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APPLICATION OF SEISMIC REFRACTION SURVEY IN ASSESSMENT OF JOINTING

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SUMMARY

Various mathematical correlations can be applied to assess the degree of jointing from seismic refraction wave velocities. From these it is possible to obtain information of the rock mass quality at an early stage during investigations when specific data on jointing is lacking. It should, however, be noticed that the calculations are based on an assumed 'basic velocity' (V_0) *of the intact rock and the accuracy of this input parameter highly influences the quality of the assessments.*

At a later stage, when the degree of jointing has been measured in drill cores or in rock exposures, the accuracy of the initial assessments can be significantly improved. The jointing along the entire seismic profile can then be characterized. In this way, the information collected in the limited volume of the rock mass along a borehole can be extended over a much larger area.

> *"Judgement is thus the intelligent use of experience or, more cautiously expressed, it is the recognition of one's limitations of the methods one uses, and of the limitations and uncertainties of the materials one works with; and this brings us back to geology."* Herbert H. Einstein, 1991

1. INTRODUCTION

Seismic refraction survey is the geophysical method most closely related to rock mass properties because the longitudinal seismic wave velocity varies with the main features, which characterizes the rock mass (rock properties, jointing, stresses etc.). Therefore, the results from such seismic measurements may assist in site selections and in rock engineering.

Seismic refraction measurements have been used in Scandinavia for at least 40 years in connection with planning of dams, tunnels and portals. The earliest applications were primarily for the determination of the depth to bedrock beneath soil cover. Since 1959 the method has also been used successfully for the location of weakness zones, such as shear zones and faults (Sjögren et al., 1979). Such zones give considerably lower and therefore easily recognisable seismic velocities than in the surrounding rocks. From the beginning of the 1960s refraction seismic velocities measured in the field have also been used to indicate rock mass quality in fresh igneous and metamorphic rocks, as shown in Fig. 1.

The seismic survey methods utilize the propagation of compression or primary seismic waves. The ratio of the shear (or transverse) and longitudinal sonic velocities can be used to determine the dynamic moduli of the rock as described by several authors including Sjögren et al. (1979), and Sjögren (1984).

The field measurements can be carried out on the ground, in boreholes, on the seabed, or just below the sea surface. In each case, the refracted head wave travels parallel to the ground surface. Seismic wave velocities are calculated from the slope in a 'travel time versus distance' graph worked out from the registrations in geophones placed along the measured profile. The determination of the seismic velocities and the thickness of the various layers of is a complex process, and a great deal of practical experience is required of the operator before the results can be regarded as reliable.

The usefulness of the seismic exploration technique can be extended through use of crosshole techniques between boreholes or between boreholes and the ground surface, as described by Nord et al. (1992).

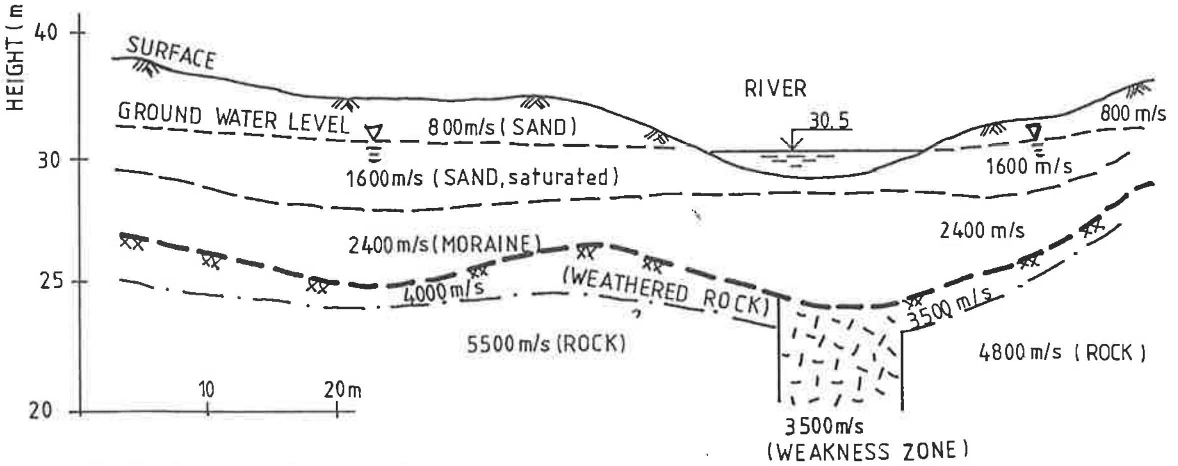

Fig. 1 Typical refraction seismic profile in hard, unweathered rocks with interpretations shown in brackets (from Broch, 1988).

2. FACTORS INFLUENCING SEISMIC VELOCITY

In the ground there are several factors that, in a complex way, may influence the propagation of seismic velocities. The main contributions stem from 1) the inherent properties of the rock material; and 2) the in situ rock mass conditions, i.e. distribution of rock types, jointing, rock stresses, and ground water condition.

Velocities of longitudinal waves vary considerably with the *type of rock* which is determined by the mineral composition, texture, density, porosity, anisotropy and degree of weathering. A representative selection of typical longitudinal (compressional) seismic velocities is given in Fig. 2. In addition, saturation, pressure, and temperature influence.

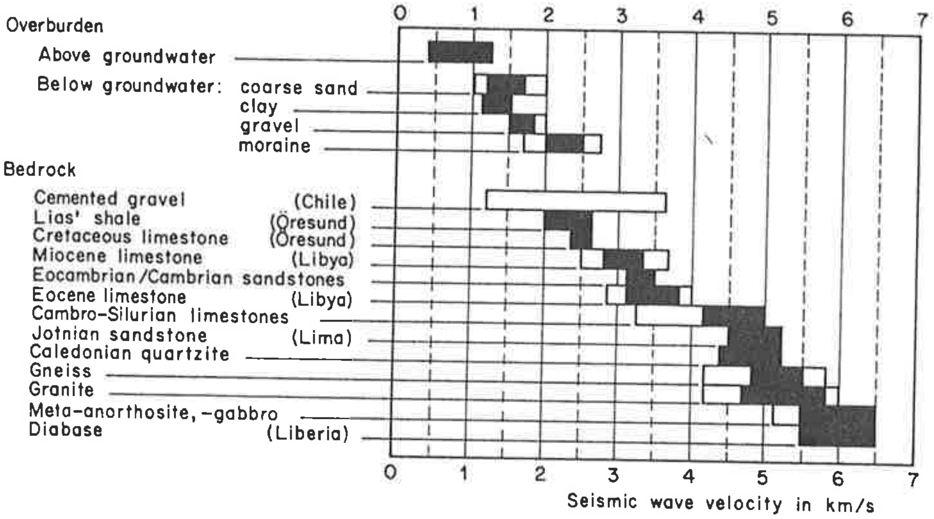

Fig. 2 Typical ranges of longitudinal seismic velocities for intact rocks (from Sjögren, 1984)

Sjögren et al. (1979) conclude from their investigations that, in addition to the influence from the inherent rock properties, the in situ longitudinal velocities in unweathered rock masses are mainly determined by:

- the stresses acting;
- the degree of jointing;
- the presence of open joints or joints with filling; and
- the ground water conditions.

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The amount of joints strongly influences the velocity of the seismic waves. This is an important feature in the interpretation of refraction seismic measurements to assess the degree of jointing. Another feature is the general increase of the seismic velocity of rocks and rock masses with depth. This is mainly caused by closing of open joints and cracks as a result of increased *pressure*. Cecil (1975) mentions that the increase in velocities from the ground surface to a tunnel 50 - 60 m below is up to 17% for high quality rock and up to 38% for low quality (highly jointed) rock. Sjögren et al. (1979) have found the same tendency with an increase of 5 - 15% in velocity at a depth 30 - 50 m compared with that of the surface and usually an even greater increase in low velocity zones. Thus, it is obvious that direct comparisons of velocities in the surface and in the tunnel cannot be made. As the ground pressure increases with depth the effect of jointing on sonic velocities is reduced. This feature reduces the ability of the refraction seismic measurements to effectively characterize the degree of jointing in deep tunnels.

Seismic refraction measurements can not be used to assess the condition of the joint itself (roughness and alteration of the joint surface; filling and size of the joint). Cecil (1975) points out that clay and other weak or low friction joint fillings, which may cause instability in a rock mass with few joints, may not influence the seismic velocity. On the other hand, one or two open joints that may not have any effect on the stability of an opening, can significantly lower the seismic velocity and give the impression of low quality rock. The possibility that such conditions may exist, must be considered in the geological interpretation of the seismic refraction results.

3. CORRELATIONS BETWEEN JOINTING AND SEISMIC VELOCITIES

In Scandinavia, an approximate method to utilize seismic velocities to estimate rock mass quality and tunnel support requirements has been frequently used for 30 years. Cecil (1971) concludes that *"It can be said almost without exception that on the surface of the hard crystalline bedrocks of Sweden seismic velocities of 4000 m/s or less are indicative of weak zones in the bedrock. Stretches on a profile with such a velocity thus can be considered to be weak zones without further question, provided the surrounding higher velocities are greater than 4900 m/s."*

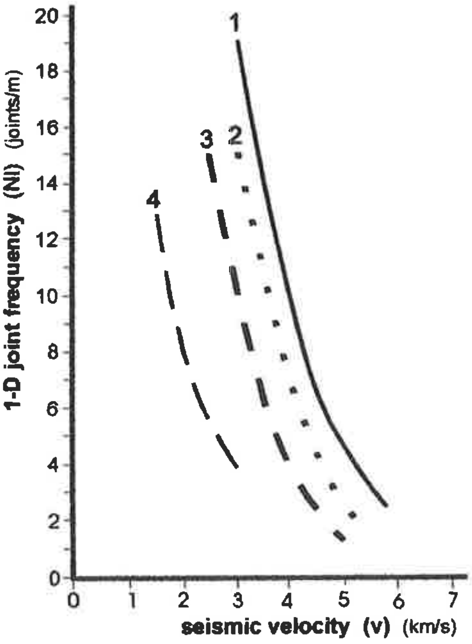
An example of a classification often used in Norway is shown in Table I. It should be noted that this classification is crude and that it is related to unweathered, hard, crystalline rocks. The classification may in many occasions be inaccurate and occasionally even wrong.

TABLE I APPROXIMATE CORRELATION BETWEEN SEISMIC REFRACTION VELOCITIES, ROCK MASS CONDITIONS AND ROCK SUPPORT IN SCANDINAVIAN TUNNELS (partly based on Sjögren et al., 1979)

In situ velocity m/s	**Probable ground conditions**	**Possible rock support**
< 3000	Cavities in the bedrock filled with soil, or completely crushed and fragmented rock material in weakness zones.	Extensive
< 4000	Ground related to faults, contact zones etc. with highly fractured rock.	High
4000-4400	Strongly to moderately jointed rock masses.	Moderate to high
4500-5000	Slightly to moderately jointed rock masses	Small - moderate
> 5000	Massive rock masses.	Generally little need for rock support

4. CORRELATIONS BETWEEN SEISMIC VELOCITIES AND JOINTING

A vast amount of experience has been gained from more than 30 years of seismic refraction surveys in Scandinavia. Sjögren et al. (1979) carried out a comprehensive investigation of field measurements and gave correlations between seismic velocities obtained in refraction surveys and joints measured in drill cores. The investigation comprised 113 km of seismic refraction profiles and 2850 m of drill cores from 8 sites in unweathered, igneous and metamorphic rocks such as amphibolite, granite, gneiss, meta-anorthosite, pegmatite, porphyry, quartzite, and mylonite. From the results they have equated the longitudinal seismic velocity (v) measured with 1-D joint frequency (Nl) in boreholes as shown in Curve 1 in Fig. 3.



KEY

1: Average results of jointed, unweathered, igneous and metamorphic rocks of Palaeozoic age in Scandinavia

2: Jointed granite, granodiorite, and andesite from the Andes, Chile (based on data from Helfrich, Hasselström and Sjögren, 1970).

3: Jointed and weathered metamorphic rocks from the Andes (based on data from Sjögren, 1993). The rock are quartzite, and various schists and shales.

4: Jointed Triassic and Permian sandstones from Tanzania (Sjögren, 1984).

Fig. 3 Correlations between seismic wave velocity (v) and joint density (Nl) for various types of rocks (from Sjögren et al., 1979, and Sjögren, 1984, 1993).

The basic longitudinal velocity (V_o) is that velocity which is considered to represent the intact rock (i.e. the rock with no joints) under the same conditions of stress and ground water regime as in the field (see Fig. 4). Extension of the curves in Fig. 3 indicates that the basic longitudinal velocity is different for each case, probably due to differences in composition and other properties of the rock. The parallel nature of the curves indicates that they possibly can be calculated fron V_o.

Correlations between seismic velocities and the degree of jointing can be found from two different approaches:

1: *Initial correlation method* for cases where no information is available on the jointing versus seismic velocity.

2: *Refined correlation method* for cases where at least two correlations between jointing and seismic velocities are already known.

These two methods are described in detail in the following sections.

4.1 Initial correlation method

Palmström (1995) has shown two different potential expressions which may be used to represent the relationship between jointing and seismic velocity where no previous correlation exists:

$$Nl = V_0^{3.4} \cdot v^{-2.8} \qquad \text{eq. (1)}$$

$$Nl = 3(V_0/v)^{Vo/2} \qquad \text{eq. (2)}$$

where V_0 is the basic velocity of intact rock under the same conditions as in the field.
v is the measured in situ seismic velocity (km/s)

Both correlations rely on the assessed magnitude of the basic velocity (V_0) which represents the site-dependent (in situ) velocity for intact rock. Where V_0 is not known, it is recommended to use the velocity for intact rock under the same conditions as in the field (wet/dry, orientation of anisotropy, stress conditions, etc.) from laboratory testing.

Joint openness and possible joint fillings may, however, effect the accuracy of both correlations described above where V_0 is assessed from laboratory measurements, or estimated from Fig. 2 or from tables in textbooks. Therefore, alt. 2 described in the next section gives more accurate results as it includes the site-dependent features.

4.2 Refined correlation method

Sjögren et al. (1979) have presented the following expression to calculate the degree of jointing from measured seismic velocities:

$$ks \cdot Nl = 1/v - 1/V_n \qquad \text{eq. (3)}$$

where V_n is the maximum or 'natural' velocity in crack- and joint-free rock (see Fig. 4).The 'natural' velocity for some rocks measured in the laboratory are shown in Table II.
ks is a constant representing the actual in situ conditions,
Nl is the 1-D joint frequency (joints/m) along the drill core or a scanline.

The method is based on known data on the jointing collected from field observations and/or logging of cores from boreholes in the seismic profile. Data from at least two different locations are required to work out a curve similar to that shown in Fig. 4.

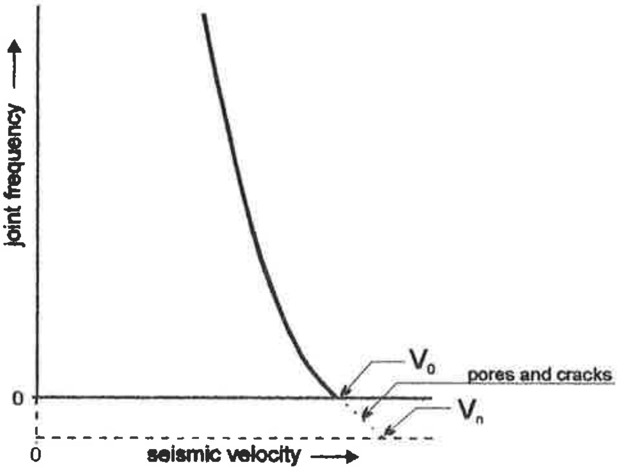


Fig. 4 The principle difference of the basic seismic velocity (V_o) and the natural or maximum velocity (V_n)

TABLE II APPROXIMATE (NATURAL) VELOCITIES OF FRESH ROCKS WITHOUT CRACKS AND PORES. (from Goodman, 1989, based Fourmaintraux, 1976).

Rock	**V_n (km/s)**	**Rock**	**V_n (km/s)**
Gabbro	7	Basalt	6.5 - 7
Limestone	6 - 6.5	Dolomite	6.5 - 7
Sandstone and quartzite	6	Granitic rocks	5.5 - 6

It is seldom possible to find V_n at the surface by seismic measurements as the rocks near the surface are seldom free from joints, cracks and pores. Therefore, V_n can best be found from a calculation procedure such as that described in the following:

The two unknown constants ks and V_n in eq. (3) can be found using two data sets of measured values of Nl and the corresponding v :

$$V_n = \frac{v_1 \cdot v_2 (Nl_2 - Nl_1)}{Nl_2 \cdot v_2 - Nl_1 \cdot v_1} \qquad \text{eq. (4)}$$

and

$$ks = \frac{1}{Nl_1} \left(\frac{1}{v_1} - \frac{1}{V_n} \right) \qquad \text{eq. (5)}$$

Here Nl_1 , v_1 and Nl_2 , v_2 are corresponding values of joint frequency and measured in situ seismic velocity, respectively, for the two pairs of measurements.

When ks and V_n have been found from eq. (4) and (5), the degree of jointing given as joints/m is found from

$$Nl = (V_n - v)/(V_n \cdot v \cdot ks) \qquad \text{eq. (6)}$$

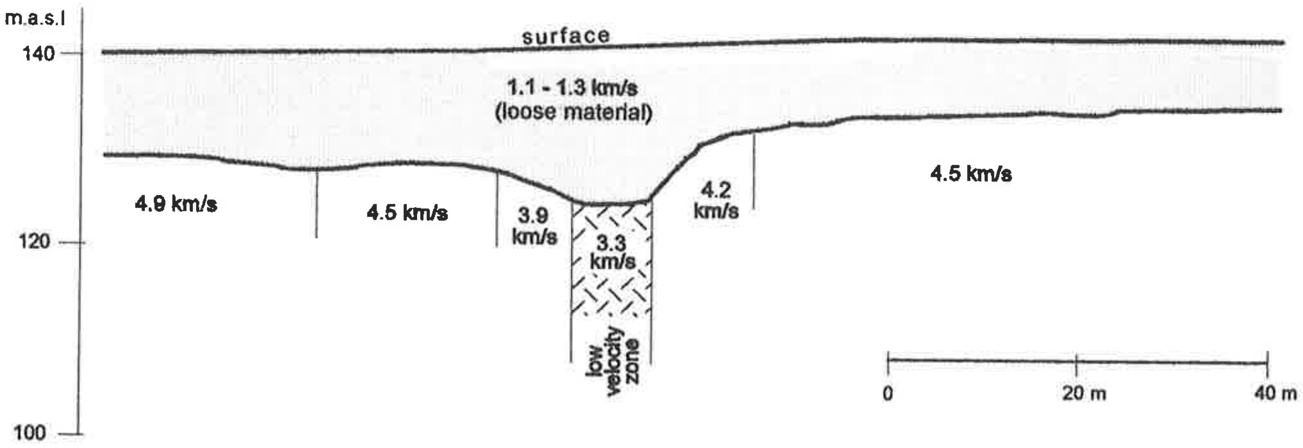
From eq. (6) a curve representing the correlation between the measured jointing density and the seismic velocities can be established.

According to Sjögren et al. (1979) these theoretical calculations of average jointing frequencies have shown a satisfactory agreement with those empirically obtained. The discrepancies between them have been less than 0.5 joints/m. In this way, seismic refraction measurements provide a useful and very attractive tool for the characterization of the degree of jointing.

5. WORKED EXAMPLES

5.1 Initial correlation method

During the initial planning stage of a project a geological survey was carried out which showed that the bedrocks in the area consisted of fresh dolomite, but no information was available on the jointing. Seismic refraction measurements were performed in an area covered by loose deposits as shown in Fig. A5-8. The rocks in this area were below the ground water table. Based on the velocities of intact rock in Fig. 2 the basic velocity of dolomite is estimated as $V_0 = 5.5$ km/s.



The correlations between the degree of jointing (given as joints/m) and sonic velocity from Section 4.1 are:

i: $Nl = V_0^{3.4} \cdot v^{-2.8} = 329\ v^{-2.8}$

ii: $Nl = 3(V_0/v)^{V_0/2} = 326\ v^{-2.75}$

These two expressions for jointing versus velocity have been illustrated in Fig. 6 as the curves 'a' and 'b'.

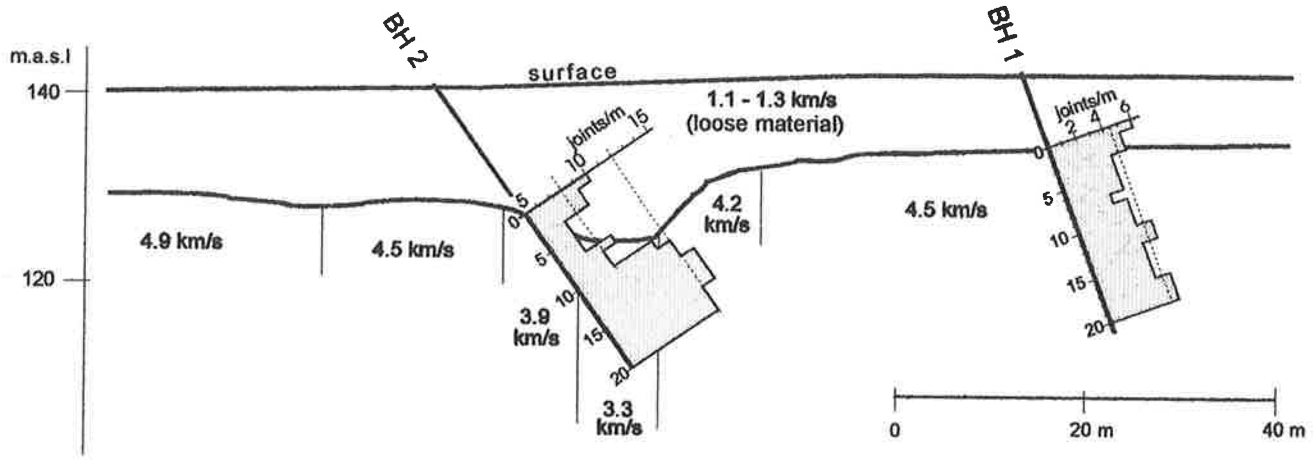


Fig. 6 Seismic refraction profile and core drilling results.

5.2 Refined correlation method

At a later phase in the project two core drillings were carried out in the seismic profile line given in Fig. 5. The joint frequencies are shown in Fig. 6.

Three pairs of data from core drilling and seismic measurements are used to establish the relationship between the degree of jointing and the longitudinal seismic velocities. These are shown in Table III.

Table III THE DATA USED FROM DRILL CORES AND SEISMIC MEASUREMENTS

Seismic velocity	Joints/m	Borehole no	Comment
1. $v_1 = 4.5$ km/s	$Nl_1 = 4.5$	BH 1	Average along the whole borehole in rock
2. $v_2 = 3.3$ km/s	$Nl_2 = 12$	BH 2	Average for 10 - 20 m along the borehole
3. $v_3 = 3.9$ km/s	$Nl_3 = 8$	BH 2	Average for 0 - 10 m along the borehole

Combining data set 1 and 2 in Table III the two unknown constants, ks and V_n, in eqs. (4) and (5) are found as:

$$V_n = \frac{v_1 \cdot v_2 (Nl_2 - Nl_1)}{Nl_2 \cdot v_2 - Nl_1 \cdot v_1} = \frac{4.5 \cdot 3.3 (12-4.5)}{12 \cdot 3.3 - 4.5 \cdot 4.5} = 5.76 \text{ km/s}$$

and

$$ks = \frac{1}{Nl_1} \left(\frac{1}{v_1} - \frac{1}{V_n}\right) = \frac{1}{4.5} \left(\frac{1}{4.5} - \frac{1}{5.76}\right) = 0.0097$$

The correlation between the degree of jointing given as joints/m and velocity is then

$$Nl = (V_n - v)/(V_n \cdot v \cdot ks) = (5.76 - v)/(5.76 \cdot 0.0097 \cdot v) = 17.9(5.76 - v)/v$$

This has been illustrated in Fig. 7 as curve 'c'. Similarly, combination of data set 2 and 3 gives curve 'd'. As is seen there is good agreement between all curves for joint frequencies higher than 6 joints/m. For the lower frequencies the initial correlation method (curve 'a' and 'b') deviates from the refined correlation method (curve 'c' and 'd') The latter is considered the most representative.

From the known value of this 1-D joint frequency (Nl) the volumetric joint count and the block volume can be calculated applying appropriate correlations.

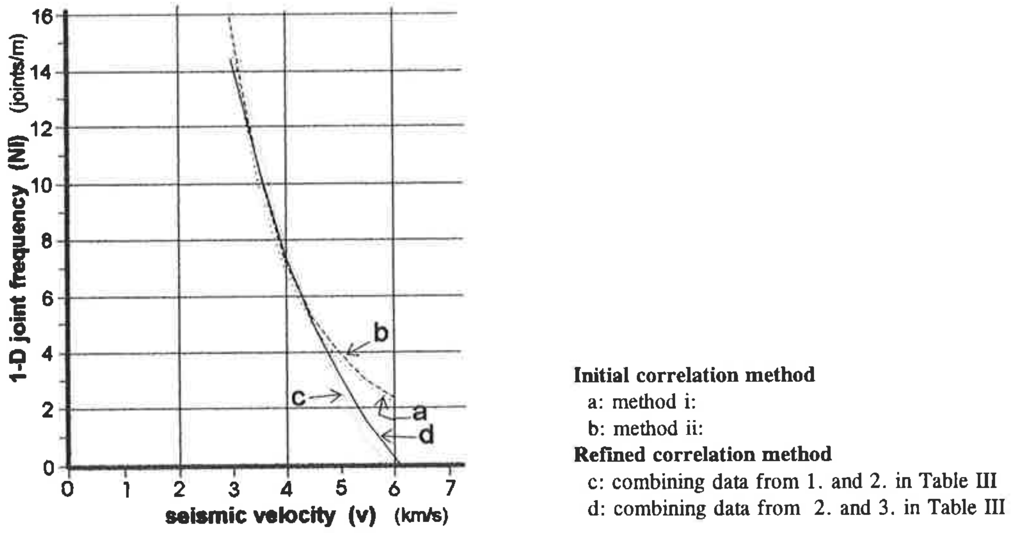


Fig. 7 Various correlations between seismic velocities and 1-D joint frequency for the worked example.

6. CONCLUSION

Mathematical correlations between seismic refraction velocities and the degree of jointing can be applied before information on jointing from core drilling or surface mapping is available. In this way, it is possible to obtain information of the probable jointing at an early stage during investigations. It should, however, be noticed that in these calculations local differences such as the composition of rock types, mineral content, etc. are averaged, and that the calculations require input of an assumed 'basic velocity' (V_0) of the intact (fresh or weathered) rock. The accuracy of V_0 highly influences the quality of the assessments.

At a later stage, when the degree of jointing has been measured in drill cores or from observations in rock exposures, the accuracy of the assessments can be significantly improved. The jointing found in this way can be used to characterize the jointing along the entire seismic profile provided it is located in the same type of rocks. Thus, the information collected in the a limited volume of the rock mass by logging a borehole or by joint observation in a surface exposure can be significantly extended.

There are *limitations* in the use of seismic refraction interpretations of jointing assessments. These mainly stem from the fact that there are several properties and features influencing on the seismic velocity, and it is impossible to avoid uncertainties when variations in the velocity is linked mainly to one or more of these. Knowledge of the geological conditions linked with comprehensive experience in refraction seismic measurements is important in reducing these limitations.

Increase in stress level is known to cause closing of the joints and hence the potetial to indicate variations in joint density is reduced where the measurements are performed in deep tunnels. Thus, for this reason the seismic refraction measurements generally give better results on or near the surface where the stress level is low or moderate.

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