Correlations between jointing and seismic velocities in highly fractured rock masses

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Abstract The paper presents the results of a study of heavily fractured calcareous rock masses outcropping in southern Italy based on both the unidimensional joint frequency (NI) and rock quality designation (RQD) of rock cores and seismic velocity data from laboratory and down-hole tests. The in situ longitudinal wave velocities (v) were always very low and were correlated with both NI and RQD. Between 1 and 2 km/s, small increases in velocity were associated with a considerable decrease in NI and significant increase in RQD value. A velocity of 1.22 km/s corresponded to an RQD value of 0. The study indicated that the simple correlation proposed by the International Society for Rock Mechanics to evaluate the RQD from the unidimensional joint frequency can underestimate the results for heavily fractured rock masses, but that good correlations can be obtained between RQD and seismic velocity.

Keywords Rock mechanics · Jointing frequency · Seismic velocities · Down hole · Southern Italy

Résumé L’article présente les résultats d’une étude relative à un massif rocheux carbonaté, intensément fracturé, à l’affleurement dans le Sud de l’Italie. L’étude est basée sur la mesure d’une densité unidirectionnelle de joints (NI) et de l’indice RQD à partir de carottes de forage, d’autre part sur des valeurs de vitesses sismiques obtenues au laboratoire et en forage par la méthode down-hole. Les mesures in situ des vitesses sismiques des ondes longitudinales (v) étaient toujours très faibles et étaient corrélées avec les paramètres NI et RQD. Pour des vitesses entre 1 et 2 km/s, de faibles augmentations de vitesse correspondaient à une diminution considérable du paramètre NI et une augmentation significative de l’indice RQD. Une vitesse de 1,22 km/s correspondait à une valeur de RQD de 0. L’étude a montré que la corrélation simple, proposée par la Société Internationale de Mécanique des Roches, pour évaluer la valeur de RQD à partir de la densité unidirectionnelle de fracturation pouvait sous-estimer les résultats pour des masses rocheuses intensément fracturées. Par contre de bonnes corrélations s’observent entre les valeurs de RQD et les vitesses sismiques.

Mots clés Mécanique des roches · Densité de joints · Vitesses sismiques · Mesures de vitesses en forage · Italie méridionale

Introduction

The evaluation of joints (frequency, trace length and orientation of joint sets) is a very important topic in rock mechanics affecting block shape, their volume in the rock masses and their mechanical strengths (compression and shear strength, deformation modulus, etc.). The degree of jointing is estimated directly at outcrops using scanlines or on drill cores by means of the rock quality designation (RQD) (Deere 1963), providing an indirect block size measure. The volumetric joint count (Jv), which measures the number of joints within a unit volume of rock mass, is related to the RQD by means of the following equation (International Society for Rock Mechanics 1978):

\[ \text{RQD} = 115 - 3.3 \text{Jv} \]  

(1)

Although this correlation must be regarded as approximate (Palmstrøm 1995). Sometimes, when the rock mass is weak or highly fractured it is very difficult to obtain a reliable measure of the jointing frequency from drill cores. In addition, the drilling torque and the stress release when the cores are removed affect the jointing seen in the recovered rock cores.

Sjögren et al. (1979) and Palmstrøm (1995) proposed two hyperbolic correlations linking respectively the unidimensional joint frequency (NI) and the RQD to the in situ...
longitudinal wave velocity ($v$), the latter being measured by means of refraction seismic survey in the following correlations:

\[ \text{NL} = \frac{(V_n - v)}{(V_n \times v \times k_s)} \]  \hspace{1cm} (2)

and

\[ \text{RQD} = \frac{(V_q - v)}{(V_q \times v \times k_q)} \]  \hspace{1cm} (3)

where $V_n$ is the seismic velocity of the unjointed rock; $V_q$ is the seismic velocity of a rock mass with RQD=0; and $k_s$ and $k_q$ are parameters taking into account the actual conditions of the in situ rock mass.

The unknown constants $V_n$ and $k_s$ (Eq. 2) can be found using two data sets of measured values of NL and the corresponding in situ velocities $v$:

\[ V_n = \frac{|v_1 \times v_2 (NL_2 - NL_1)|}{|NL_2 \times v_2 - NL_1 \times v_1|} \]  \hspace{1cm} (4)

and

\[ k_s = \frac{1}{NL_1} \left(\frac{1}{v_1} - \frac{1}{V_n}\right) \]  \hspace{1cm} (5)

where $NL_1$, $v_1$ and $NL_2$, $v_2$ are corresponding values of 1-D jointing frequencies (joints/m) and in situ seismic velocities (km/s) respectively for the two pairs of measurements. The two unknown constants $k_q$ and $V_q$ in Eq. (3) can be found with the same procedure.

The method based upon Eq. (2), referred to as the “refined correlation method” (Palmstrøm 1995), can be used if two pairs of NL and $v$ values are already known. This gives good results because it includes site-dependent conditions such as joint openness or possible joint infilling. When NL has been calculated, a rough estimate of the volumetric joint count ($J_v$) can be quickly performed by substituting in Eq. (1) the $J_v$ calculated from:

\[ J_v = kl \times NL \]  \hspace{1cm} (6)

Unfortunately, the correlation factor $kl$ may vary widely (Fig. 1) due to the poor correlation between NL and $J_v$ when the jointing frequency is measured in drill cores (Palmstrøm 1996). Alternatively, Eq. (3) represents a useful way to calculate the RQD after the proper values of the $k_q$ and $V_q$ constants have been found.

In this way the use of the simple correlations shown above allow the RQD and NL values of a rock mass to be obtained by means of seismic surveys. The information collected in limited volumes of a rock mass can, with some restriction, be extended to neighbouring zones with similar lithological, geostuctural and geomechanical characteristics.

To analyse the correlations between the longitudinal wave velocity and the degree of jointing of rock masses in more detail, velocities from seismic down-hole prospecting and the corresponding NL and RQD values determined for each metre depth have been used in the present work. It is considered that the large number of pairs of data (NL–v and RQD–v) acquired using down-hole prospecting provides more reliable correlations. Moreover, this kind of seismic prospecting allows low velocity zones under more rigid rock masses to be investigated, such as fault zones or heavy jointed zones.

Both methods were used to calculate the correlation curves between NL–v and RQD–v in the Atrani area of southern Italy (Fig. 2), using core drillings, down-hole prospecting and laboratory tests on calcareous specimens.

**Geological outline**

The town of Atrani is situated within the narrow valley at one end of the Torrente Dragone gorge and is dominated on both the east and west by steep rock cliffs from which boulders, sometimes huge, often fall (Budetta and Santo 1994). In this area the bedrock is typified by Liassic