An improved definition of rock quality designation, RQD_c

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ABSTRACT: The rock quality designation, RQD, is a commonly used index for the description of rock mass fractured state. The RQD was initially introduced for civil engineering applications, and it has been quickly adopted in mining engineering as well. The success of the RQD is, in great part, due to its simplicity. However, this also leads to a number of limitations, including among other, a dependency of the RQD value on the borehole orientation and on the selected threshold value for the minimum intact core length. The latter limitation is briefly reviewed in this paper. Then, a new approach is introduced to overcome, at least in part, such limitation when assessing the value of the RQD. This leads to a corrected definition of rock mass quality designation, RQD_c.

1 INTRODUCTION

The rock quality designation, RQD, was initially proposed by Deere (1963), and it has since then been the topic of various assessments (e.g., Deere et al. 1967, 1988; Deere 1989), mainly for civil engineering projects. Its application has also been quickly extended to other areas of rock mechanics, and it has become a fundamental parameter in geotechnical engineering (e.g., Hoek & Brown 1980; Hoek and Bray 1981). The success of the RQD is due, in large part, to its simple definition, which is the ratio (percentage) of intact core pieces longer than 10 cm over the total drilling length. However, this index is affected by a number of well known limitations. For instance, its value can be different for a given location when obtained from cores with different drilling orientations. In addition, the RQD may be affected by the rock strength and core size.

Other neglected influence factors include water conditions, and joints aperture, alteration and roughness. Although these limitations have been addressed in rock mass classifications, such as the Rock Mass Rating (RMR; Bieniawski 1973, 1976, 1979), the Norwegian Geotechnical Institute's Q system (Barton et al. 1974), and the cumulative core index (Sen 1990), the RQD is still used on its own, without correction, in many geotechnical engineering applications (e.g., Kulhawy & Goodman 1980).

Another significant limitation of the RQD definition is its dependency on the selected threshold length of unbroken rocks (e.g., Terzaghi 1965; Priest & Hudson 1976; Harrison 1999; Hack 2002; Choi & Park 2004; Chen et al. 2005). This signifies that the RQD value would typically vary with different threshold length for the same core. In practice, a familiar observation associated with this drawback is that the RQD values tend to be either high or low (often above

70% or below 10 to 20 %) in most rock engineering projects. Some values (e.g., between 40% and 60%) are less frequently encountered, due to the customarily and universally adopted, but very arbitrarily selected threshold value of 10 cm (for NX cores) in the assessment of RQD (Harrison 1999). This phenomenon can be illustrated using the example with fictive cores shown in Figure 1; this aspect is further discussed below. To obtain a wider range of RQD values, Harrison (1999) proposed a technique for determining an optimal threshold length. However, this approach is only appropriate for a particular rock mass. Besides, this technique requires the determination of the minimum and maximum values of discontinuity frequency in the rock mass, which generally means that the original RQD's simplicity is lost.

In this paper, the definition of rock quality designation, RQD, is reviewed and a simple modification is proposed. This leads to a corrected definition of rock quality designation, RQD_c.

2 LIMITATION OF ORIGINAL RQD IN THRESHOLD VALUE

Figure 1 shows schematically some fictive NX drilling cores. Taking a threshold length of 10 cm, the induced results would be RQD = 100% for cores (a) to (f) and 0% for (g) and (h). This means that even though the difference in core segment length between cores (f) and (g) is negligible, the application of the artificially cut-off of 10 cm makes a huge difference in the RQD value. This is because any slightly shorter core segments than the threshold length would be rejected in counting the unbroken length. On the other hand, even though the rock mass quality represented by core (a) is much better than the rock mass quality represented by core (f), this significant difference can not be seen with the original RQD, which gives 100% for both (a) and (f) cores.

This fictive example shows that the original definition of the RQD does not always represent accurately the actual quality of rock masses. Consequently, a high RQD value does not always translate into a high quality rock mass in practice (e.g., Milne et al. 1998). In the following, a new definition of rock mass quality designation will be proposed. It will be seen that the corrected index, RQD_c, inherits the original RQD's simplicity, but without the drawback associated with threshold length value.

3 CORRECTED DEFINITION OF THE RQD

By examining the cores (a) to (f) shown in Figure 1, one sees that the quality of the rock mass not only depends on the accumulative length of unbroken pieces, but also the number of unbroken pieces, N. Thus, the designation could be expressed using the following function:

$$RQD_{\mathrm{c}} = \frac{p_{\mathrm{r}}}{f(N)} \tag{1}$$

where RQD_c is the corrected rock quality designation, p_r is the ratio of recovered cores in length:

$$p_{\mathrm{r}} = \left(\sum_{i=1}^{N} L_i \right) \Big/ L \tag{2}$$

In this equation, L is the travel or run length (also called scanline length), L_i is the length of i^{th} unbroken piece. In Equation (1), $f(N)$ is a function of the total number of unbroken pieces. It can take various forms, such as,

$$f(N) = N^a \tag{3}$$

where a is a material parameter that serves as the exponent in the power law function.

4 SCHEMATIC PRESENTATION

Figure 2 shows the variation of RQD_c with parameter a varying from 0 to 1.0 in normal (a) and log-log (b) planes, respectively. In the latter case, the variation of RQD_c with the number of pieces N becomes straight lines (with the slope equal to a). It can be seen that RQD_c remains constant if parameter $a = 0$ (or $f(N) = 1$), as with the RQD, which is independent of the number of unbroken pieces. Another difference between RQD_c and RQD is that the former considers the total length of all unbroken pieces (p_r, equivalent to the recovered rate commonly used by geological engineers) while the latter includes only those segments longer than 10 cm.

The advantages of the corrected definition, RQD_c, over the original definition of RQD are fairly clear. For instance, for two cores broken in pieces longer than 10 cm, the RQD will be 100% for both cores whatever the number of unbroken pieces, while the corrected definition will give two different RQD_c values based on their unbroken pieces number; a smaller index is expected to be associated with the more fractured core. Also, for two cores broken in pieces smaller than 10 cm, the original definition simply gives a RQD of 0%, while the former can make a distinction based on the number and broken length of the cores.

In order to assess the influence of the core segment number, Figure 2 indicates that parameter a should not be too small (i.e. close to zero). In the following, parameter a will be taken as 1. Thus, the corrected definition of RQD_c can describe the quality of rock mass from very bad to very good quality, with the index varying in a continuous rather than in an abrupt manner. Another advantage is that the definition of RQD_c simplifies and accelerates the surveying work due to the fact that one does need to verify if the length of unbroken pieces is larger than the (arbitrarily selected) threshold value.

5 EXAMPLES OF CALCULATION

By taking the fictive example shown in Figure 1, one obtains the quality description of the rock mass with the two different definitions as shown in Table 1 and Figure 3. From Figure 3, one sees that the quality rating with the definition of RQD_c decreases progressively from core (a) with a maximum value of 100% to (h) with a very small but non-zero value. This corresponds well to the quality of the rock mass shown in Figure 1. As mentioned above, with the original definition of RQD, only two extreme values (100% vs. 0%) are obtained. This does not represent well the variation of the rock mass quality shown in Figure 1.

Table 1. RQD and RQD_c for cores shown in Figure 1.

Core	N	RQD_c (%)	RQD (%)
(a)	1	100	100
(b)	2	50	100
(c)	4	25	100
(d)	8	12.5	100
(e)	16	6.3	100
(f)	30	3.3	100
(g)	30	3.3	0
(h)	60	1.7	0

A more practical case can be illustrated using Figure 4, which shows some representative cores from a Quebec mine. The description of the rock mass quality is given in Figure 5. In general, both definitions give similar quality tendency, i.e., the rock mass quality becomes generally better from (a) to (e), and both RQD_c and RQD increase from (a) to (e). However, the reduction in the RQD_c is much more progressive than that of the RQD. More specific differences can also be observed using both definitions when comparing (a) to (b) or (d) to (e). With the original definition of RQD, the quality of the core (b) is considered significantly better than (a) with RQD = 67.8% for core (b) compared to RQD = 49.5% for core (a). With the definition of RQD_c, the quality of core (b) is only slightly better than core (a) with RQD_c = 5.4% for core (b) compared to RQD_c = 5.2% for core (a). In our opinion, the latter values better reflect the actual quality of these cores (see Figure 4).

Another difference can be seen with the quality description of cores (d) and (e), using both definitions. The original definition indicates that the quality of core (e) is only slightly worse than that of core (d) with RQD = 82.0% for core (e) and RQD = 82.2% for core (d). The corrected definition considers that both cores are quite different (on a relative scale) with RQD_c = 9.1% for core (e) compared to RQD_c = 11.8% for core (d).

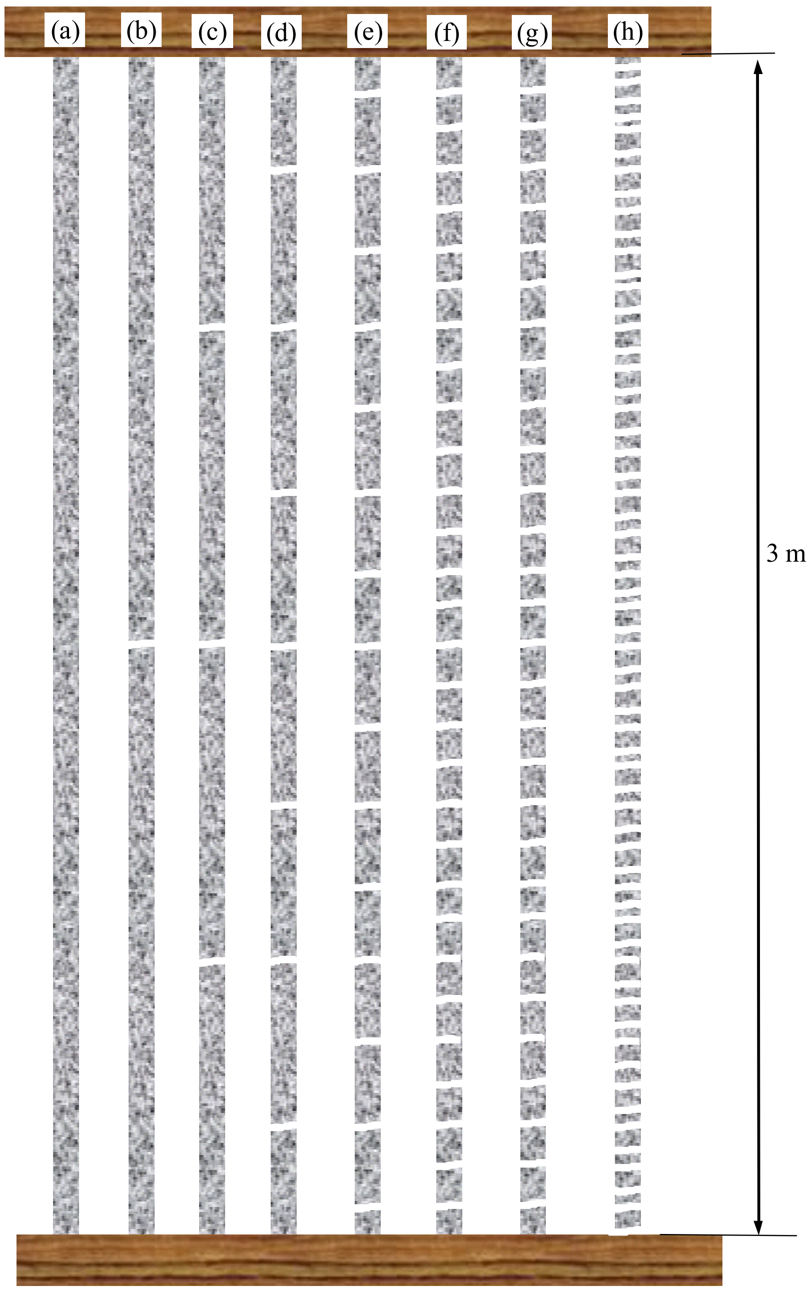

Figure 1. A schematic presentation of different drilling cores: Core (f) segments are each 10 cm long and core (g) segments are each 9.99 cm long.

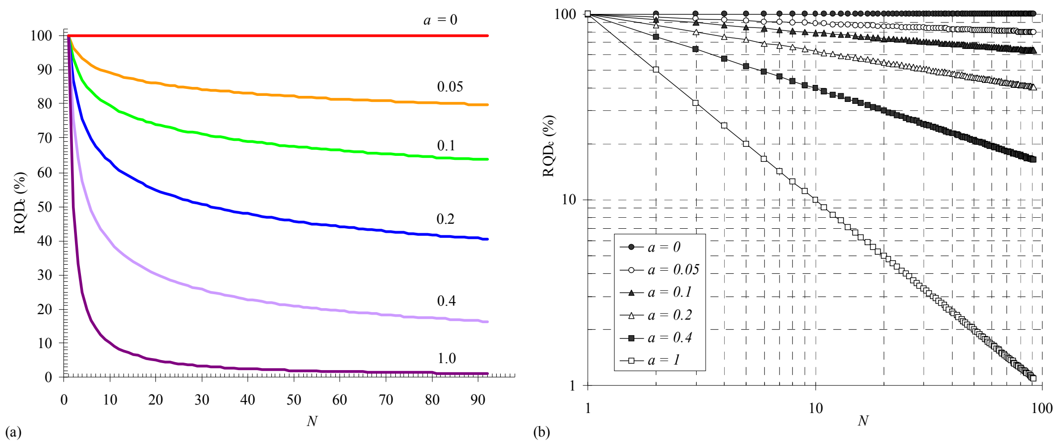

Figure 2. Variation of RQD_c with number of pieces N using different values for parameter a, which varies from 0 to 1.0 (p_r = 100%): (a) in normal plane; (b) in log-log plane.

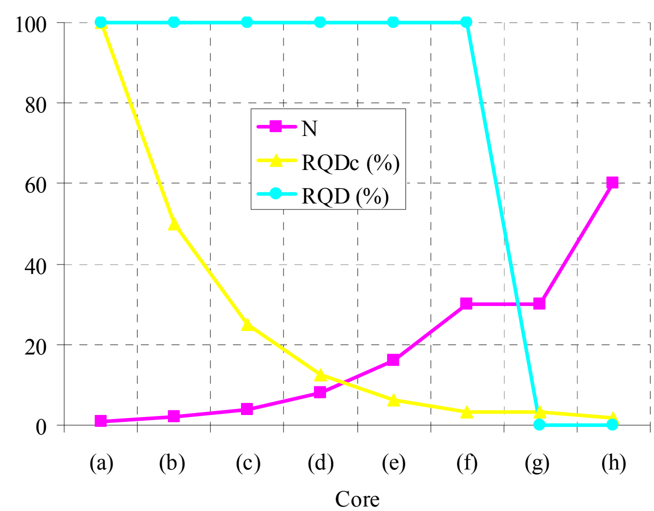

Figure 3. Variation of rock mass quality with the new definition of RQD_c and the original definition of RQD for cores shown in Figure 1.

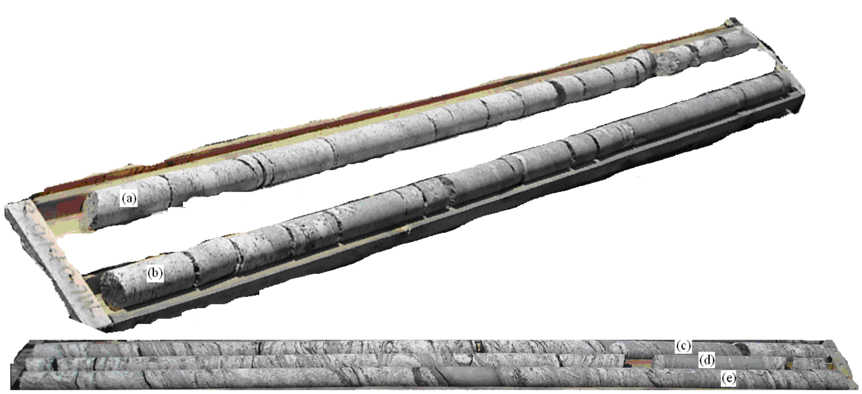

Figure 4. Representative cores from a Quebec mine.

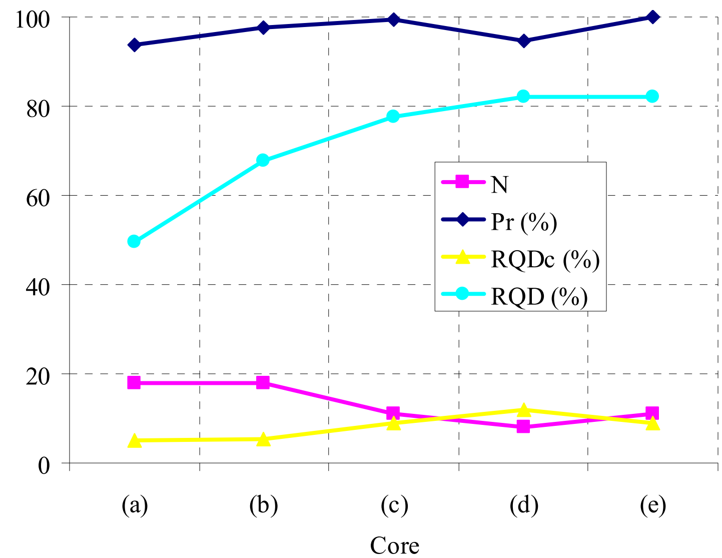

Figure 5. Rock mass quality description of the cores shown in Figure 4 with the new definition of RQD_c and the original definition of RQD.

6 DISCUSSION

The new definition of RQD_c does not involve the threshold length value. Thus, the threshold dependency limitation of the original definition of RQD is overcome with the corrected index. However, this new definition is not free of limitations. For instance, if one assumes that the core broken planes correspond to joints, even though this is seldom the case (as shown in Figure 4), one can show that this new definition is dependent on the scan interval selected.

Figure 6 shows a fictive core with uniformly distributed joints. In such a case, the rock mass quality described with the new designation is given as:

$$RQD_c = \frac{1}{\mathrm{JF} \times L + 1} \tag{4}$$

Here, the core recovery rate p_r is assumed to be 100%, JF represents joint frequency (m^{-1}).

Figure 7 shows the variation of RQD_c with the joint frequency when the scan interval varies from 1 m to 6 m. In this figure, the variation of the original definition of RQD is also plotted with the frequency. It is seen that the original definition of RQD does not depend on the scan interval L nor on the joint frequency, provided that the joint frequency is smaller than a threshold value to ensure that the joint spacing is larger than the threshold length. With the new definition, the RQD_c decreases with the increase of joint frequency. This corresponds well to the reality, as the quality of rock masses decreases with an increase of joint frequency. Figure 8 shows that the rock mass quality RQD_c decreases with the increase of the scale interval. This feature is not surprising, in a sense, as it corresponds to a tendency observed with many other geomechanical properties of rocks, which tend to decrease with an increase of the sample size (i.e. the so-called size effect; e.g., Bieniawski 1968; Hoek & Brown 1980; Cunha 1990; Aubertin et al. 2000; Li et al. 2007). Correction of this scale effect can be made with following equation:

$$\frac{RQD_{cL}}{RQD_{cL0}} = \frac{\mathrm{JF} \times L_0 + 1}{\mathrm{JF} \times L + 1} \tag{5}$$

where RQD_{cL0} is the RQD_c with a standard scan interval of L_0 (usually 3 m), RQD_{cL} is the RQD_c with non standard scan interval of L.

Figure 9 shows the variation of the ratio RQD_{cL0}/RQD_{cL} with the normalised scan interval, L/L_0 with different joint frequencies. It can be seen that the scale effect depends on the joint frequency JF. However, the influence of the joint frequency on the scale effect tends to vanish when its value becomes higher than 10. On the other hand, the scale effect tends to disappear when the joint frequency becomes very small. In fact, Equation (5) is reduced to the following equations:

$$\frac{RQD_{cL}}{RQD_{cL0}} = \frac{L_0}{L} \tag{6}$$

when JF is very high, or:

$$\frac{RQD_{cL}}{RQD_{cL0}} = 1 \tag{7}$$

when JF is very low.

Finally, one has to point out that even though there are clear advantages with the proposed definition of the RQD_c (when compared with the RQD), the authors do not expect that the new index will replace the original definition in the near future. The new index should rather be seen for now as a complementary means of assessing the quality of fractured rock masses.

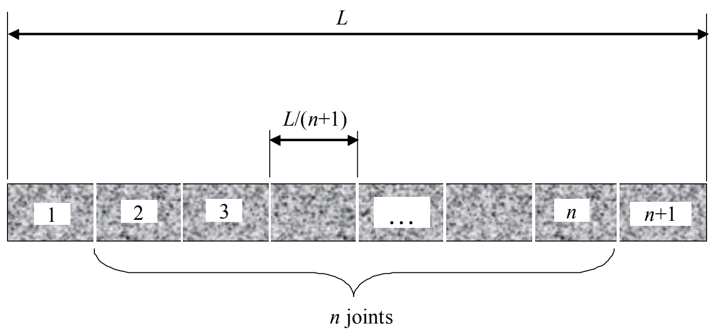

Figure 6. A fictive core with idealized uniformly distributed joints.

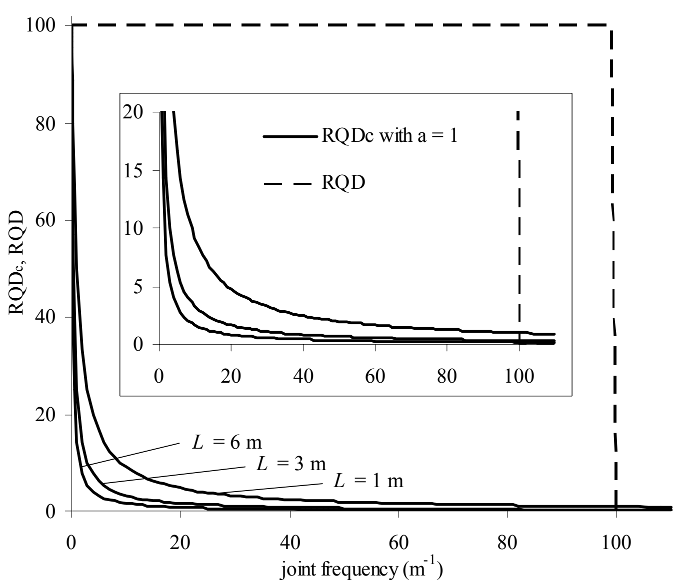

Figure 7. Variation of RQD with idealized joint frequency.

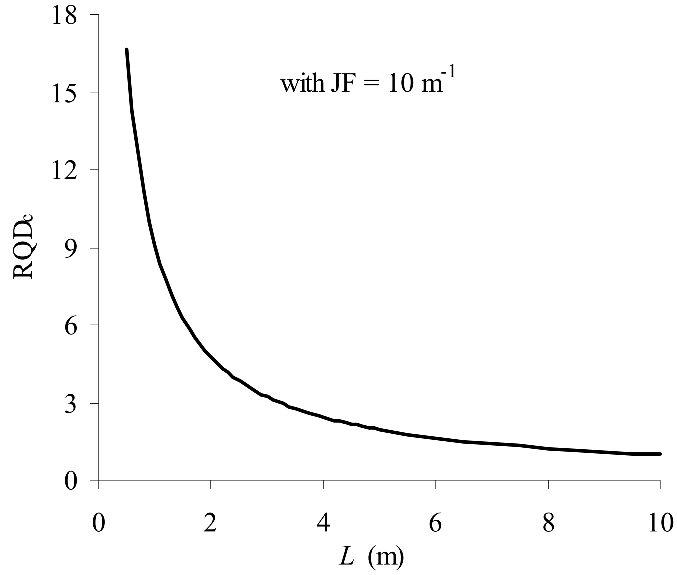

Figure 8. Scan interval or scale effect on the RQD_c value.

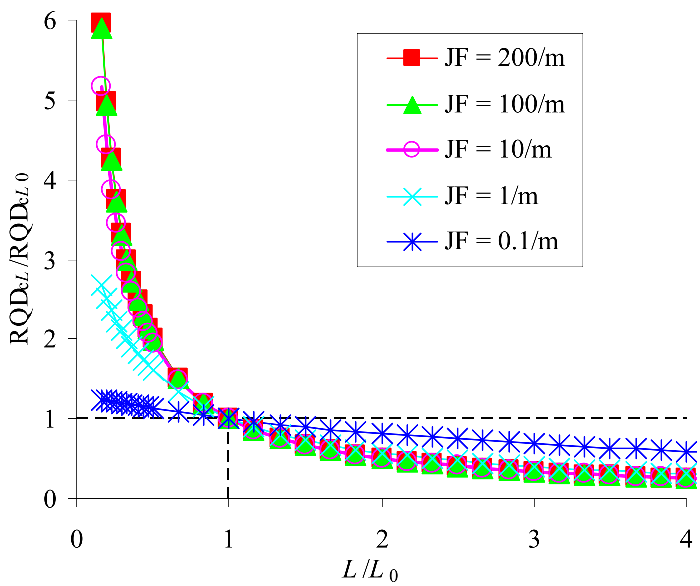

Figure 9. Variation of the normalized RQD_{cL} with the normalised scan interval L with different join frequencies.

7 CONCLUSION

In this paper, the original rock quality designation, RQD, was revised and a new definition was proposed. The corrected rock mass quality designation, RQD_c, considers both the core recovery ratio and the number of unbroken pieces. This new definition keeps the original definition's simplicity, but does not require an arbitrary definition of threshold length, thus eliminates the limitation of the original RQD. It has been shown that this new definition can describe the quality of rock masses from very bad to very good quality in a continuous and progressive manner, which gives a better representation of the actual quality of rock masses. It has been further shown that this new definition of rock mass quality designation behaves as other geomechanical properties (such as strengths and deformability), with an inherent scale (scan interval) effect. In some cases, corrections may be required when the scan interval differs from the classical value (of 3 m).

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