From Palmstrom A.: RMi - a rock mass characterization system for rock engineering purposes.
PhD thesis, Oslo University, Norway, 1995, 400 p.

APPENDIX 5

USING REFRACTION SEISMIC VELOCITIES TO CHARACTERIZE JOINTING

> *"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

Refraction seismic measurement is the geophysical method most closely related to rock mass properties because the longitudinal sonic velocity recorded varies with rock properties as well as jointing, stresses etc. in the rock mass. The results from such seismic measurements may therefore 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 depths 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 velocities in fresh rocks. From the beginning of the 1960s refraction seismic velocities have also been used as indicator of rock mass quality in fresh igneous and metamorphic rocks, as shown in Fig. A5-1.

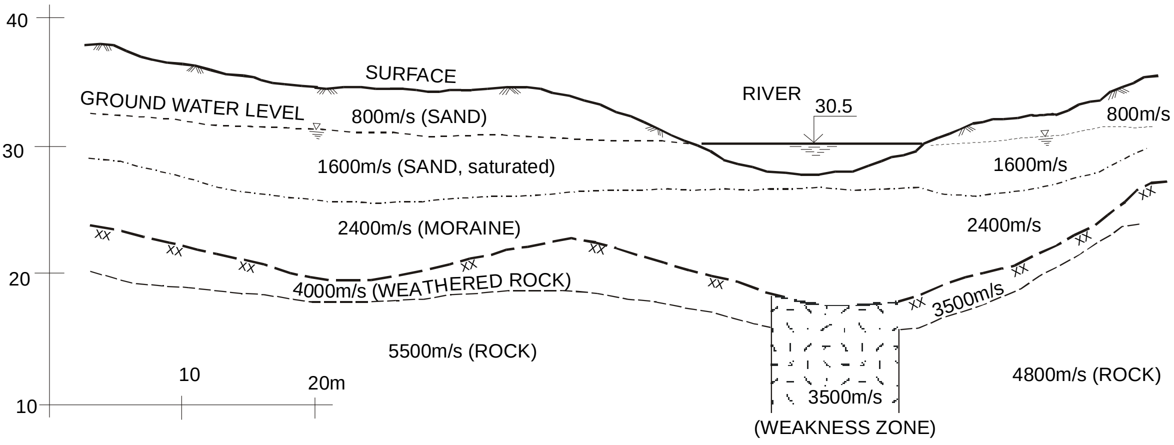


Fig. A5-1 Typical refraction seismic profile in hard, unweathered rocks with interpretations shown in brackets (from Broch, 1988).

The seismic refraction measurement utilizes the propagation of elastic waves in the ground. The compression or primary (P) sonic waves are easiest to detect and have mainly been used in the measurements. 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 Sjögren et al. (1979) and several other authors. In this appendix only the use of the longitudinal sonic velocities are described.

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 surface. Velocities are calculated from the slope in a 'travel time versus distance' graph worked out from the registrations. The determination of the sonic velocities in the various layers is a complex process, and a great deal of practical experience is required of the operator before the results can be regarded reliable.

The usefulness of the seismic exploration technique can be extended through use of cross-hole techniques between boreholes, as described by Nord et al. (1992).

1 FEATURES INFLUENCING THE MAGNITUDE OF LONGITUDINAL SONIC VELOCITIES

In the field there are several factors that, in a complex way, may influence the propagation of sonic velocities. The main contributions stem from:

- The inherent properties and condition of the rock material consisting mainly of:
    - rock type (mineral content, texture, density, porosity, anisotropy);
    - weathering or alteration of the rock material;
    - saturation;
    - pressure; and
    - temperature.
- The in situ conditions, with the main contributions from:
    - distribution of rock types;
    - quantity of joints;
    - joint openings;
    - rock stresses; and
    - ground water condition.

The most important of these factors are briefly discussed in the following.

1.1 Factors influencing the sonic velocities in intact rock

Velocities of longitudinal waves vary considerably with the *type of rock*. A representative selection of typical longitudinal (compressional) sonic velocities is given in Tables A5-1 to A5-3.

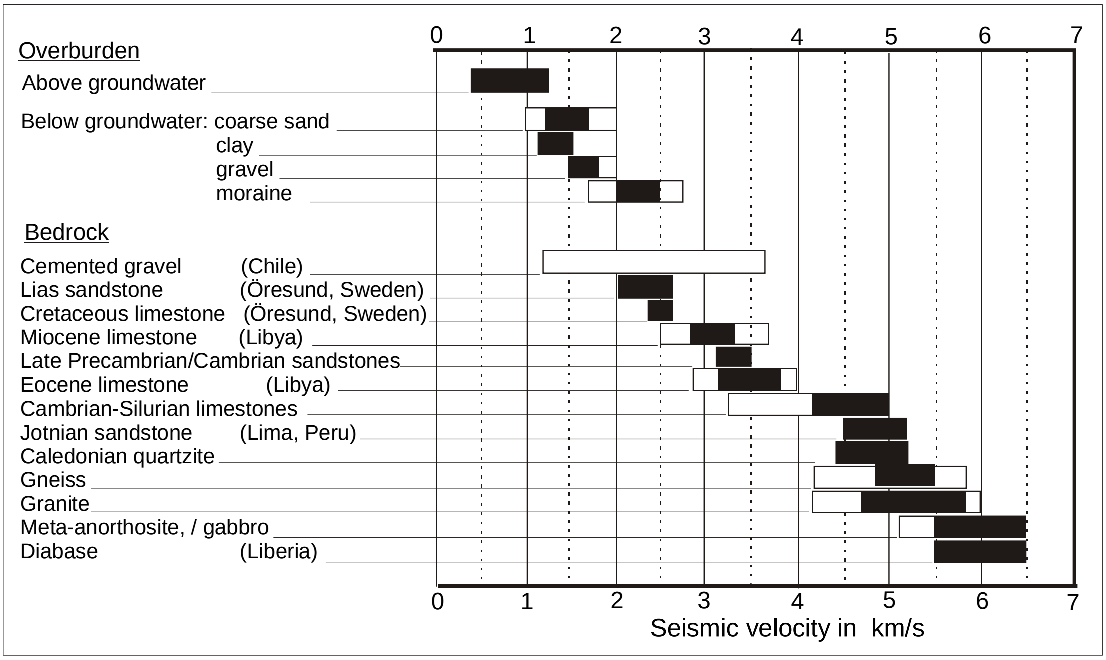
TABLE A5-1 LONGITUDINAL VELOCITIES OF SOME MINERALS.
(data from Fourmaintraux (1976), presented by Goodman, 1989).

Mineral	**V_m (km/s)**	**Mineral**	**V_m (km/s)**	**Mineral**	**V_m (km/s)**
Amphibole	7.20	Epidote	7.45	Orthoclase	5.80
Augite	7.20	Gypsum	5.20	Plagioclase	6.25
Calcite	6.60	Magnetite	7.40	Pyrite	8.00
Dolomite	7.50	Muscovite	5.80	Olivine	8.40
				Quartz	6.05

TABLE A5-2 AVERAGE SONIC VELOCITIES FOR INTACT ROCKS (partly from Lama and Vutukuri, 1978)

Compact rocks	**(km/s)**	**Less compact rocks**	**(km/s)**	**Unconsolidated rocks**	**(km/s)**
Dunite	7	Limestone	4	Alluvium	1
Diabase	6.5	Slate and shale	4	Loam	1
Gabbro	6.5	Sandstone	3	Sand	1
Dolomite	5.5			Loess	0.5
Granite	5				

TABLE A5-3 TYPICAL RANGES OF LONGITUDINAL SONIC VELOCITIES FOR INTACT ROCKS (from Sjögren, 1984)



The *density* of the rock is one factor, which affects the velocity of longitudinal sonic waves. In the elastic wave theory the velocity decreases with increasing density. The effect of density is, however, overruled by the dynamic stiffness of the rock, which generally varies with the density. Therefore, the sonic velocity seems incorrectly to vary with the density of the rock as shown in Fig. A5-2.

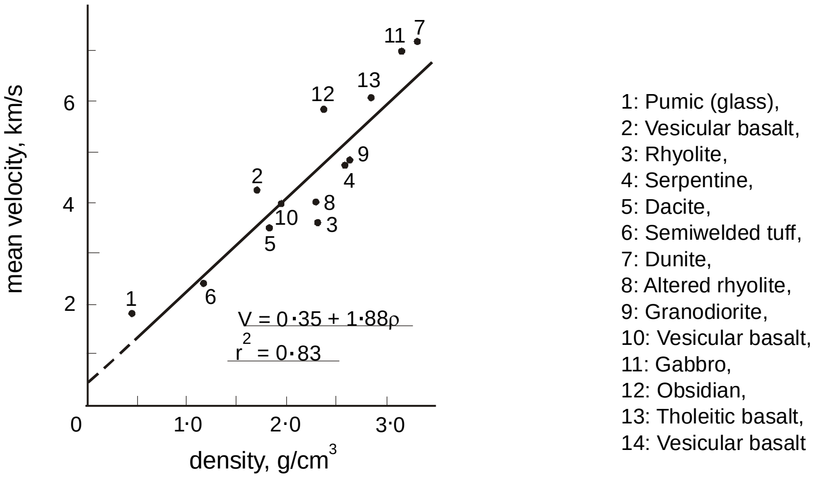


Fig. A5-2 Mean longitudinal pulse velocity versus density of the rock.
(Data from Bur and Hjelmstad, 1970, compiled by Lama and Vutukuri, 1978).

The *wetting* of porous rocks leads to change of elastic wave velocities in them. The higher the sound velocity in the pore filling material, the greater is the total velocity in the rock sample (Lama and Vutukuri, 1978). Since the sonic velocity in water (V_l) is five times greater than air, water saturation leads to a rise in the elastic wave velocity in hard rocks. However, the wave velocity in more porous rocks completely saturated with water is lower than in slightly porous rocks, because V_l is less than the sound velocity in the mineral skeleton.

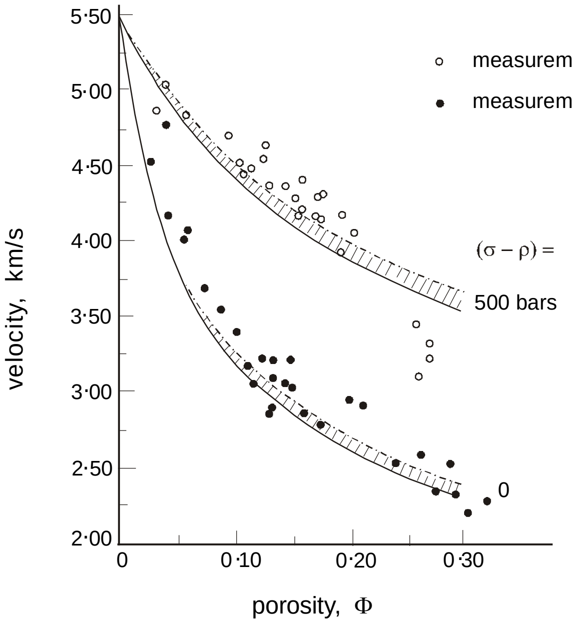


Fig. A5-3 Longitudinal wave velocity versus porosity for two different effective stresses (from Lama and Vutukuri, 1978)

TABLE A5-4 ANISOTROPY COEFFICIENTS FOR SOME ROCKS (from Lama and Vutukuri, 1978)

ROCK	Anisotropy coefficient $V_{¦}/V_{-.}$	ROCK	Anisotropy coefficient $V_{¦}/V_{-.}$
Austin chalk	1.17	Anhydrites	1.12 - 1.16
Limestones	1.04 - 1.30	Marl	1.10
Salt	no anisotropy	Sandstones	1.0 - 1.19
Shales	1.07 - 1.40	Gneisses	1.20 - 1.27
Mica schist	1.36	Granodiorite	1.33
Serpentine	1.18		

In *anisotropic* rocks the velocity parallel to the layers ($V_{¦}$) is always greater than the velocity perpendicular to the layers ($V_{-.}$). The coefficient of anisotropy (defined as the ratio of the velocity along and across the layers) in Table A5-4 vary between 1.0 and 1.40. Measurements performed by Bergh-Christensen (1968) on schists and phyllites show that this coefficient can have considerably higher values. Increasing the pressure on rock reduces the effect of anisotropy.

Usually, the velocity of longitudinal waves falls with rise in *temperature*. Below 400^{o}C and at atmospheric pressure, the temperature coefficient of variation of velocity has the values given in Table A5-5.

The presence of pores, cracks and flaws highly influences the sonic velocity in the rock. At low *pressure* the pulses are transmitted through the water or air-filled gaps and the velocity is significantly affected by the gaps and voids. However, at high pressure the content of gaps becomes less important since, as the cracks are closed; in this situation the increase in velocity is determined by the rock framework. A generally rapid increase in velocity at low pressures is due to a decrease in porosity from closing of cracks and defects, leading to an increase in the mechanical contact between the grains. See Fig. A5-4.

TABLE A5-5 COEFFICIENT OF TEMPERATURE INCREASE FOR SOME ROCKS GIVEN AS % INCREASE IN THE SEISMIC VELOCITY (from Ide, 1937, Lama and Vutukuri, 1978).

ROCK	% per 100°C	ROCK	% per 100°C
Quartzitic sandstone	-1	Danby marble	-3
Solenhofen limestone	-1.2	Sudbury norite	-4
French Creek norite	-1.6	Vinal Haven diabase	-5

The velocity increase at higher pressure results from changes in intrinsic properties of the rock, such as finite compression of the minerals. In some rock specimens, the sonic velocity is observed to decrease (as in salt) and in others it decreases when pressure exceeds a certain value (as in some limestones).

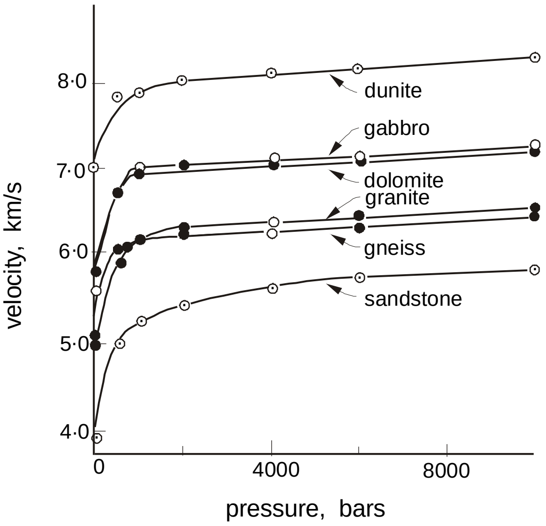


Fig. A5-4 Longitudinal wave velocity versus pressure (from Lama and Vutukuri, 1978, based on data from Birch, 1960).

1.2 The influence from in situ factors on measured sonic velocities

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

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

Both compression and shear sonic velocities of rocks generally increase with increasing *pressure*. There is often a rapid velocity increase at low pressures due to a closing of the joints. In and near the surface with low stress level the joints are generally more or less open. Thus, the degree of joints will strongly influence velocity of the waves. This is an important feature in interpretation of refraction seismic measurements to assess the degree of jointing.

The increase in stress level by depth, therefore, causes increase in longitudinal sonic velocities. Cecil (1975) mentions that the difference between velocities measured on the ground surface and in the 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 from their investigations found the same tendency with an increase of 5 - 15% at a depth 30 - 50 m from the rock surface, and a usually greater increase in low velocity zones.

This trend can be explained by:

1. An overall loosening of rock at the bedrock surface that has occurred after glacial retreat (as in Scandinavia). Weak zones at the bedrock surface probably are considerably more relieved and loosened than sounder rock.
2. A tightening effect of joints with depth caused by the increase of ground stresses.
3. The effect of weathering in upper the 10 - 30 m of the ground (in Scandinavia). This may have resulted in development of additional joins as well as opening up of joints in addition to increased weathering along joints.

Thus, it is obvious that direct comparisons of velocities in the surface and in the tunnel cannot be made. As the ground pressure increases by 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.

2 EARLIER METHODS USED TO CHARACTERIZE ROCK MASSES FROM SEISMIC VELOCITIES

Although there is a clear correlation between jointing and seismic refraction velocities, the latter also includes the averaged effect of other factors such as rock properties and stress conditions as further dealt with later in this section.

TABLE A5-6 APPROXIMATE CONNECTIONS BETWEEN REFRACTION SEISMIC 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 rock support.
< 4000	Ground related to faults, contact zones etc. with highly fractured rock.	High amount of rock support.
4000-4400	Strongly - moderately jointed rock masses.	Moderate to high amount of rock support.
4500-5000	Slightly - moderately jointed rock masses.	Small to moderate amount of rock support.
> 5000	Massive rock masses.	Generally little need for rock support.

2.1 Connections between jointing and seismic velocities

In Scandinavia, an approximate method to utilize seismic velocities measured in the field 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 A5-6. It should be noted that this classification is crude and that it is related to unweathered, hard, crystalline rocks. The method may in many occasions be inaccurate and even wrong.

2.2 Rock quality estimated from the seismic velocity ratio

Some authors have compared in situ velocities of longitudinal waves in the rock mass with the velocity of intact rock cores tested in the laboratory in order to characterize rock quality. The 'Seismic Velocity Ratio' introduced by Merritt (1968) is defined as

$$SVR = V_f / V_r \qquad \text{eq. (A5-1)}$$

where V_f is the longitudinal seismic wave velocity measured in the field, and
V_r is the basic sonic wave velocity measured in the laboratory.

For a massive rock mass containing only a few joints, the velocity ratio (V_f / V_r) should approach unity; but as the degree of jointing becomes higher, (V_f / V_r) will be reduced.

The squared seismic velocity ratio named 'Velocity Index' $VI = (V_f / V_r)^2$ of Coon and Merritt (1970) is comparable to SVR. The ratio has been squared to make the velocity index (VI) equivalent to the ratio of the dynamic moduli. Table A5-7 illustrates the relationship between the velocity index, velocity ratio and rock mass quality. Cecil (1971) did not find that the squaring of the seismic velocity ratio had any advantages over the first power of seismic velocity ratio (SVR) other than a wider numerical band for the intermediate support category.

TABLE A5-7 RELATIONSHIP BETWEEN TUNNEL SUPPORT CATEGORY AND SEISMIC VELOCITY RATIO (based on data from Cecil, 1970 and Bieniawski, 1984)

Seismic velocity ratio (SVR = V_f / V_r)	**Velocity index** VI = SVR^2	**Description of rock mass quality**		**Tunnel support category**
> 0.9	> 0.8	very good		minimum
0.8 - 0.9	0.6 - 0.8	good		intermediate
< 0.8	0.4 - 0.6	fair	)	
	0.2 - 0.4	poor	}	maximum
	< 0.2	very poor	)	

2.3 Correlations between seismic velocities and rock mass characteristics

A vast amount of experience has been gained from more than 30 years with refraction seismic measurements in Scandinavia. Sjögren et al. (1979) have from a comprehensive investigation of field measurements shown correlations between seismic velocities and joints measured in drill cores taken in seismic profiles. The investigation comprised 113 km of refraction seismic 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 longitudinal seismic velocity with 1-D joint frequency in boreholes as shown in Fig. A5-5.

The curve in Fig. A5-5 may be representative for jointed unweathered hard, crystalline rocks near the surface. The high velocities are well represented in the curve, but for velocities below about 3500 m/s the data are more scattered. The curve may, therefore, be less representative in this part. Additional uncertainties may stem from the fact that logging of drill cores is generally less accurate in highly jointed and crushed rock. Cecil (1971) proposed a multiplication factor of 0.8 for the higher in situ velocities in order to overcome this problem.

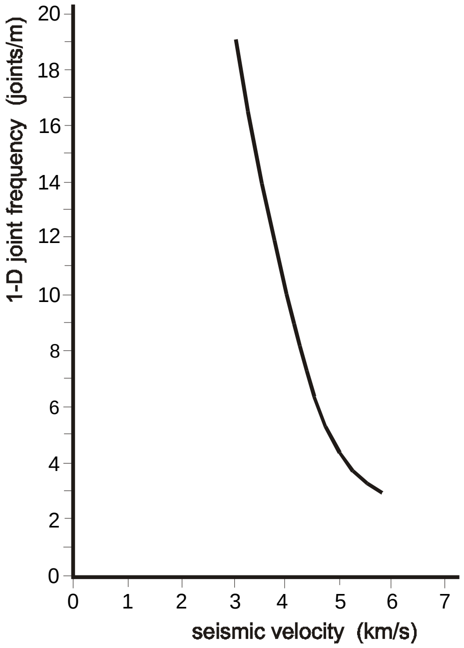


Fig. A5-5 Average regression curve of the correlation between longitudinal sonic velocity (v) and joint density. The curve is derived from 5 sites comprising igneous and metamorphic rocks with 1670 m of cores (from Sjögren et al.,1979).

Sjögren et al. (1979) found from their studies that a factor of 0.75 for the rocks of higher velocities and 0.85 for the relatively low velocities gave a better result. This idea has not been further developed, probably because it may be difficult to define more accurately for which velocity range the factor should be applied.

Another investigation has been presented by Cecil from various projects in Sweden. Refraction seismic measurements in tunnels and at the ground surface above were compared. The seismic velocities were correlated to the amount of rock support installed in the tunnel. Unfortunately, the descriptions of the rock mass quality have not been included in this investigation; therefore, the results are of limited value in this work.

3 METHODS FOR ASSESSING THE DEGREE OF JOINTING FROM IN SITU SEISMIC VELOCITIES

Fig. A5-6 shows 4 different correlations between seismic velocity and joint density. The curves represent various geological conditions including both fresh and weathered rocks. It is interesting to notice that all the four curves are almost parallel for the higher degrees of jointing (>10 joints/m). The basic longitudinal velocity (V_0) for the various curves is different, probably caused by different properties and compositions of the intact rock. V_0 is considered to represent the velocity of intact rock under the same conditions (i.e. stress and water conditions) as in the field, see Fig. A5-7. Thus, the jointing is considerably lower for the same sonic velocity as the basic velocity (V_0) decreases.

Curve 2 and 3, contrary to the other two curves, show that there is a stronger influence from few joints on the sonic velocities. This may be due to a generally larger aperture (opening) of the joints in these two sites.

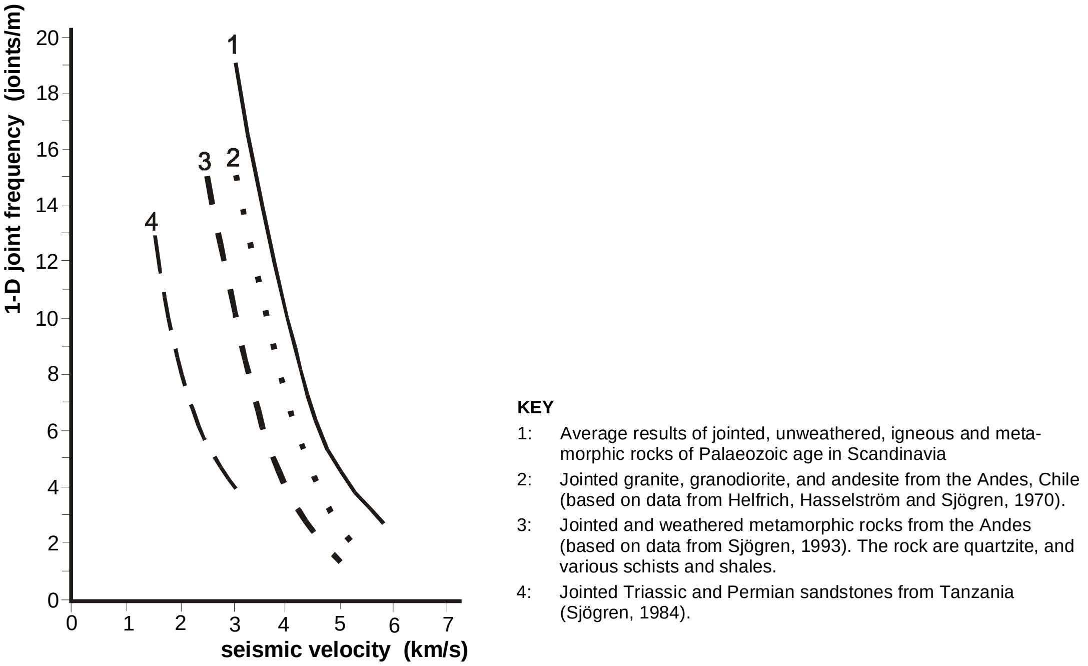


Fig. A5-6 Correlations between velocity and joint density for various types of rocks based on results from Sjögren et al. (1979) and Sjögren (1984, 1993).

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

1: No information is available on the jointing versus seismic velocities.
2: At least two correlations between jointing and seismic velocities are known.

The application of these two methods is described in the following.

3.1 Alt. 1. Correlations between jointing and sonic velocity are not known.

The generally exponential distribution of joints (see Table A1-4 in Appendix 1) has been applied to express the curves in Fig. A5-6 as

$$Nl = b \cdot v^{a} \qquad \text{eq. (A5-2)}$$

where Nl is the 1-D joint frequency (joints/m) along the drill core or scanline,
v is the seismic velocity (km/s) measured in the field,
a and b are constants related to the local conditions (rock material, stress conditions, jointing features etc.).

Two different methods have been developed to find the values of a and b:

i: *The correlation*[1] *is expressed as* $Nl = b \cdot v^{-2.8}$. The factor b, which represents the local conditions, is found from $b = V_0^{3.4}$ which gives

$$Nl = V_0^{3.4} \cdot v^{-2.8} \qquad \text{eq. (A5-3)}$$

where V_0 is the basic velocity (velocity of intact rock under the same conditions as in the field).

As seen in Table A5-8 the deviation is generally less than 25% for the four curves, except for very high and very low degree of jointing.

ii: *The constants (a) and (b) vary with the basic velocity* (V_0). The following correlations have been found based on the curves in Fig. A5-6:

$$a = -V_0/2 \qquad \text{eq. (A5-4)}$$

$$b = 3/V_0^{a} = 3V_0^{Vo/2} \qquad \text{eq. (A5-5)}$$

From this eq. (A5-2) can be written

$$Nl = b \cdot v^{a} = (3/V_0^{a})\, v^{-Vo/2} = 3(V_0/v)^{Vo/2} \qquad \text{eq. (A5-6)}$$

The comparison between eqs. (A5-3) and (A5-6) for the curves 1 - 4 in Fig. A5-6 is shown in Table A5-8. There is a relatively acceptable accuracy for all curves except curve 3 for which the calculated results are somewhat higher than the real. Method ii gives a better correlation between jointing density and seismic velocity than method i.

Important in both methods is 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.).

Joint openness and possible fillings may, however, disturb the accuracy of both correlations described above where V_0 is estimated from laboratory measurements, or from Table A5-2 or similar tables in textbooks. Therefore, alt. 2 described in the next section gives more accurate results as it includes the site-dependent features.

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[1] The constant value of a = -2.8 and the eq. (A5-3) have been found from trial and error fitting to the curves in Fig. A5-6.

TABLE A5-8 CORRELATIONS BETWEEN SEISMIC VELOCITY AND JOINTING FOR VARIOUS VALUES OF THE FACTORS (a) AND (b) IN Eq (A5-2). THE CURVES REFERRED TO ARE THOSE IN FIG. A5-6.

Correlation	**FIELD VELOCITY in km/s**						
$Nl = b \cdot v^a$	1.5	2	2.5	3	4	5	5.5
Joints/m in curve 1				**19**	**9.5**	**4.5**	**3.5**
($V_0 = 5.8$ km/s)							
i: $Nl = 394\ v^{-2.8} =$				18.2	8.1	4.3	3.3
ii: $Nl = 490\ v^{-2.9} =$ →				20	8.8	4.6	3.5
Joints/m in curve 2				**15**	**7.5**	**3**	**2**
($V_0 = 5.5$ km/s)							
i: $Nl = 329\ v^{-2.8} =$				15.2	6.8	3.6	2.8
ii: $Nl = 325\ v^{-2.75} =$ →				15.8	7.2	3.1	3.0
Joints/m in curve 3			**15**	**10.5**	**4**	**1.5**	
($V_0 = 5.3$ km/s)							
i: $Nl = 290\ v^{-2.8} =$			22	3.4	6.0	3.2	
ii: $Nl = 229\ v^{-2.65} =$ →			20	12.5	5.8	3.2	
Joints/m in curve 4	**13**	**8**	**5.5**	**4**			
($V_0 = 3.5$ km/s)							
i: $Nl = 70\ v^{-2.8} =$	22	10	5.4	3.2			
ii: $Nl = 27\ v^{-1.75} =$ →	13.3	8	5.4	3.9			

V_0 is the basic velocity (for intact rock).
i: The factors a = constant = -2.8 and $b = V_0^{3.4}$ (eq. (A5-3))
ii: The factors $a = - V_0/2$ and $b = 3/V_0^a$ (eq. (A5-6))
→ best fit equation of of **i:** and **ii:**

3.2 Alt. 2. Two or more correlations exist between jointing and velocities

Sjögren et al. (1979) have presented a method to calculate the degree of jointing from measured velocities in seismic profiles. The method is based on known data on jointing and velocities in least two different locations in the profile. They developed the following relation:

$$x/V_z + (1 - x)/V_n = 1/v \qquad \text{eq. (A5-7)}$$

where V_n is the maximum or 'natural' velocity of rock, see Table A5-9. Both V_0 (the basic velocity of intact rock) and Vn refer to seismic velocities in intact rock. As shown in Fig. A5-7 Vn are for rocks without cracks and pores.

V_z is the velocity in the crushed or highly jointed rock material,
v is the in situ velocity recorded in the field,
x is the length with the velocity V_z along the measured profile.

This expression has been derived into

$$ks \cdot Nl = 1/v - 1/V_n \qquad \text{eq. (A5-8)}$$

in which ks is a constant representing the actual in situ conditions,
Nl is the 1-D joint frequency (joints/m) along the core, and
v is the measured in situ velocity (km/s).

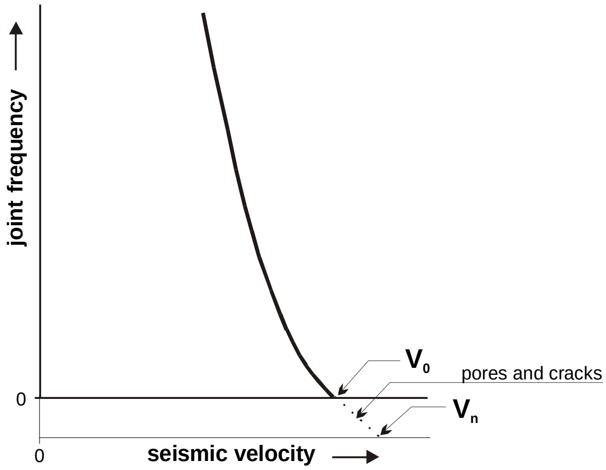

Fig. A5-7 The principle difference of the basic seismic velocity ($V_{0.}$), and the natural or maximum velocity (V_n).

TABLE A5-9 APPROXIMATE (NATURAL) VELOCITIES OF FRESH ROCKS, FREE FROM CRACKS AND PORES. THE VELOCITIES ARE BASED ON THE CONTENT AND VELOCITIES OF THE MINERALS SHOWN IN TABLE A5-1 (from Goodman, 1989, based on data from 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 generally seldom possible by seismic measurements to find (V_n) at the surface as the rocks in the surface seldom are free from joints, cracks and pores. Therefore, (V_n) can best be found from eq. (A5-8) using the calculation procedure described in the following.

The two unknown constants (ks) and (V_n) can be found using two data sets of measured values of (Nl) and the corresponding (v). From this, the natural or maximum velocity is

$$V_n = \frac{v_1 \cdot v_2 (Nl_2 - Nl_1)}{Nl_2 \cdot v_2 - Nl_1 \cdot v_1} \qquad \text{eq. (A5-9)}$$

When V_n has been determined the factor representing the in situ conditions is

$$ks = \frac{1}{Nl_1} \left(\frac{1}{v_1} - \frac{1}{V_n}\right) \qquad \text{eq. (A5-10)}$$

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

After ks and V_n have been found from eq. (A5-9) and (A5-10), the degree of jointing given as joints/m is found from

$$Nl = (V_n - v)/(V_n \cdot v \cdot ks) \qquad \text{eq. (A5-11)}$$

From eq. (A5-11) a curve similar to that in Fig. A5-7 which represents the actual connection between the measured jointing density and the sonic velocities can be established.

Sjögren et al. (1979) showed that 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. Thus, seismic refraction measurements provide a useful tool to characterize the degree of jointing which may be found very attractive.

3.3 Worked examples

3.3.1 No field information is available on jointing versus sonic velocities

During the initial planning stage a geological survey was carried out which showed that the bedrocks in the area consisted of fresh dolomite. No information was available on the jointing. Refraction seismic 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 Table A5-2 and A5-3 the basic velocity of dolomite is estimated as $V_0 = 5.5$ km/s (from Table A5-2). V_0 is used to find the value of the constants 'a' and 'b' in eqs. (A5-3) to (A5-6)

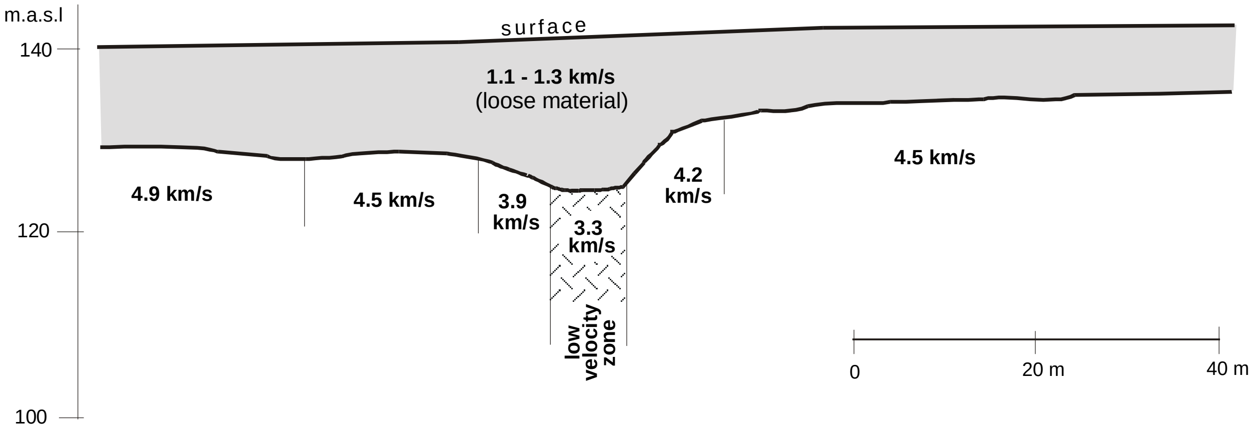

Fig. A5-8 The velocities measured in a refraction seismic profile located in dolomite.

method i: *The constant a = const. = -2.8*

The factor b varies with V_0. Based on the general expression $Nl = b \cdot v^{-2.8}$ the constant

$$b = V_0^{3.4} = 5.5^{3.4} = 329$$

The correlation between the degree of jointing (given as joints/m) and sonic velocity is

$$Nl = b \cdot v^{-2.8} = 329\, v^{-2.8}$$

method ii: *Both constants (a) and (b) vary with the basic velocity* (V_0).

From eqs. (A5-4) and (A5-5) the constants

$$a = -V_0/2 = -5.5/2 = -2.75$$

$$b = 3/V_0^{a} = 3/5.5^{-2.75} = 326$$

The degree of jointing versus sonic velocity is then

$$Nl = b \cdot v^{a} = 326\, v^{-2.75}$$

These two expressions for jointing versus velocity have been illustrated in Fig. A5-10 as 'a' and 'b'.

3.3.2 Field data on jointing and sonic velocity are available.

Two core drillings were later carried out in the seismic profile in Fig. A5-8 as shown in Fig. A5-9.

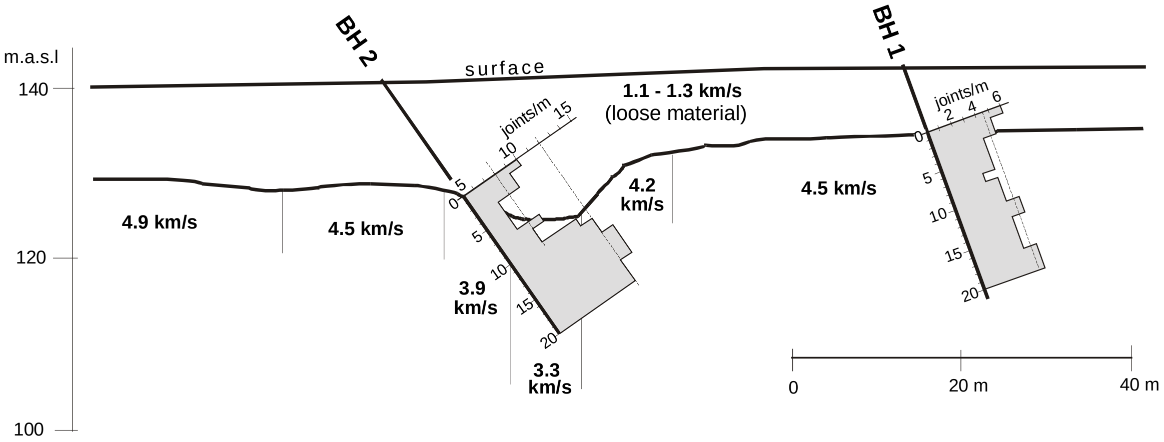

Fig. A5-9 Refraction seismic profile and core drilling results.

Three pairs of data from core drilling and seismic measurements are used to establish the relation between the degree of jointing and the longitudinal velocities. These are shown in Table A5-10.

Table A5-10 THE DATA USED FROM DRILL CORES AND SEISMIC MEASUREMENTS

sonic velocity	joints/m	borehole	comment
1. $v_1 = 4.5$ km/s	$Nl_1 = 4.5$	BH 1	(average along the whole borehole in rock)
2. $v_2 = 3.5$ km/s	$Nl_2 = 12$	BH 2	(average for 0 - 10 m along borehole)
3. $v_3 = 3.9$ km/s	$Nl_3 = 8$	BH 2	(average for 10 - 20 m along borehole)

Combining data set 1 and 2 in Table A3-10 the two unknown constants, ks and V_n, in eqs. (A5-9) and (A5-10) are found as:

$$V_n = \frac{v_1 \cdot v_2 (Nl_2 - Nl_1)}{Nl_2 \cdot v_2 - Nl_1 \cdot v_1} = \frac{4.5 \cdot 5.5(11 - 4.5)}{11 \cdot 3.5 - 4.5 \cdot 4.5} = 5.61 \text{ km/s}$$

and

$$ks = \frac{1}{Nl_1} \left(\frac{1}{v_1} - \frac{1}{V_n} \right) = \frac{1}{4.5} \left(\frac{1}{4.5} - \frac{1}{5.61} \right) = 0.010$$

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

$$Nl = (V_n - v)/(V_n \cdot v \cdot ks) = (5.61 - v)/(5.61 \cdot 0.01 \cdot v) = 17.8(5.61 - v)/v$$

This has been illustrated in Fig. A5-10 as curve 'c'. Similarly, combination of data set 2 and 3 gives curve 'd'. As is seen there is a good accordance between all curves for joint frequencies higher than 6 joints/m. For the lower frequencies curve 'c' or 'd' are considered as being the most representative.

From the known value of 1-D joint frequency, Nl, the block volume can be calculated applying the expressions derived in Appendices 3 and 4.

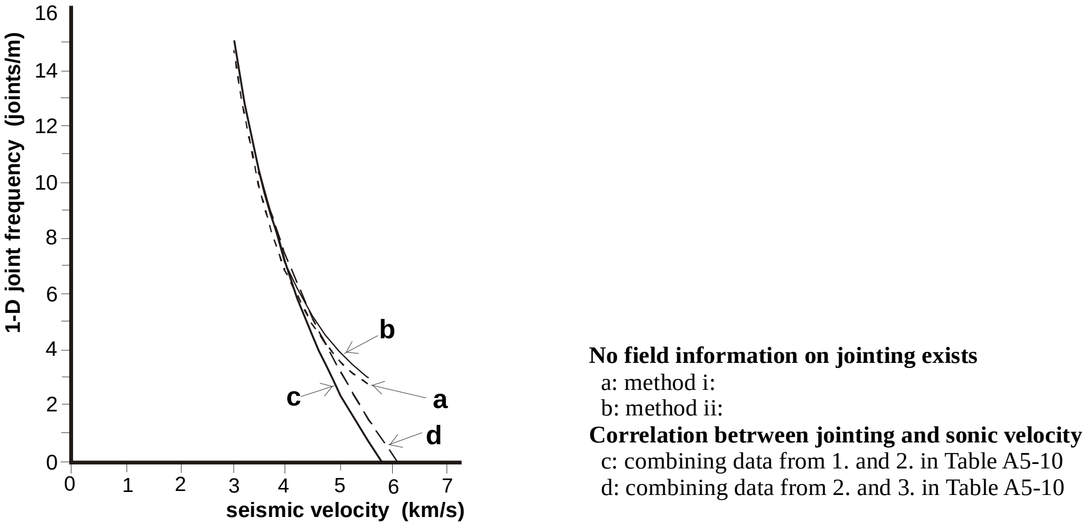

Fig. A5-10 Correlation between the results in the example.

4 Summary

Mathematical correlations between seismic velocities and the degree of jointing have been developed so that the degree of jointing can be estimated at an early stage during investigations where field data on jointing are lacking. 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 rock. The accuracy of V_0 highly determines 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 of jointing from seismic velocities can be significantly improved. The jointing found in this way can be used to characterize the block size along the entire seismic profile provided it is located in the same type of rock; thus, the information collected in the very limited volume of the rock mass covered by the borehole can be largely extended.

There are *limitations* in the use of seismic refraction interpretations in rock mass quality assessments. These stem mainly from the fact that there are several properties and features influencing on the velocity, and it is impossible to avoid uncertainties when variations in the velocity is linked only to one or a few of these.

Refraction seismic measurements cannot be used to assess the joint condition (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. Therefore, a thorough knowledge of the geological conditions linked with comprehensive experience in seismic measurements is important

As an increase in the stress level causes closing of the joints, the possibility to indicate variations in jointing is reduced. Therefore, refraction seismic measurements are preferably performed near the surface where the stress level is low or moderate.