Evaluation of different methods for determining rock masses stiffness

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ABSTRACT: Surface and underground excavations in rock are designed for ensuring stability. In many tunnel, underground cavern and rock slope projects, designing to acceptable deformation limits or tolerances is just as critical as stability. Understanding rock mass stiffness and deformability becomes an integral part of ground characterization and subsequent design. Deformation moduli for rock masses are often estimated using empirical methods that may have been developed from limited data, specific ground conditions, and provide a single result representing the behavior of an isotropic, homogeneous rock mass. However, most rock masses are heterogeneous or anisotropic, and deformation moduli can vary significantly depending on the loading direction. This paper reviews available empirical methods for evaluating deformation moduli and compares them with an observational model from monitored slope deformations in siltstones, sandstones and quartzite at a surface and underground mine in Australia.

Keywords: Rock mass stiffness, empirical methods, deformation modulus, E_m.

1 INTRODUCTION

Deformation moduli of intact rock and rock masses are affected by several factors including scale effects (e.g. intact rock versus rock mass; and the scale of the rock mass from a small underground excavation to a large slope), confining stresses, anisotropy and loading direction, temperature, water content and calculation methods such tangent versus secant moduli (Zhang, 2017).

Recent comparative studies on the empirical estimation of deformation moduli have a general consensus that is very difficult to decide which empirical approach is most accurate since they are based on databases of vastly different ground types and are largely dependent on subjective rock mass classifications (Kayabasi et al. 2003; Birid, 2014; Alemdag et al. 2015; Vasarhelyi & Kovacs, 2016; Zhang, 2017; Kayabasi & Gokceoglu, 2018).

In this paper, empirical estimations of rock mass deformation moduli (E_m) are compared against observational models within siltstones, sandstones and quartzites at Telfer gold mine, which is located within the Great Sandy Desert in Western Australia, approximately 485 kilometers southeast of Port Hedland. Telfer has surface mining operations across multiple open pits and underground operations using open stoping and sub-level caving methods (Nicoll et al. 2017).

2 ROCK MASS STIFFNESS ESTIMATION

Over the last 50 years, empirical methods for estimating rock mass stiffness or deformation moduli have been derived from intact rock modulus (E_i), rock quality designation (RQD), rock mass rating (RMR), geological strength index (GSI), Q-system (Q), P-wave velocity (V_p) and the unconfined compressive strength of intact rock (σ_c).

Equations 1-3 estimate E_m from E_i and RQD (Coon & Merritt, 1970; Gardner, 1987; Zhang & Einstein, 2004). Equations 4-15 estimate E_m from RMR, which refers to RMR_{89} (Bieniawski, 1989) except where otherwise stated as RMR_{76} (Bieniawski, 1978; Serafim & Pereira, 1983; Aydan et al. 1997; Gokceoglu et al. 2003; Nicholson & Bieniawski, 1990; Mitri et al. 1994; Ramamurthy, 2004; Sonmez et al. 2006; Chun et al. 2006; Galera et al. 2007; Shen et al. 2012; Kavur et al. 2014). Equations 16-21 estimate E_m from GSI and related parameters from the Hoek-Brown failure criterion (Hoek & Brown, 1997; Zhang, 2017; Gokceoglu et al. 2003; Hoek & Diederichs, 2006; Sonmez et al. 2004). Equations 22-24 estimate E_m from the Q-system and V_p (Barton 1983, 2002). Equations 25-26 estimate E_m from σ_c (Rowe & Armitage, 1984; Palmström & Singh, 2001), and Equations 27-28 estimate E_m from multiple parameters (Beiki et al. 2010).

Analytical approaches and numerical simulations of synthetic rock masses can also be used to estimate deformation moduli, but results are highly dependent on several input parameters, some of which can be difficult to determine precisely (Bar, 2020).

$$E_m = E_i(0.0231RQD - 1.32) \tag{1}$$

$$E_m = 0.15E_i \tag{2}$$

$$E_m = 10^{(0.0186RQD-1.91)}E_i \tag{3}$$

$$E_m = 2RMR_{76} - 100 \tag{4}$$

$$E_m = 10^{\frac{RMR_{76}-10}{40}} \tag{5}$$

$$E_m = 0.1\left(\frac{RMR}{10}\right)^3 \tag{6}$$

$$E_m = 0.0736e^{0.0755RMR} \tag{7}$$

$$E_m = E_i\frac{0.0028RMR^2+0.9e^{\frac{RMR}{22.82}}}{100} \tag{8}$$

$$E_m = E_i\frac{1-cos\left(\pi\,x\frac{RMR}{100}\right)}{2} \tag{9}$$

$$E_m = E_ie^{(RMR-100)/17.4} \tag{10}$$

$$E_m = 10^{\frac{(RMR-100)(100-RMR)}{4000e^{-\frac{RMR}{100}}}}E_i \tag{11}$$

$$E_m = 0.3228e^{(0.0485RMR)} \tag{12}$$

$$E_m = E_ie^{(RMR-100)/36} \tag{13}$$

$$E_m = 1.14E_ie^{-\left(\frac{RMR-116}{41}\right)^2} \tag{14}$$

$$E_m = 4^{\frac{RMR-20}{20}} \tag{15}$$

$$E_m = \sqrt{\frac{\sigma_c}{100}}10^{(GSI-10)/40} \tag{16}$$

$$E_m = 0.33e^{0.064GSI} \tag{17}$$

$$E_m = 0.1451e^{0.0654GSI} \tag{18}$$

$$E_m = 100\left(\frac{1-D/2}{1+e^{(75+25D-GSI)/11}}\right) \tag{19}$$

$$E_m = E_i\left(0.02+\frac{1-D/2}{1+e^{(60+15D-GSI)/11}}\right) \tag{20}$$

$$E_m = E_i(s^a)^{0.4} \tag{21}$$

$$E_m = 40log_{10}(Q) \tag{22}$$

$$E_m = 10\left(Q\frac{\sigma_c}{100}\right)^{\frac{1}{3}} \tag{23}$$

$$E_m = 10x10^{(V_p-3.5)/3} \tag{24}$$

$$E_m = 0.215\sqrt{\sigma_c} \tag{25}$$

$$E_m = 0.2\sigma_c \tag{26}$$

$$E_m = \tan(\ln(GSI))\,log_{10}(\sigma_c)(RQD)^{\frac{1}{3}} \tag{27}$$

$$E_m = \tan\left(\sqrt{1.56+(\ln(GSI))^2}\right)(\sigma_c)^{\frac{1}{3}} \tag{28}$$

3 GROUND CONDITIONS, SLOPE PERFORMANCE AND OBSERVATIONAL MODEL TO ESTIMATE STIFFNESS

The Telfer gold deposit is hosted within Proterozoic stratigraphy of the Yeneena Supergroup. Rock types include calcareous and argillaceous siltstones, sandstones and quartzites as shown in Figure 1. Geological structure is complex and is the primary reason behind the mineralization.

Rock mass and discontinuity properties in the gold deposit are well understood (Bar & Weekes, 2017). Intact rock and rock mass strength, and to a lesser extent, bedding strength, vary with the degree of weathering and the type of alteration (clay or silica enrichment). Table 1 summarizes intact rock and rock mass characteristics.

Planar sliding along adversely oriented bedding planes within siltstone, sandstone and quartzite are the most common mode of slope instability. Underground, delamination along bedding planes may occur if unsupported stope sizes are excessive.

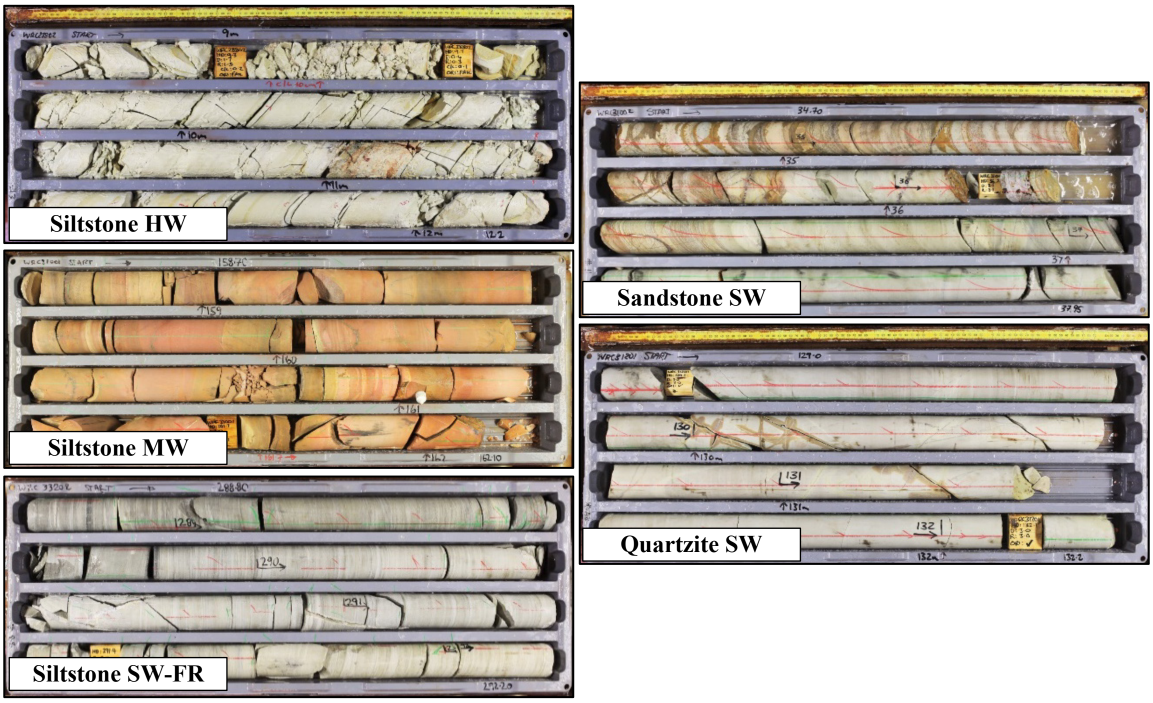

Figure 1. Examples Photographs of Typical Ground Conditions in Siltstone, Sandstone and Quartzite.

Table 1. Summary of Typical Rock Mass Conditions.

Rock Mass Conditions		Siltstone HW	Siltstone MW	Siltstone SW-FR	Sandstone SW-FR	Quartzite SW-FR
σ_c	[MPa]	35.9	57.0	83.3	121.4	203.4
E_i	[GPa]	9.0	28.7	47.4	54.1	74.8
RQD	[%]	25.6	39.4	60.8	68.5	63.4
RMR_{89}*		40	47	57	62	62
GSI*		35	42	52	57	57
Q*		0.41	0.70	1.36	1.77	1.82
V_p*	[km/s]	-	3.40	3.80	4.25	-
Obs. E_m^	[GPa]	3	7	15	17	25

** Median values presented.*

^ Observational model E_m: back-calculated using FE analysis to simulate monitored displacements.

Pit slope displacements across various slopes at Telfer gold mine have been monitored using survey prisms and automatic, robotic total stations for over 20 years. Survey prisms were installed at, and several meters behind the pit crests during various pushbacks.

For the cases investigated, the pit slope geometry relative to the orientation of the bedding was such that the loading direction was sub-perpendicular to the bedding. All slopes were stable with rock masses exhibiting elastic creep-like behavior with less than 0.2 mm/day displacement rates, 24 months after excavation. Based on the available data, total displacements for different pushbacks were estimated to range from 172 to 343 mm over a 20-year period (Bar, 2020).

Numerical simulations using finite element (FE) analysis software, RS2 (Rocscience Inc), were completed to adjust stiffness properties and replicate the monitored displacements. Back-calculated E_m from the observational model have been presented in Table 1.

4 COMPARISON OF ROCK MASS STIFFNESS EMPIRICAL ESTIMATES AND THE OBSERVATIONAL MODEL

Empirical estimates of rock mass stiffness were derived for siltstones with different degrees of weathering, sandstone and quartzite based on the rock mass conditions displayed in Table 1 and Equations 1-28.

Figure 2 graphically illustrates the rock mass moduli, E_m, estimated from various equations. Very little consistency is visible between various equations or methods for the different ground conditions. By way of example, E_m for Siltstone SW-FR varies between 2.0 and 28.9 GPa, which represents an order of magnitude in terms of variability.

Only 15 of 127 (12%) empirical estimates in Figure 3 attained E_m values within 10% of the observational model results. Ratios of observational to empirical E_m values were as low as 0.2 and as high as 10, indicating very little to no correlation for some materials using some of the equations.

For the ground conditions at Telfer, Equations 5, 13, 15, 19 and 21 were generally more reliable with E_m estimates ranging from <10 to 40% of the observational model results. For hard rock, σ_c>50 MPa, Equations 23 and 24 were also very reliable.

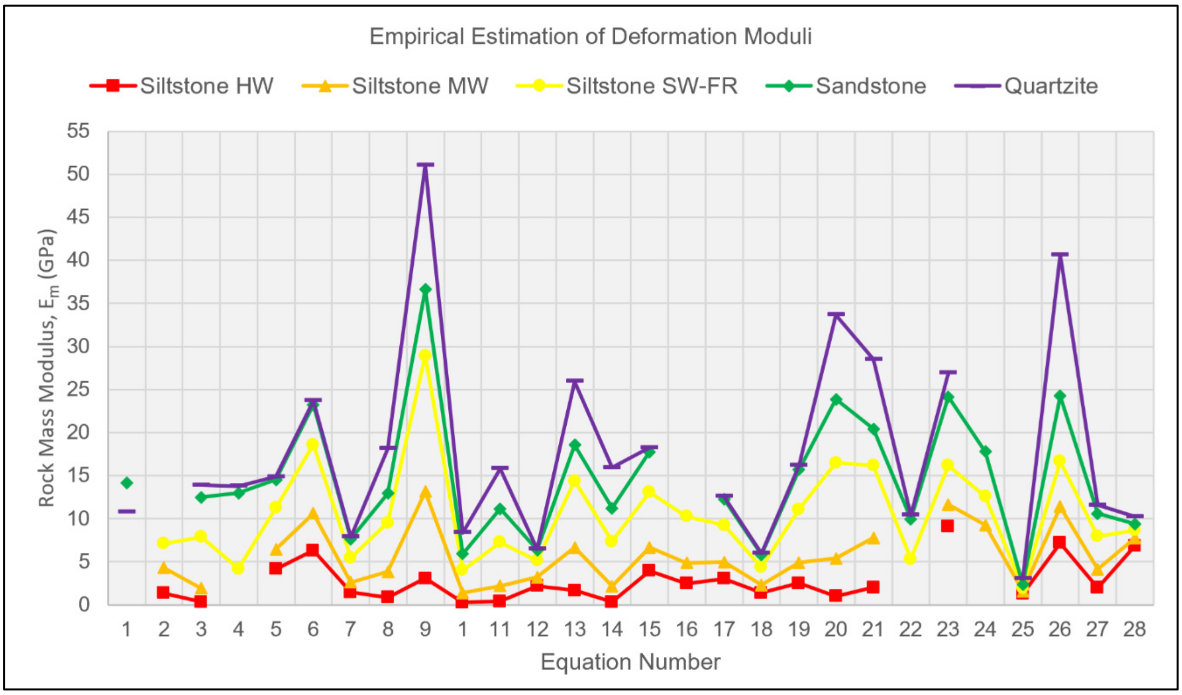

Figure 2. Empirically derived Deformation Moduli for Siltstone, Sandstone and Quartzite based on various empirical methods and their respective equation numbers. Note: data gaps represent limitations or constraints within the specific empirical methods.

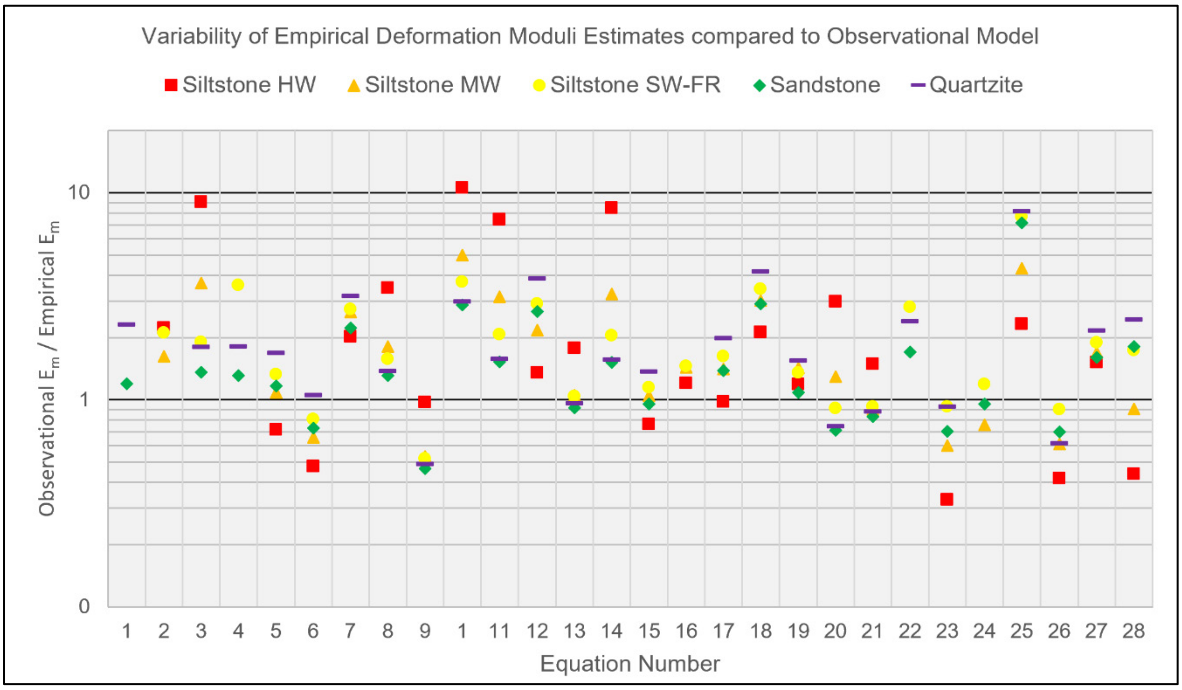

Figure 3. Variability of empirical deformation moduli estimates compared to the observational model.

5 CONCLUSION

Evaluation of rock mass stiffness using different empirical methods yielded vastly different and variable results, consistent with previous studies. The observational model was useful for identifying the most applicable empirical methods for the specific ground conditions at Telfer.

Empirical methods for rock mass stiffness evaluation remain useful where no observational data is available. Users of empirical methods are strongly encouraged to understand the limitations of the methods they apply as predictive tools. They are further encouraged to consider and apply parameter sensitivity (a range of values rather than single deterministic values) on their local site conditions, and to validate these in the field with routine ground characterization and monitoring.

Although limited to siltstone, sandstone and quartzite with the loading direction sub-perpendicular to anisotropy (bedding), this study provides some insights into the magnitude of variability that could be expected from empirically derived rock mass stiffnesses.

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