a preliminary design or at PFS or FS level analysis where there is no data, but it is difficult to defend in an operating mine. It is definitely not acceptable when the analysis is part of a failure investigation.

The challenge of selecting appropriate reinforcement data is illustrated in greater detail with reference to friction stabilizers. The tensile capacity of friction stabilizers can vary significantly as a function of material properties and bolt diameter. Table 4 summarizes the data from two suppliers of friction rock stabilizers in the Sudbury basin, [8]. It is interesting that, while both suppliers report minimum ultimate tensile strength values, only supplier A provides a “typical value. None of the suppliers provide bonding strength values, which is not surprising given that these vary significantly during pull tests. A large number of consulted users indicated that they rely on the UnWedge default value for friction stabilizer bond strength as this is the” industry standard”. This is clearly not the intent in providing “default values”.

As shown in Tables 2 and 3 the bond strength default strength for friction stabilizers is 3 tonnes/m or 29.41 kN/m. It is interesting that this is consistent with the 31.9 kN/m value reported by Tomory et al. [10] based on a statistical analysis of pull tests. In a more recent study by Nicholson and Hadjigeorgiou [9] of pull tests in the Sudbury basin a significantly higher value of 38.9 kN/m was obtained. This variation is attributed, to a degree, that a large majority of the friction stabilizers in the Tomory et al. [10] database were installed using jacklegs. As shown in Fig. 5 the use of a bolter results in higher

Table 4. Supplier data for friction stabilizers, [8]

Nominal Diameter	33 mm		35 mm		39 mm		46 mm	
Supplier	A	B	A	B	A	B	A	B
UTS min (kN)	71	89	71	89	89	102	133	145
UTS typical (kN)	107	-	107	-	125	-	178	-
Initial capacity (kN)	27–54	27–54	27–54	27–54	27–54	27–54	54–89	54–89
Elongation (%)	-	21	-	21	-	21	-	21
Recommended drill bit diameter (mm)	30–33	31–33	32–35	31.8–33.3	35–38	35–38	41–44	41–45
Slot width (mm)	11–16	-	15–19	-	14–19	-	21–23	-
Available lengths (m)	0.5–3.1	0.45–2.4	0.5–3.1	0.45–2.4	0.5–3.1	0.45–3.0	1.5–4.9	0.9–3.7

bonding strength as opposed to manual installation. Of course, there are significant variations as a function of bolt diameter, Fig. 6, ground conditions etc. Recent years have seen the introduction of 46 mm diameter friction stabilizers.

A ground support system requires that both surface support and reinforcement elements work as a system. The discussion in this paper did not address the role of mesh or shotcrete as part of the system. It is important to comment on the role of plates as

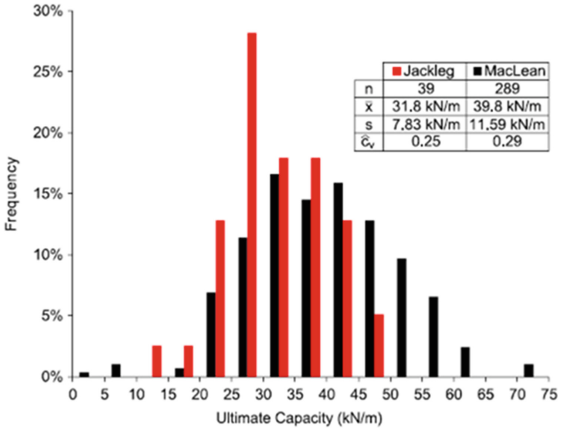

Fig. 5. Comparison of friction stabilizers installed by jackleg vs bolters [9]

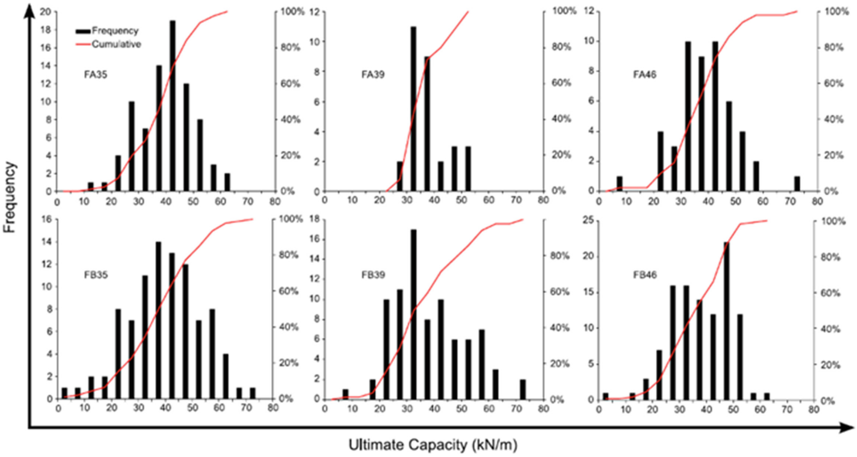

Fig. 6. Capacity distributions for friction stabilizers from two suppliers [9]

they constitute part of the reinforcement system. In practice the objective is to select an appropriate plate that will ensure good load distribution. Assuming that a plate has zero capacity as shown in Tables 2 and 3 for a number of rockbolts is misleading. In practice all friction stabilizers and expandable rockbolts are installed with a plate.

3 Conclusions

The primary challenge in any analysis is in selecting an appropriate tool that captures the anticipated or observed failure mechanism. In a low stress structurally defined rigid wedge, Unwedge provides such a tool.

The second step is ensuring that input data is representative. This includes adequate information on the geomechanical conditions, stress regime, excavation dimension and shape etc. Quality ground support data are a prerequisite for any meaningful stability excavations in excavations in hard rock.

This paper highlights the importance of recognizing the variations in capacity of different reinforcement elements. Although the recommendations from this paper may appear self-evident it is surprising how often users rely on default values. This can result in misleading interpretation of the provided capacity.

It is important to clearly recognize the limitations of any assumptions specific to ground support and their safety implications. Ultimately, however, it is the responsibility of the design engineer to justify the choice of ground support input data.

Acknowledgments. The intent of this paper is to generate a discussion on the selection of rock reinforcement data in an analysis. The discussions with colleagues at different organizations over many years is greatly appreciated.

References

1. Potvin Y. and J. Hadjigeorgiou (2015). Empirical ground support design of mine drives. Proc. Underground Design Methods 2015, Y Potvin (ed.), Perth, pp. 419–430.
2. Barton N., R. Lien. & J. Lunde 1974. Engineering Classification of Jointed Rock Masses for the Design of Tunnel Support. Rock Mechanics, 6, p. 189–239.
3. Grimstad, E. & Barton, N. 1993. Updating of the Q-System for NMT. Proceedings of the International Symposium on Sprayed Concrete - Modern Use of Wet Mix Sprayed Concrete for Underground Support, Fagernes, 1993, (Eds Kompen, Opsahl and Berg. Norwegian Concrete Association, Oslo.
4. Potvin Y. & J. Hadjigeorgiou (2016). Selection of ground support for mining drives based on the Q-System. Ground Support 2016, the Eighth International Symposium on Ground Support in Mining and Underground Construction, Luleå, Sweden.
5. UnWedge – Underground Wedge Stability Analysis. RocScience. February 10, 2023.
6. Lorig, L. J. & P. Varona (2013), ‘Guidelines for numerical modelling of rock support for mines’, in Y Potvin & B Brady (eds), Proceedings of the Seventh International Symposium on Ground Support in Mining and Underground Construction, Australian Centre for Geomechanics, Perth, pp. 81–106.
7. Potvin Y. J. Hadjigeorgiou (2020). Ground Support for underground mines. Australian Centre for Geomechanics p. 520.
8. ASTM Designation: F432 – 19. Standard Specification for Roof and Rock Bolts and Accessories. ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States
9. Nicholson L. & J. Hadjigeorgiou (2018). Interpreting the results of in situ pull tests on Friction Rock Stabilizers (FRS). Transactions of the Institutions of Mining and Metallurgy: Section A. Mining Technology, 127:1, 12–25.
10. Tomory, P., Grabinsky, M., Curran, J., and Carvalho, J. (1998). Factors influencing the effectiveness of Split Set friction stabilizer bolts. CIM Bulletin, 91:205–214, 1.