BUILDING 3D MODEL OF ROCK QUALITY DESIGNATION ASSISTED BY CO-OPERATIVE INVERSION OF SEISMIC AND BOREHOLE DATA

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SUMMARY

The rock quality designation (RQD) is an important factor for geotechnical work in mining operations. A 3D model of RQD is significant for mine design. In practice, the mine design needs information of the whole mine area, but, borehole data is localised in only a small part of the whole area. Although, surface seismic methods can provide information of the whole survey (mine) area, the resolution of such data is generally smaller than the borehole data. The combination of seismic and borehole data may provide very useful information for geotechnical features like RQD if we can exploit seismic data as a means of interpolating the borehole information to the whole model of that geotechnical feature. In this work, we build a 3D model of RQD from seismic and borehole data acquired in Kevitsa mine site, Northern Finland. We investigate the relationship between Vp and RQD from eight boreholes to build a functional conversion between theses parameters. The seismic model obtained by co-operative inversion of seismic reflection and borehole data is converted into a RQD model using this function. Our model is assessed by comparison between RQD of core measurements and estimation from Vp of borehole data and seismic inversion. The results demonstrate that our process can build a reasonable 3D RQD model for geotechnical purposes.

Key words: Rock quality designation; co-operative inversion; seismic; borehole.

INTRODUCTION

A reliable assessment of mechanical properties of rock masses at depth is a key factor of mine design and pit planning. Rock characterization is usually based on rock quality indexes such as Rock Quality Designation (RQD) (Deere 1963). RQD represents the degree of core recovery and is indicative of the rock quality in terms of degree of discontinuety due to fracturing, jointing, and alteration. It can be used to delineate poor quality, weak rock that may affect engineering structures (Deere, 1988). Since RQD values are based on core measurements alone, this information is only available along the borehole trajectory and not throughout the area of the future mine or pit. In engineering pecpectives, types of rock mass behavior depends on scale (Hoek et al., 1995). Therefore, mining structure needs information of rock quality in both local and regional scale. It would be of great benefit to be able to infer RQD properties from volumetric measurements, such as seismic velocities from 3D seismic surveys. The surface seismic method can provide information over a large area, but the resolution is usually lower than that of the borehole data. If the seismic data can be used to interpolate the higher resolution borehole data to the whole volume it might be possible to infer areas of weak (and strong) rock away from the localised boreholes. The relationship between RQD values and seismic velocities is such that both are influenced by similar rock properties such as fractures, joints and alteration zones.

Our work is applied to a data set acquired in the Kevitsa mine site. The geological map (Figure 2a) shows that fracture systems of this area is complicated and dominated by two main fault zones striking NW-SE and NE-SW. Deep holes are mainly located in the vicinity of the open pit (Figure 2b). Therefore, a 3D model of RQD built from the borehole data is insufficient and the model is likely unreliable because of artefacts from the interpolation process. Surface geophysical data can provide information over a large area and help to build a 3D model of RQD on a regional scale. The problem of using information from surface geophysical methods such as the potential field and interpreted structure from migrated seismic reflection (Lindqvist, 2014) is low resolution. The quality of 3D RQD model is significantly improved if we can exploit high-resolution data such as seismic reflection. A critical issue for reflection seismic data is that it only provides information about relative variations of acoustic impedances, hence it is usually impossible to directly link the seismic reflection data with a RQD model. This problem can be solved if we can convert reflection seismic data into an acoustic impedance model.

In this work, the first step is to establish the relationships between Vp and RQD. These relationships are usually nonlinear and complicated (Zhang, 2016). Thus, we use a nonlinear correlation to build the functional relationship. Our method is much simpler than using regression techniques because the correlation of Vp and RQD in hard rock environment usually shows scatters. This relationship is used to convert the 3D seismic model obtained by co-operative inversion of seismic and borehole data into a 3D model of RQD.

METHOD AND RESULTS

Establishing a relationship between Vp and RQD

We analyse the correlation between Vp and RQD instead of AI and RQD because AI and Vp are highly correlated, and in this dataset there are very few holes with all measurements: Vp, specific gravity and RQD. The drill-core is classified into three types A, B and C (Figure 1) relating to three zones of Vp. The total core run includes *L* samples (equation 3). RQD is defined as follow:

$$RQD = 100\frac{N}{L}, \tag{1}$$

where *N* is defined by equation (2a) and (2b)

$$n_i = \begin{cases} 0 & if\ Vp \le Vmin \\ \frac{Vp}{Vmax} & if\ Vmin < Vp < Vmax, \\ 1 & if\ Vp \ge Vmax \end{cases} \tag{2a}$$

$$N = \sum n_i. \tag{2b}$$

$$L = n_1 + n_2 + n_3 + n_4. \tag{3}$$

In equation (2a), the key issue is how to define lower (*Vmin*) and upper (*Vmax*) bound of of Vp. In this work we define *Vmin* and *Vmax* as follow:

$$Vmin = mean\ (Vp)\ -\ 2 \times \sigma, \tag{4a}$$

$$Vmax = mean\ (Vp) + 2 \times \sigma, \tag{4b}$$

where σ is standardised diviation of Vp.

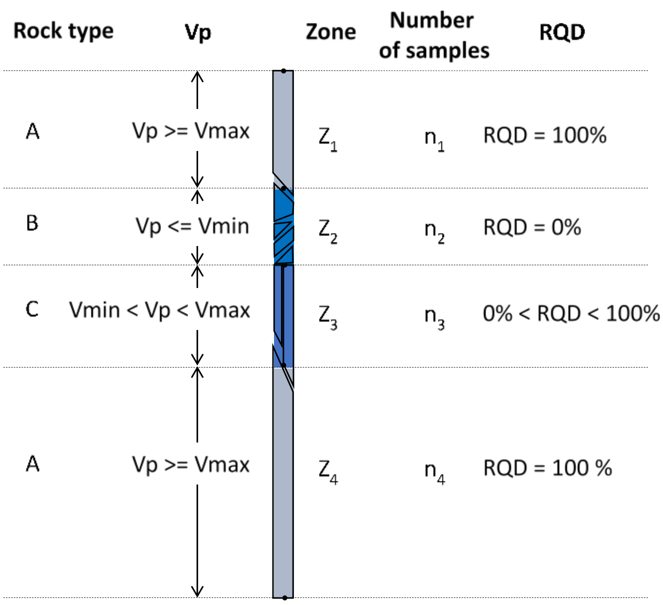
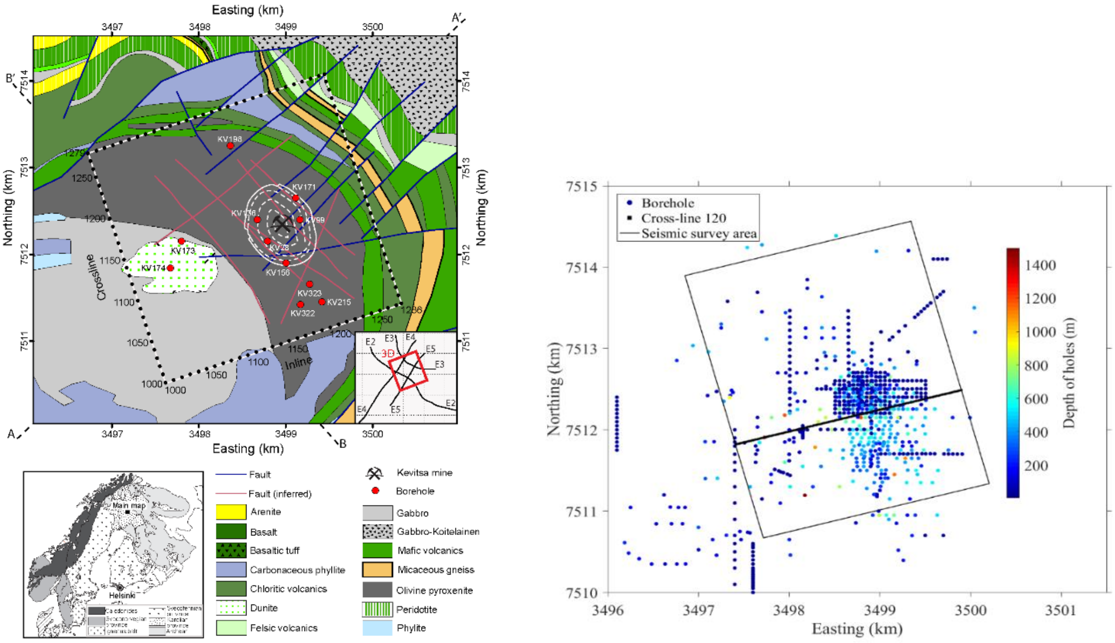


Figure 1: Schematic classification of core run (Modified from Deere (1988)). The core is separated into three types A, B, and C relating to RQD and Vp. If Vp is equal or smaller than *Vmin*, RQD is zero (Rock type B). If Vp is equal or larger than *Vmax*, RQD is 100% (Rock type A). Vp varies from *Vmin* to *Vmax* that corresponds to RQD changes from 0 to 100 % (Rock type C).

We trialled this approach on a data set comprised of core measurements of eight holes: KV136, KV156, KV171, KV173, KV174, KV198, KV215 and KV99. The location of these holes is shown in Figure 2a. The lower and upper bound of Vp, *Vmin* and *Vmax*, are defined by equation (4a) and (4b) respectively. RQD is computed by using equation (1), (2), and (3) for regular intervals of 6m length along the borehole trajectory. This length of 6m is equal to the distance that seismic waves propagates in one-way time sample of seismic data, 1 ms, through a media with velocity 6000m/s, an average seismic velocity in this area.

Figure 5 shows a comparison between RQD estimated by using Vp and RQD directly measured on the core. The general trend of predicted RQD matches with the measured RQD. However, in detail there are some differences at some parts of the holes that are likely related to many factors: the different scale of measurement between RQD and Vp; measurement errors of both RQD and Vp and the natural variability of rock mass properties in this area. For example, the first 200m of borehole KV136 contains weathered rock (overburden) and shows low seismic velocity. Consequently, the estimated RQD from Vp is low, but the core measurement show high RQD values here.



(a) **(b)**

Figure 2: (a) Geological map of Kevitsa area (after Malehmir et al. (2012)). (b) Map of borehole and seismic data locations. The colour of the dots shows the depth of hole. The deep holes (>500 m) are located in the centre of mine site, the north of the seismic survey areas show less dense holes, most of which are shallow.

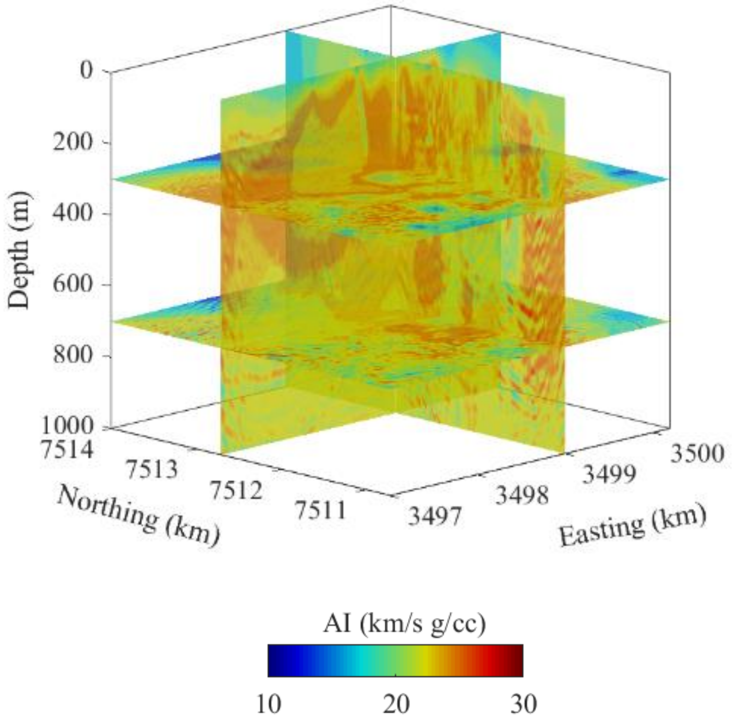
Conversion 3D RQD model

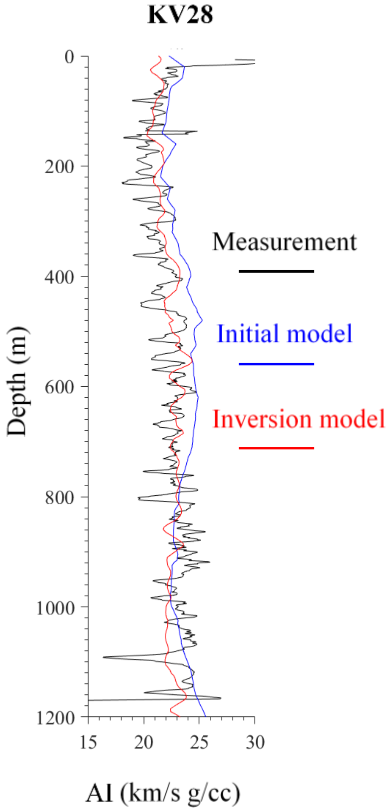
Firstly, a co-operative inversion of seismic and borehole data process is performed to build a 3D model of acoustic impedance (Figure 3a). The inversion process is validated by comparing our process and the borehole data of KV28. This borehole locates at centre of Kevitsa mine site and it is one of the deepest borehole (Figure 1). Our initial model is generated from borehole information using both measured and predicted data from other borehole data features (Kieu et al., 2016). The inversion is constrained by petrophysics (Kieu and Kepic, 2015) and cooperate with spatial information of borehole (Kieu and Kepic, 2017). The comparison between initial and inversion models with borehole data (Figure 3b) demonstrates that our process is robust. The initial model trend matches nicely with the measured data. The low-frequency band of the initial model compensates the lack of this information in the seismic reflection data. The inversion process then provides higher frequency information and produces a model that is closer to the borehole data.

Secondly, the RQD model is built by conversion of the seismic model. The acoustic impedance achieved by inversion process is transferred into a Vp model, and then the Vp model is converted into the RQD model. The process of conversion Vp into RQD is same as the approach of conversion borehole data. In this case, the number of samples is one, the sample of seismic. The lower and upper bounds (*Vmin* and *Vmax*) information are defined by borehole data. Figure 4 shows a RQD section of a cross-line 120 (Figure 1b). In general, weak zones found by seismic inversion are consistent with weak zones identified by core measurement. A detailed comparison between the inversion results and borehole information is presented in Figure 5. These results show that the RQD model from inversion can match the trend of RQD from borehole information but is different in detail. This can be explained by the difference of scale. While seismic inversion is of lower resolution than borehole data and should be considered for larger scale usages.

CONCLUSIONS

We combine seismic and borehole data to build a 3D model of rock quality designation (RQD), this model provides useful information for geotechnical engineering of mining production. Seismic and borehole data are used to build a Vp model by implementing co-operative inversion. Then, by using the relationship between Vp and RQD, determined from borehole data analysis, we can convert the seismic inversion results into the RQD model. Our RQD model shows a good match with the RQD values from core measurements; an encouraging result that demonstrates how low cost, routine borehole data in combination with volumetric geophysical surveys can greatly improve the understanding of subsurface engineering properties of a prospect. The result is a volumetric data set that can guide engineering decisions about design and better measurement strategies; such as extra geotechnical boreholes before committing to excavation.





(a) (b)

Figure 3: (a) Acoustic impedance from the seismic inversion. (b) Comparison between initial, inversion result with borehole data of KV 28.

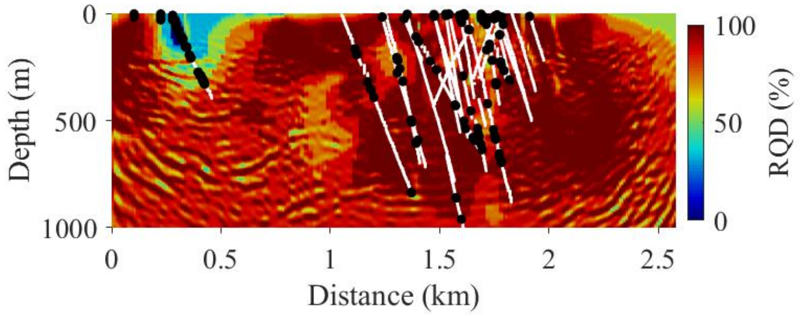


Figure 4: RQD estimation from acoustic impedance model. Weak zones (low values of RQD) achieved by the inversion approach show consistent with RQD from core measurement (black dots).

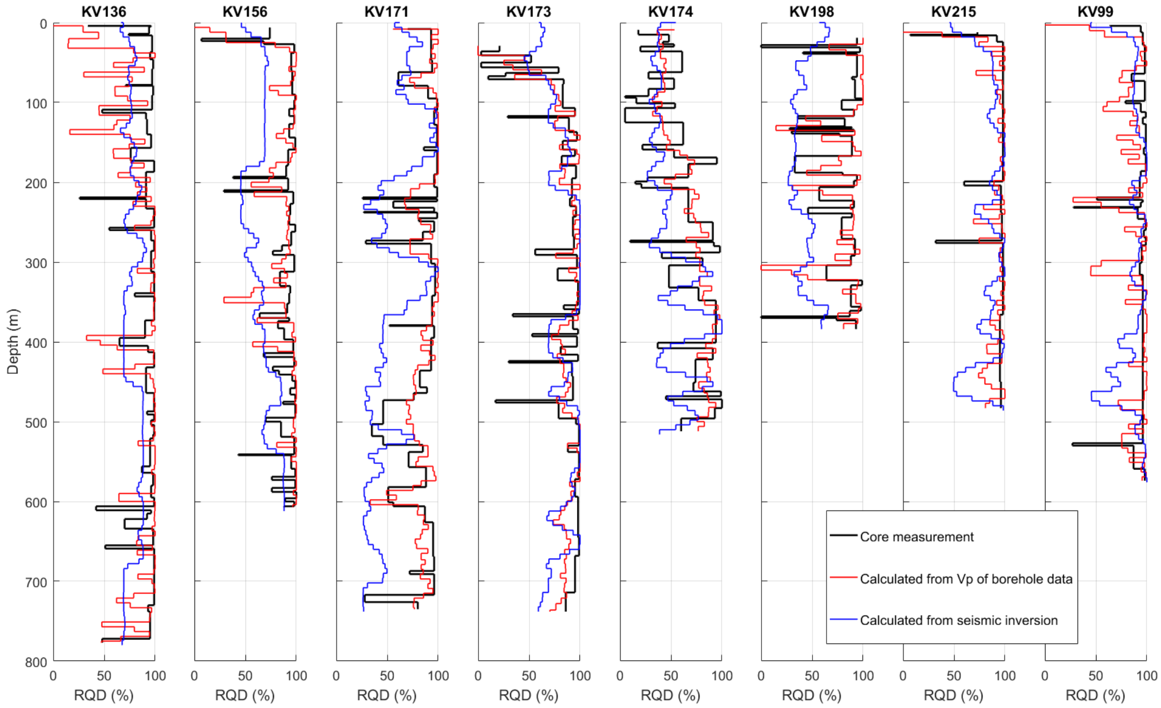


Figure 5: Comparison between RQD measured on core (black lines) and calculated from Vp of the borehole data (red lines) and inversion model (blue lines). Note that the values of RQD vary with scale. Estimated RQD results from Vp data is higher resolution and closer to measured RQD than RQD model obtained by seismic inversion process. The important result is that they fit the general trend of RQD.

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