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TECHNICAL NOTE

Practical Investigations on Use of Weighted Joint Density to Decrease the Limitations of RQD Measurements

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1 Introduction

Various techniques have been established in geotechnical engineering to determine the quality of rock drilled out from a borehole. These simple and inexpensive methods include total core recovery (TCR), solid core recovery (SCR), and rock quality designation (RQD). Among these, RQD provides a general indication of rock mass quality and is widely used as an index to evaluate rock quality by expressing the degree of fracturing in drill cores.

The RQD was modified from the TCR method by Deere (1963) to indirectly measure the number of fractures and amount of softening or/and alteration in rock mass for engineering applications. Its simplicity, low cost, and reproducibility generally resulted in quick development of the RQD for a wide variety of rock engineering applications, such as tunnels, mining engineering, and large caverns. Nowadays, this method is considered as a standard method in drill core logging and forms a basic element of the most widely used rock mass classification systems, such as the rock mass rating (RMR) and Q-system (Bieniawski 1989; Barton 1995).

However, a number of limitations such as dependence on borehole orientation and the selected threshold value for the minimum intact core length restrict the consistency of the measured values. Accordingly, several methods have been established to overcome these limitations, such as the corrected rock quality designation (RQDc) (Li et al. 2009), volumetric joint density (Jv) (Palmstrom 1982, 1985, 1986; Sen and Eissa 1992), cumulative core index (Sen 1990), and weighted joint density (WJD) (Palmstrom 1995, 2005). Although such new methods have been developed, the RQD is still used with the initial definition, without correction, in many geotechnical engineering applications, e.g., rock mass classification, rock mass strength, and modulus of elasticity.

This paper reviews the conventional RQD measurement techniques by Deere (1963) and RQD measurements from the WJD (hereafter called RQD_{WJD}) by Palmstrom (2005) using rock cores drilled out from directional boreholes at the Bakhtiary Dam site. In this way, the RQD values from different methods were compared, and a new modification is proposed, called RQD_{M-WJD}.

2 Background

2.1 Conventional RQD

RQD was first introduced in 1963 by Deere as the percentage of total length of core pieces longer than 100 mm (L_i) to the total length of the core run (L), expressed as follows (Fig. 1):

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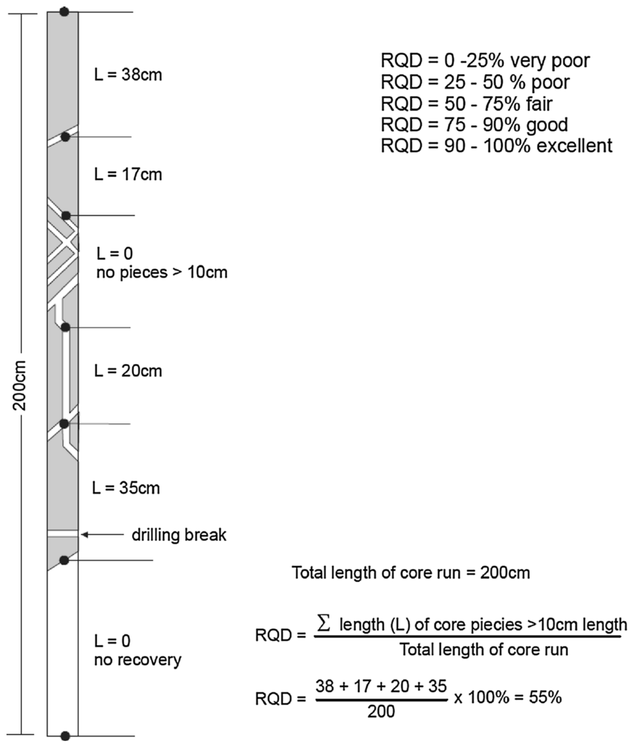


Fig. 1 Measurement of RQD value using core drilling, and classification of rock mass using this index value based on the method proposed by Deere (1963)

$$\mathrm{RQD} = \frac{\sum L_i}{L} \times 100. \quad (1)$$

Several definitions have been suggested for selection of the core length (L) to be considered in the RQD calculation. These include (a) equivalent to a drill run, (b) a change in the formation or rock type, and (c) a zone of concern.

According to the ASTM (2008) standards for rock core quality designation, only hard or sound intact rocks should be counted whereas soft materials should never be used, even if they are 100 mm in length.

2.1.1 *Applications*

The RQD as an indication of rock quality is widely used as a warning for low-quality rock zones and to provide an initial source of data for design decisions in rock engineering projects, such as:

- Estimation of required excavation depths for foundations.
- Assessment of rock quality in quarries for concrete aggregate, rock fill or large riprap.
- Evaluation of rock mass behavior, such as rock mass strength and modulus of elasticity (Zhang and Einstein 2004), or shear strength and dilation (Barton 1990; Goodman 1993).
- Rock mass classification systems for rock engineering purposes, e.g., the rock mass rating (RMR) and Q-system (Bieniawski 1989; Barton 1995).

2.1.2 *Limitations of Conventional RQD*

Various limitations on RQD measurements restrict their application in many geomechanical fields (see Sect. 2.1.1) (Choi and Park 2004; Palmstrom 2005):

- Dependence on the selected threshold length of 100 mm for unbroken rocks, which results in different RQD values even due to a ±1 mm change in the threshold length; For instance, if all sticks are 99 or 101 mm long, the RQD would be 0 and 100 %, respectively (Fig. 2a).
- The RQD is sensitive to the orientation of joint sets and dependent on the coring direction. So, different RQD values are obtained for a given location when cores are drilled out parallel or perpendicular to a joint set (Fig. 2b).
- The RQD does not give any information on the quality of core pieces similar to earth-like materials or fresh rock pieces smaller than 100 mm in length.

Due to the aforementioned limitations, the original definition of the RQD does not comprehensively represent the actual quality of rock mass. Consequently, a high RQD value does not always imply a high-quality rock mass in practice (Milne et al. 1998).

Because of the dependence of the conventional RQD value on the evaluation direction, one may state that this method can be directly related to the anisotropy of a rock mass. In this regard, it should be mentioned that anisotropy assessment of rock mass using the RQD method is not commonly utilized in rock engineering work. In contrast, the RQD is generally used as an index value in rock engineering projects. So, modification of the RQD would be valuable and helpful in rock engineering designs to obtain a correct impression of the whole rock mass quality.

2.2 Weighted Joint Density (WJD)

The weighted joint density (WJD), introduced by Terzaghi (1965), was developed by Palmstrom (1996) to obtain better information from boreholes and surface observations. It is principally based on measurement of the angle between each joint with the scan line at the surface or axis of the drill hole (δ), as presented in Fig. 3:

$$\mathrm{WJD} = \frac{1}{L}\sum \frac{1}{\sin \delta}. \quad (2)$$

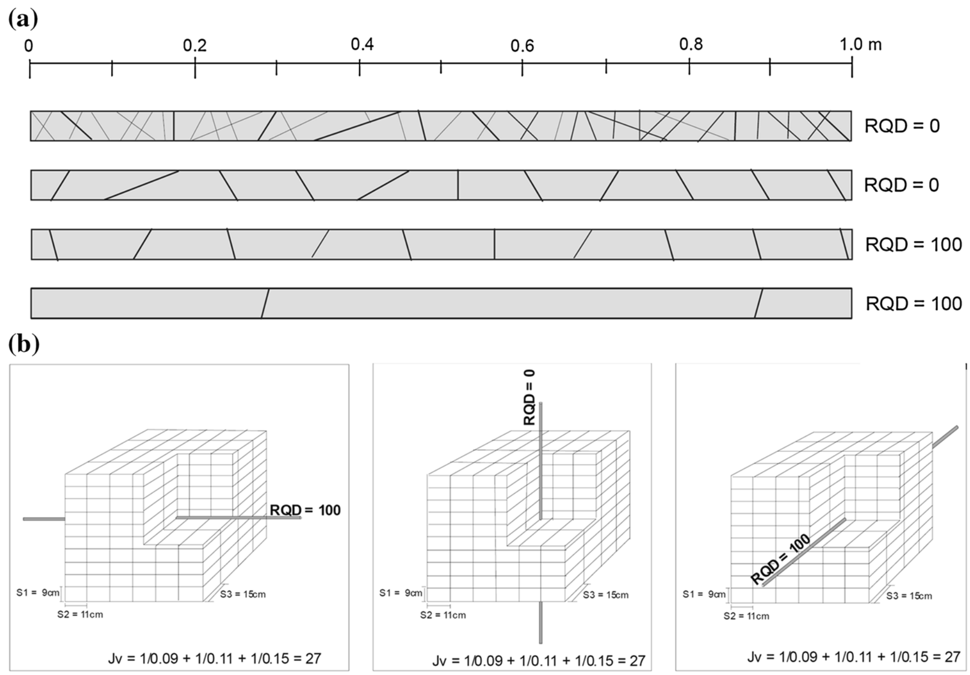
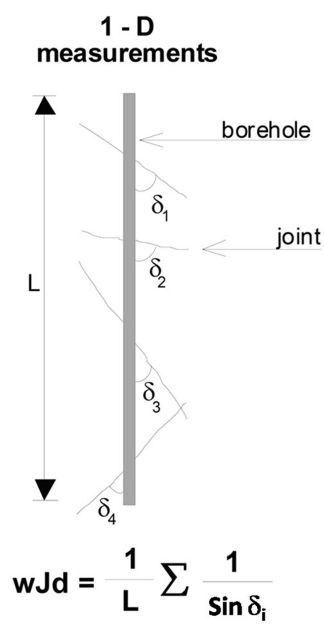


Fig. 2 Some limitations on RQD measurements by the conventional method: **a** differences between maximum and minimum RQD values regarding the size of core sticks, and **b** dependence of RQD values on drilling direction (Palmstrom 2005)



angle interval (δ)	$1/\sin\delta$	value of fi
> 60°	< 1.16	1
30° - 60°	1.16 - 1.99	1.5
15° - 30°	2 - 3.86	3.5
< 15°	> 3.86	6

Fig. 3 Definitions of WJD measurement in boreholes and ratings of the factor f_i in each interval (Palmstrom 2005)

To simplify observations, the δ angles are categorized into four intervals, and an average value of f_i is determined for each category (see table in Fig. 3). Thus, Eq. (2) can be rewritten as follows:

$$\mathrm{WJD} = \frac{1}{L}\sum f_i. \tag{3}$$

The RQD can be estimated from the number of joints (discontinuities) per unit volume (Jv), which can be found directly from core logging or surface observations. A simple relationship which may be used to convert Jv into RQD for clay-free rock masses is (Palmstrom 1974, 1982)

$$\begin{aligned}\mathrm{RQD} = 115 - 3.3\,\mathrm{Jv}\ (&\mathrm{RQD} = 0 \text{ for Jv } > 35,\\ &\text{and RQD } = 100 \text{ for Jv } < 4.5).\end{aligned} \tag{4}$$

Some time later, Palmstrom (2005) found that this empirical correlation (Eq. 4) was deficient and recommended the following new equation to give a more appropriate average correlation (Palmstrom 2005):

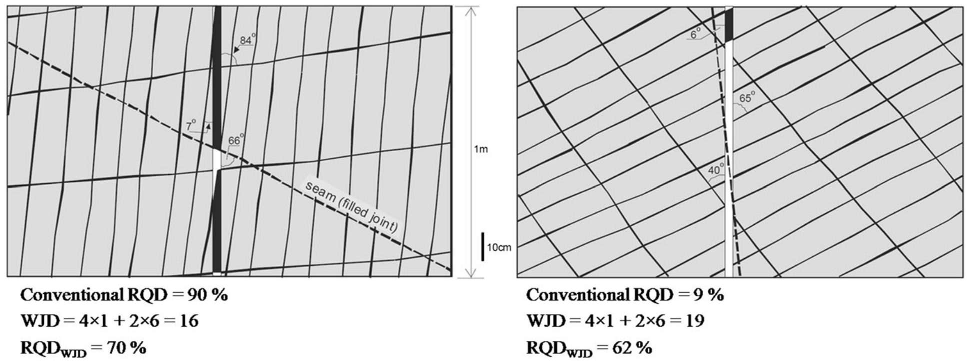


Fig. 4 Comparison of RQD, WJD, and RQD_{WJD} measurements in the same domain (Palmstrom 2005)

$$\text{RQD} = 110 - 2.5\ \text{Jv (for Jv between 4 and 44)}. \tag{5}$$

The weighted joint density is practically equivalent to the volumetric joint count. Thus, Eq. (5) can be rewritten as (Palmstrom 1996)

$$\text{RQD}_{\text{WJD}} = 110 - 2.5\ \text{WJD}. \tag{6}$$

2.2.1 *Advantages of the WJD Method*

Figure 4 compares the conventional RQD and WJD measurements for two boreholes in different directions, drilled in the same jointing vicinity (Palmstrom 2005). In this figure, different RQD values (90 and 9 %) are obtained, while the WJD values (16 and 19) are approximately similar. From Eq. (6), RQD_{WJD} is found as 70 and 62 % for the WJD values of 16 and 19, respectively. The RQD_{WJD} values are reasonably close and situated in the fair rock mass RQD classification. Therefore, the weighted joint density method, which compensates for errors originating from the threshold value and coring direction, leads to a better description of the rock mass fracturing degree.

2.2.2 *Limitations of WJD Method and Proposal of a Modified WJD*

Although the WJD method leads to a better description of rock mass quality, finding the angle of each joint with the core axis (δ) in fractured zones is the main restriction of this method. Indeed, in a fractured zone, several joints cross a small part of the rock mass and create very small rock blocks, i.e., very intensely to intensely fractured zones. Clearly, the fractured zone reduces the rock mass quality, and this must be considered in the calculation of the RQD using WJD in Eq. (6). In this regard, if the fractured zones are neglected, the RQD value from Eq. (6) would be higher than the appropriate value and in some cases would even be above 100 % (Figs. 5, 6).

Thus, in cases where fractured zones are encountered in boreholes, the value of RQD should be modified to consider or compensate the influence of these zones, using the following equation:

$$\text{RQD}_{M-\text{WJD}} = \text{RQD}_{\text{WJD}} \times \left[\frac{L_{\text{t}} - L_{\text{FZ}}}{L_{\text{t}}}\right], \tag{7}$$

where $\text{RQD}_{M-\text{WJD}}$ represents the modified RQD value from WJD considering the fractured zone, RQD_{WJD} is the RQD value calculated from Eq. (6), L_{FZ} is the length of the fractured zone, and L_{t} is the total length of the core run.

A comparison between RQD_{WJD} and $\text{RQD}_{M-\text{WJD}}$ is presented in Figs. 5 and 6. It is shown that a more reasonable value of rock quality is obtained when using $\text{RQD}_{M-\text{WJD}}$ rather than RQD_{WJD}.

3 Study Area and Geological Setting

Practical investigations on RQD measurements using different methods were carried out at the Bakhtiary Dam & Hydropower Project, which is located on Bakhtiary River (the main branch of Dez River), in Lorestan Province, southwest Iran.

The Bakhtiary Dam site and its reservoir are located in the northwestern part of the folded Zagros, at the boundary of the Lorestan and Dezful embayment zones. The sediments of this area were precipitated in the Triassic through Pliocene era and were deformed in the Plio-Pleistocene age by means of the last Alpine orogenic phase (Motiei 1993). Tectonic activities formed parallel sets of anticlines and synclines mostly with NW–SE trend and subvertical axial planes associated with a number of thrust faults in the Zagros area.

The most important rock type at the dam site and reservoir is a siliceous limestone of the Sarvak Formation; it belongs to the Bangestan Group, Middle Cretaceous period. Four sets of discontinuities intersect the rock mass of the dam site area: a bedding and three major joints. Different geometries (dip and dip direction) for bedding planes were observed at the upstream (u/s) and downstream (d/s) limbs of the Siah Kuh Anticline. Joint set systems J1 and J2 were each divided into two subsets: J1A/J1B and J2A/J2B, respectively (BJVC 2009). It should be stated that the frequency and occurrence of the discontinuities are not identical in the whole of the dam site and vary at different locations.

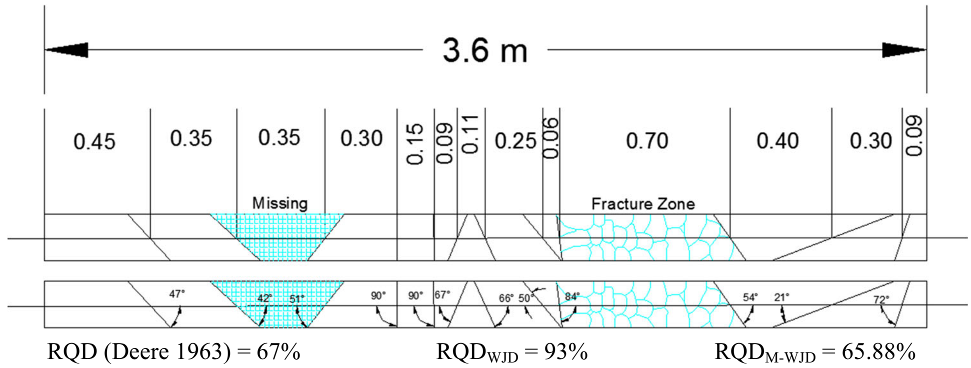


Fig. 5 Effect of fractured and missed zones on the RQD value by Deere (1963) and Palmstrom (2005)

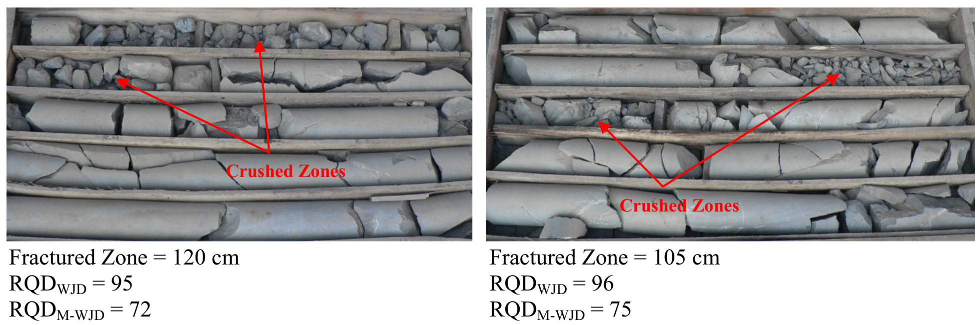


Fig. 6 Crushed zone in boreholes; the cores were drilled in gallery GR3 in the study area

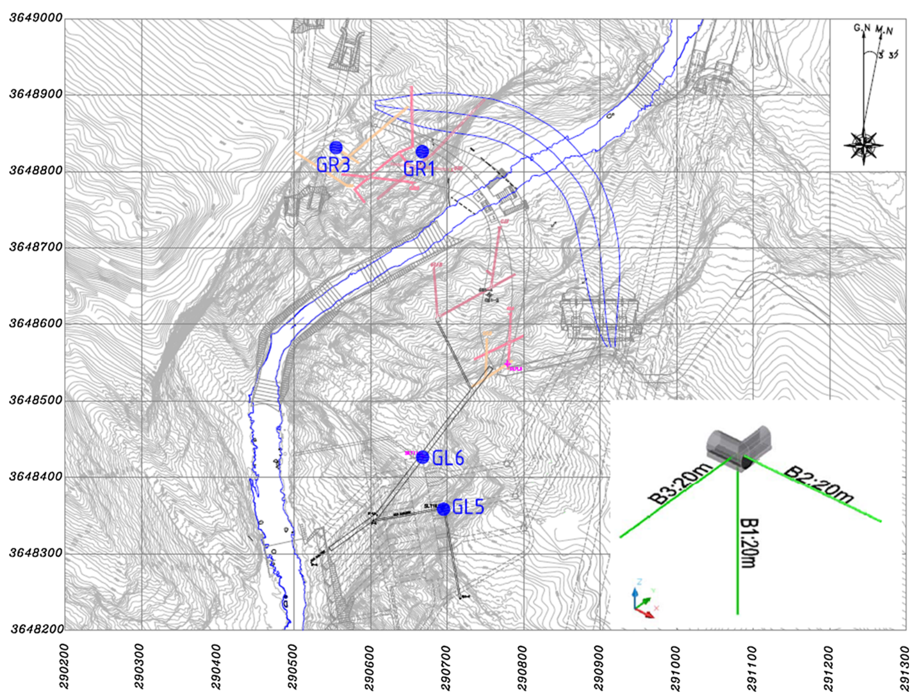


Fig. 7 Location of rock blocks where boreholes were drilled, and schematic view of boreholes drilled into a rock shaped like a block with dimensions of $20 \times 20 \times 20$ m^3

3.1 Research procedures

Directionally drilled boreholes at the Bakhtiary Dam site were used to compare the application of different RQD measurement methods (conventional RQD, RQD_{WJD}, and RQD_{M-WJD}). These boreholes were drilled at four locations at different elevations (557–754 m.a.s.l.) inside the galleries, including (Fig. 7):

Table 1 Results of discontinuity surveying at the drilling locations

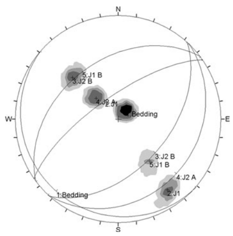
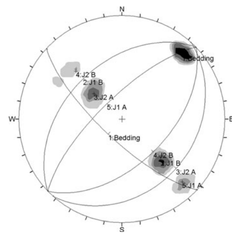
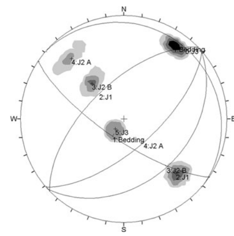
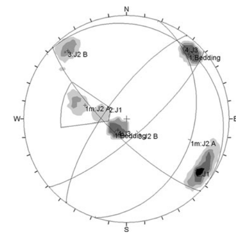
Location	Gallery GR1	Gallery GR3	Gallery GL5	Gallery GL6
Discontinuities	B # 221/09; S # 6–20 cm J1A # 325/72; S # 6–20 cm J1B # 323/42; S # 6–20 cm J2A # 133/24; S # 6–20 cm J2B# 132/50; S # 6–20 cm	B # 223/74; S # 6–20 cm J1A # 316/73; S # 6–20 cm J1B # 316/45; S # 6–20 cm J2A # 132/30; S # 6–20 cm J2B # 136/54; S # 6–20 cm	B # 214/74; S # 6–60 cm J1B # 316/62; S # 6–20 cm J2A # 138/38; S # 6–20 cm J2B # 139/66; S # 6–20 cm J3 # 041/10; S # 6–20 cm	B # 224/79; S # 6–60 cm J1A # 306/73; S # 6–20 cm J2A # 108/35; S # 6–20 cm J2B # 139/76; S # 6–20 cm J3 # 039/11; S # 6–20 cm
Stereographic projection				

Table 2 Comparison of RQD values from the methods proposed by Deere (1963), Palmstrom (2005), and the authors of this paper

Borehole			Length of fractured zone (cm)	WJD (Eq. 2)	Deere (1963)	Palmstrom (2005)	Authors
Location	Borehole name	Drilling direction			RQD (Eq. 1)	RQD_{WJD} (Eq. 6)	RQD_{M-WJD} (Eq. 7)
GR1	B1R1	Vertical	110	9.53	60	86	82
	B2R1	Horizontal	130	9.50	57	89	83
	B3R1	Horizontal	115	8.45	31	89	84
GR3	B1R3	Vertical	50	9.73	77	86	84
	B2R3	Horizontal	30	10.38	86	84	83
	B3R3	Horizontal	120	7.90	86	90	85
GL5	B1L5	Vertical	165	3.40	87	102	93
	B2L5	Horizontal	240	1.85	85	105	93
	B3L5	Horizontal	305	3.50	80	101	86
GL6	B1L6	Vertical	362	6.15	66	95	78
	B2L6	Horizontal	489	2.53	75	104	78
	B3L7	Horizontal	275	4.80	80	98	84

- Gallery GR1: near the dam axis on the right bank at elevation of 557 m.a.s.l.
- Gallery GR3: near the dam axis on the right bank at elevation of 754 m.a.s.l.
- Gallery GL5: underground powerhouse area on the left bank at elevation of 557 m.a.s.l.
- Gallery GL6: underground powerhouse area on the left bank at elevation of 560 m.a.s.l.

At each location, three directional boreholes were drilled perpendicularly into a rock block of volume 20 × 20 × 20 m^3. Cores were used to evaluate the degree of fracturing in the rock mass.

In Table 1, the orientation and spacing (*S*) of discontinuities for each location with their relevant stereographic projection are presented.

3.2 Results of RQD logging

The required data were obtained from the drill cores, and RQD values were calculated using Eq. (1) (Deere 1963), Eq. (6) (Palmstrom 2005), and Eq. (7) (proposed by authors), as presented in Table 2.

It is shown that the RQD values for GL5 and GL6 are in some cases greater than 100 %, which results from

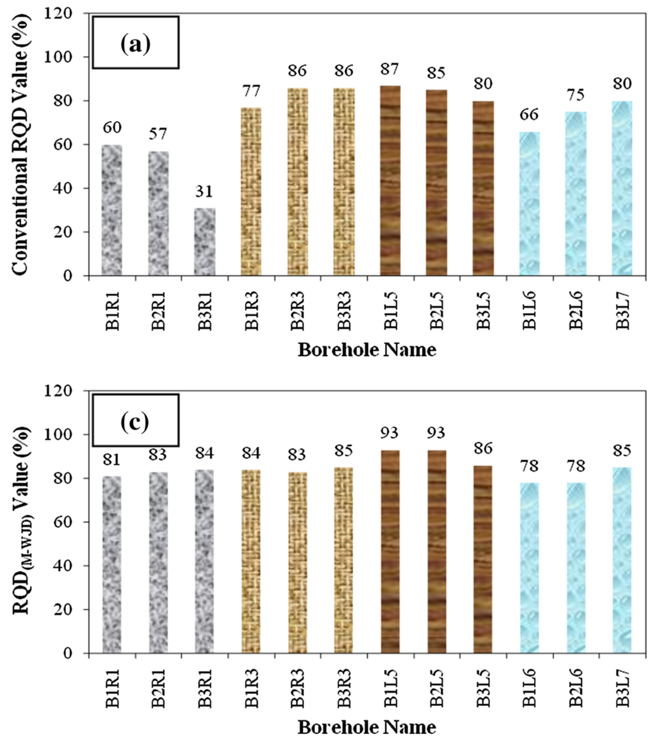


Fig. 8 Comparison of RQD values: **a** RQD (Deere 1963), **b** RQD_{WJD} (Palmstrom 2005), and **c** RQD_{M-WJD} (authors of this paper); *each color* reflects boreholes drilled at the same location (color figure online)

Table 3 Average values and variation of maximum and minimum values of RQD measured using the different methods in each of the rock blocks (or borehole locations)

Drilling location	Average RQD values (%)			Difference between max. and min. RQD values (%)		
	RQD (Eq. 1)	RQD_{WJD} (Eqs. 3, 6)	RQD_{M-WJD} (Eqs. 3, 6, 7)	RQD (Eq. 1)	RQD_{WJD} (Eqs. 3, 6)	RQD_{M-WJD} (Eq. 3, 6, 7)
GR1	49	88	83	29	3	3
GR3	83	87	84	9	6	2
GL5	84	103	91	7	4	7
GL6	74	99	80	14	9	7
Average				15	6	5

neglecting the fractured zones in the RQD measurement. However, when the fractured zones are modified by Eq. (7), the values fall into the acceptable range.

From the RQD values measured by the different methods in the directional boreholes at a rock block, the following conclusions can be drawn:

- The conventional RQD (using the method proposed by Deere) gives inconsistent RQD values which are categorized into different rock quality classifications.
- When using the RQD_{WJD} method, although the RQD values are in some cases more than 100 %, the values are approximately similar and situated in the same categories.
- When using the new proposed method (i.e., RQD_{M-WJD}), the effect of fractured zones is compensated and the values are approximately similar and situated in the same rock classes.

Comparison of the RQD values obtained using the different methods shows less variation of the RQD values in directional boreholes when using the RQD_{M-WJD} (Fig. 8).

In each rock block, the average and deviation between the maximum and minimum RQD values obtained from the different methods were calculated (Table 3). Generally, the differences between the maximum and minimum values were about 15, 6, and 5 % for the RQD, RQD_{WJD}, and RQD_{M-WJD} methods, respectively.

4 Conclusions

This paper reviews the conventional RQD method and tries to confirm a recently proposed RQD definition by Palmstrom (RQD_{WJD}) using rock cores obtained from directional boreholes. The results show that RQD_{WJD} can logically overcome some of the limitations of the original RQD, while it is not recommended when fractured zones are present. Thus, a modified RQD measurement (RQD_{M-WJD}) is proposed to consider the fractured zone in RQD measurements. The investigations performed show that RQD_{M-WJD} can reasonably overcome the limitations of conventional RQD and RQD_{WJD} in RQD measurements.

Even though there are some advantages of the newly suggested modified RQD (in comparison with conventional RQD), the authors do not believe that RQD_{M-WJD} will substitute the original definition of RQD in the near future. Indeed, RQD_{M-WJD} should rather be seen as a complementary means of assessing the quality of fractured rock masses.

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