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ASSESSMENT OF GROUTING EFFICIENCY IN A ROCK MASS IN TERMS OF SEISMIC VELOCITIES

ESTIMATION DE L'EFFICACITÉ DES INJECTIONS DANS UN MASSIF ROCHEUX PAR LES VITESSES DE PROPAGATION DES ONDES

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Abstract

Grouting is a geotechnical process involving, for example, injection of a cement sand and water mixture or chemical resins into the ground to improve the strength and to decrease the permeability of rocks and soils. The efficiency of grouting operations is generally assessed by carrying out permeability and loading tests. Additionally, the comparison of the seismic field velocities of a rock mass obtained before and after the grout injection operation can give a qualitative indication of the effectiveness of grouting. However, for a quantitative assessment of grouting efficiency, more complex analysis of the rock mass seismic velocity is required.

Analysis of field seismic velocity data from different dam sites in the U.K. (Knill, 1970), according to the time average equation has given a relation between the field seismic fracture index and the field P wave velocity of the rock mass that is best represented by a curve. The relation between the fracture index and the seismic P wave velocity is extended by assuming a P wave velocity of 1.46 km/s for groundwater, 2.40 km/s for grout, and taking the intact rock P wave velocity value from the analysis of data given by Knill. The results are presented as a diagram which can be used for grout efficiency assessment of the rock mass. Comparison of the published results from various dam sites with the diagram indicates that the diagram gives an upper bound curve. Additionally, a dimensionless version of the diagram is also presented for practical application.

Résumé

La consolidation par injection est une méthode géotechnique qui consiste à injecter par exemple un mélange de mortier de ciment et d'eau ou de résines chimiques dans les sols et les roches afin d'en améliorer la résistance et de diminuer la perméabilité. L'efficacité des injections est vérifiée en général au moyen d'essais de chargement et de perméabilité. En outre la comparaison des vitesses de propagation des ondes dans une masse rocheuse en place avant et après les opérations d'injection peut donner une idée qualitative de l'efficacité de ces dernières. Cependant une estimation quantitative de l'efficacité des injections nécessite une analyse plus complexe de la vitesse de propagation des ondes dans le massif rocheux.

L'analyse des mesures de vitesse des ondes sur un certain nombre de sites de barrages en Grande Bretagne a permis d'établir une corrélation entre l'indice de fracturation du massif et la vitesse de propagation de l'onde P. Pour établir cette corrélation, on a admis que la vitesse de l'onde P dans l'eau souterraine est de 1.46 km/s, dans le coulis injecté de 2.40 km/s et que les vitesses de propagation de l'onde P dans la roche saine sont celles indiquées par Knill. Les résultats sont présentés sous forme d'un diagramme qui peut être utilisé pour vérifier l'efficacité de l'injection dans un massif rocheux. La comparaison des résultats publiés sur différents sites de barrages avec le diagramme montre que ce dernier donne une courbe située en haut du fuseau.

Introduction

Grouting is a geotechnical process which involves injection of, for example, cement, soil and water mixture or chemical resins into weak and permeable ground in order to improve its properties. The injected materials harden over a period of time and make the ground stronger and less permeable. The properties of grouted ground are controlled by the properties of the materials comprising the grout mixture and its interaction with the rock or soil mass. Since, the injected materials can only travel in voids or joints, the permeability and porosity of the rocks and soils to be grouted are of prime importance in the selection of the right grout type and for the success of the grouting operation.

Grouting finds a wide field of application in construction of civil and mining engineering structures and improvement of already existing structures. For example, grouting is regularly carried out to reduce the permeability and increase the strength of rock and soil masses in dam foundations. Other applications of

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grouting include filling voids in old mine workings, caverns in limestone, shaft and tunnel lining and undepinning of already existing structures (Cambefort, 1977; Littlejohn 1985).

Grouting is an expensive operation and, thus, it is highly desirable to be able to predict the required grout intake with reasonable accuracy before the construction of structures. However, at present, grouting tends to be a rule of thumb operation and is generally carried out according to the experience of the operators or contractors.

The efficiency of grouting is generally assessed by carrying out in situ permeability and/or loading and unloading tests. Attempts have also been made to establish the influence of grouts on ground properties by comparing the seismic velocities before and after the grouting operations. Lancaster-Jones (1967) gave lists of dam sites where improvements in static and dynamic moduli and seismic velocity have occurred due to grouting. Knill (1970) attempted to establish the relation between seismic velocity and grout intake in dam sites from the U.K., but with limited success. Blinde *et al.*, (1983 a,b) determined the seismic velocities in a borehole in granite before and after grouting. They also tried to establish the relation between the fracture frequency, in situ permeability and rock mass velocity. Rodrigues *et al.*, (1983), determined the changes which occurred in seismic velocity with grouting in the Cabril dam site in Spain, but did not find a very good correlation between the seismic velocity increase grout intake and permeability of the rock mass. Bonaldi *et al.*, (1983) found that the changes in seismic velocity after grouting decreased with depth in the Passante dam foundation in Italy. Additionally there was little correlation between increase in seismic velocity and the rock mass permeability. Bruce and George (1985) compared the relation of grout intake versus rock mass P wave velocities (Knill, 1970), with the Wimbleball dam results and did not find a conclusive relation.

In this paper, initially a brief summary of the factors influencing the seismic velocity of rocks is given. Then, the methods of seismic rock mass characterization for assessing ground improvement efficiency by grouting is given. The time average equation has been applied to the seismic P wave velocity results given by Knill (1970) from various damsites in the U.K., for grout efficiency assessment purposes. It is shown that there is a relation between the field seismic fracture index and field P wave velocities of a rock mass. This relation is extended by assuming a P wave velocity of 1.46 km/s for groundwater and of 2.40 km/s for grouts, and is presented as a diagram for the cases of fully and partially grouted rock masses. Additionally the field P wave velocity results obtained before and after grouting in various damsites have been compared with the diagram (Fig. 2). The problems of prediction of grout intake and grout efficiency assessments are discussed.

Factors affecting seismic velocities in rocks

Since rock materials are easy to handle and characterize in the laboratory, most studies on the factors influencing rock seismic velocity have been carried out on rock specimens. The influence of different factors on the seismic velocities of rocks can be summarized as follows (Gregory, 1977; Lama and Vutukuri, 1978 and Yale, 1985).

The factors that influence the seismic velocities of rocks, can be divided into two groups : internal and external. While the important internal factors include rock type, grain size, texture, anisotropy, density and porosity, the external factors include porewater, compressive and confining pressures, temperature, water content, and pore fluid properties.

The seismic velocities are higher for dense and compact rocks than for light and porous rocks. Seismic velocity is influenced by the size of the mineral grains comprising the rock. The velocity is greater in fine grained rocks than in coarse grained rocks. The mineral grains have directionally varying seismic velocities. Thus, in anisotropic rocks, the seismic wave velocities differ along and across the layers and the velocity parallel to the layers is always greater than the velocity normal to the layers. While the velocity of rock increases with increasing density, it decreases with increasing porosity.

Increasing pore water pressure decreases seismic velocity, whereas increasing compressive and confining pressures increase the velocity. The saturation of rock specimens with water increases the seismic P wave velocity. Since shear waves can only pass through the mineral skeleton, the S-wave velocity is almost the same for both dry and saturated rocks. It has also been found that the P wave velocity of sedimentary rocks, at varying degrees of water saturation, is porosity dependent (Gregory, 1977). Generally, an increase in temperature causes a decrease in the velocity of seismic waves. However, an abrupt rise in seismic velocity is observed when the temperature of saturated rocks falls below the freezing point of water (Lama and Vutukuri, 1978).

The seismic velocity of the rock mass will not only be influenced by factors affecting the rock materials, but also by the rock mass features. The important features are : rock types; distribution of weathering and alteration zones; thickness, dip and strike of the beds; the properties of the joints, i.e. frequency, openness, the presence of fill and water, dip and strike of the joint planes; depth and the presence of water (fresh, saline or geothermal). Therefore, any field seismic velocity value gives an overall picture of the influence of these factors.

While seismic velocities of rock materials are estimated using ultrasonic waves in the laboratory, seismic waves are generally used in field explorations. Although the seismic velocities of rocks are frequency dependent, this is not thought to be an important factor in comparison to the influence of the above-mentioned factors on the seismic velocity of rocks.

Seismic rock characterization

Various attempts have been made to characterize rocks in terms of their seismic velocities including for example groutability assessment purposes.

Some researchers have attempted to grade the ground into various zones by comparing the field seismic velocity with the velocities obtained on the same material in the laboratory. Onodera (1963) defined the velocity ratio, which is the ratio of the P wave velocity of the rock mass to the intact specimen, as the quality index of the rock mass. When the ground has a high quality, it implies that the rock mass has only a few tight joints and the velocity ratio should approach unity. As the degree of fracturing becomes greater, the velocity ratio will be reduced and thus, the grout requirement will also increase. The sonic velocity, it is suggested, should be determined for cores in the laboratory under an axial stress equal to the estimated or computed overburden stress at the depth from which the sample was taken and at a moisture content equivalent to that assumed for the in situ rocks, i.e. air dry or saturated.

Knill (1970) defined fracture index of the groundmass as the ratio of the in situ P wave velocity to the laboratory P wave velocity on saturated cores. Knill also attempted to correlate the fracture index and grout intake of the rock mass at dam sites, and found that his fracture index alone was not a sensitive measure of grout intake.

Wyllie *et al.* (1956) proposed that the time average equation should be used to describe or estimate the P wave velocity of saturated rocks. Several researchers have attempted to use their equation to characterize the rock mass either in the original or in a modified form (Militzer, 1967; Voronkov, 1967; Malone, 1968; Sjogren *et al.*, 1979 and Blinde *et al.*, 1983 a,b). Most of these attempts tried to relate fracture frequencies to the seismic P wave velocities of rock masses without giving any consideration to the joint direction and width and the presence of groundwater or any fill material. Thus, the application of the time average equation to characterize the rock mass has had only limited success.

The application of the time average equation to P wave velocities of saturated weathered andesite specimens from Turkey, has given higher estimates of porosities than the values determined by laboratory saturation (Table 1). Similarly, the time average equation has been found to give an upperbound curve fit to the saturated rock mass porosity values by Eaton and Watkins (1970) on field test results from different sources (Fig. 1). Additionally, the time average equation does not give a good fit for the P wave velocities of dry rock mass as expected (Fig. 1). Blinde *et al.*, (1983 a) reported that in their experience, the seismic fracture index was observed to be too high, indicating that the time average equation gives the upperbound relation. Boyce (1976) also demonstrated that the time average equation gave the upperbound relations for saturated sedimentary rocks when their porosities were plotted against the average P wave velocities.

Table 1 : Laboratory determined (n) and P wave velocity estimated (n_v) porosities and seismic fissuration indices (K) for weathered andesites from Turkey.

Andesite	n %	K	n_v %
Fresh	1.9	0.21	5.6
Slightly weathered	3.6	0.48	13.2
Moderately weathered	9.1	0.68	16.3

Recently, Turk & Dearman (1986) have proposed new methods of rock characterization in terms of seismic velocities. These methods not only include rock material properties, but also take into account the presence of water and pressure. The seismic fissuration index, K, is defined as the ratio of the difference in P or S wave velocities obtained when a dry rock specimen is test both under a load equal to the uniaxial compressive strength (V_o) and without an applied load (V_d) to the velocity measured without an applied load as $K = (V_o - V_d)/V_d$ for the rock material.

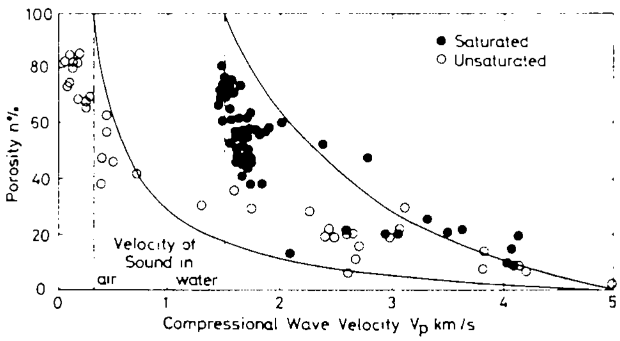


Fig. 1 : Porosity versus P wave velocity for saturated rocks and consolidated sediments. Values assumed in calculation of the theoretical curves: V_{pgrain} = 5.0 km/s; V_{pair} = 0.33 km/s and V_{pwater} = 1.5 km/s (Source Fig. 13, Eaton and Watkins 1970).

The seismic fissuration index is shown to be related to the porosity of rocks. Similarly, a field seismic fissuration index is obtained by considering the rock mass depth, rock material velocity and porosity corresponding to the rock mass depth. The P wave and S wave fissuration index values are different because of the difference in their propagation properties for the same rock material and mass.

The proposed fissuration index can also be used for characterizing the saturated rock material and mass using the S wave velocities. However, the time average equation should be used for characterizing the saturated rocks in terms of the P wave velocity, even though it gives upper bound porosity values. Additionally, the efficiency of rock mass grouting can be assessed by applying the time average equation to the field P and S wave velocities. Table 2, gives a summary of the suggested methods for material and mass characterization in terms of seismic velocities and an applicable equation for each situation.

Application

Knill (1970) published laboratory determined and field seismic P wave velocities of saturated rocks from a number of dam sites in the UK. When these results are analysed by applying the time average equation and assuming Vo is equal to the saturated rock material velocity in Table 2, a high correlation is obtained between the field seismic fracture index (F) and the field P wave velocity (Fig. 2). It is interesting to note that the best fitting line gives a field P wave velocity of 1.65 km/s corresponding to $F = 1.0$. This velocity value is greater than the groundwater P wave velocity, which is about 1.50 km/s, indicating that there must be fill material in the joints in addition to water. Additionally, a P wave velocity of $V_f = 5.546$ km/s has been obtained for $F = 0$, from the analysis of Knill's data. However, when the time average equation curve is drawn, by taking the intact rock mass field velocity $V_f = 5.546$ km/s and water P wave velocity $V_w = 1.46$ km/s, the curve obtained gives an upperbound envelope to 39 out of 41 of Knill's test results (Fig. 3).

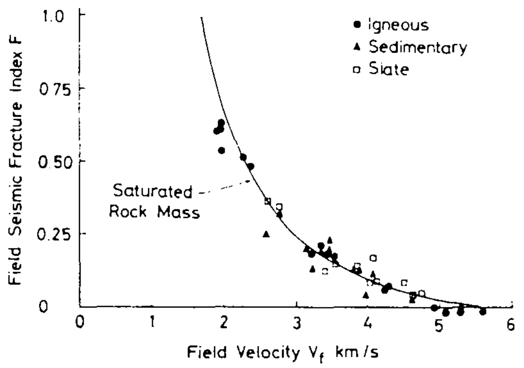


Fig. 2 : Seismic field fracture index versus field P wave velocity for the saturated rock mass (Data from Knill, 1970). The best fitted line is Log (F + 0.1) = 6.4 − 2.0 Log V_f, (r = − 0.96, n = 41).

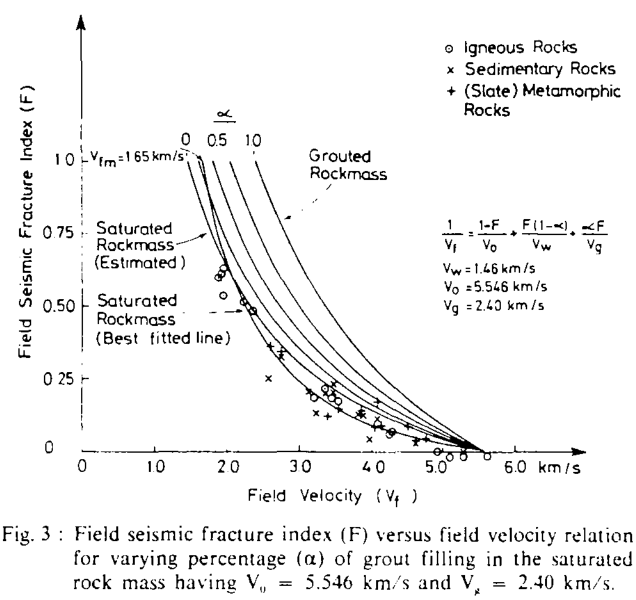


Fig. 3 : Field seismic fracture index (F) versus field velocity relation for varying percentage (α) of grout filling in the saturated rock mass having V_0 = 5.546 km/s and V_g = 2.40 km/s.

The seismic fracture index versus the field P wave velocity relation is also extended by assuming that the joints would be filled with grout having a P wave velocity of 2.40 km/s (Fig. 2). The relations for the cases of partial grouting at 25, 50 and 75 % on the seismic fracture index, have also been determined and plotted on the Fig. 3. Thus, it is suggested that Fig. 3 can be used as a reference diagram for assessing the efficiency of grouting operations in similar rock masses. Comparison of Fig. 3 with published seismic velocity values of a rock mass before and after grouting shows that the grouted rock mass curve gives the upperbound envelope, thus supporting earlier finding (Table 1, Fig. 1).

Grouting efficiency assessment

Grouting efficiency can be defined as the optimum amounts of voids, pores and fractures filled by material injected into the ground in order to achieve a required degree of ground permeability and/or strength. This implies that if possible, the minimum volume of ground should be fully grouted. This is difficult to achieve in practice. On the one hand, it is very difficult to predict or control the horizontal or vertical spread of the grout; on the otherhand, complete grouting is not always achieved by the end of the grouting operation. Therefore, successive grouting is generally applied to achieve specified ground properties.

Improvements in rock mass properties due to grouting can be assessed by carrying out permeability, loading and seismic velocity determinations. Since the grouted rock mass will have fewer voids, this should be reflected in the seismic properties. Thus, the seismic velocity of the grouted rock mass, in general, is expected to be higher than its pre-grouted seismic velocity. However, any direct increase in the seismic velocity due to grouting does not necessarily give an indication of grout intake and efficiency alone.

Grout intake and efficiency determinations require that not only the volume of the grouted rock mass, but also the intact rock and fracture porosities and their filled percentages should be known. While the extent and depth of grout penetration can be determined from comparison of seismic velocities before and after grouting, the grouted intact rock and fracture porosity determinations require more elaborate analysis of the seismic velocities.

Table 2 shows that, depending on the seismic wave type and moisture saturation condition, the seismic rock mass characterization parameters change. While the seismic fracture index (F) is theoretically related to the porosity of saturated ground, the relation between the seismic fissuration index (K) and porosity should be determined for dry ground, in order to be able to use the seismic index parameters for grout efficiency assessment. If all the pores and fractures are filled by the grout, the time average equation can be written for the fully grouted rock mass as :

$$\frac{1}{V_f} = \frac{1 - F}{V_0'} + \frac{F}{V_g} \qquad (1)$$

where

V_f = field velocity

V'_0 = intact rock velocity at a pressure equal to the depth of the rock mass concerned

V_g = grout velocity

F = seismic fracture index

The time average equation for the partially saturated case is :

$$\frac{1}{V_f} = \frac{1 - F}{V'_0} + \frac{F(1-\alpha)}{V_w} + \frac{\alpha}{V_g} \qquad (2)$$

where

V_w = seismic velocity of water

α = grouted percentage of the seismic fracture index. $\alpha = 0$ fully grouted, $\alpha = 1$ fully saturated.

The other parameters are as given above. By knowing or assuming the seismic velocities, then the change in F value with grouting can be determined from the above equations. Thus, the grouting efficiency can be determined either by comparing the (F) values obtained for the saturated and grouted rock mass or by determining "α" from the above equation.

The following points should also be considered in attempting to assess the grout efficiency in the rock mass :

1) The seismic waves travel along the quickest path. There may be some voids left between the fracture surfaces after grouting and not picked up by the seismic studies.

2) Vertical joints would take up most of the grout and P waves tend to travel parallel to the vertical joints.

3) In dry ground a high velocity increase is generally observed.

4) In wash-out zones, the field velocity after grouting would decrease and F would increase.

5) Intact rock porosity and permeability may be as important as the rock mass joints.

6) Suitable grouts should be selected to achieve the required properties in the grouted ground.

Discussion

Attempts to predict the grout intake in a rock mass using seismic velocities have not proved to be successful (Knill, 1970; Rodrigues *et al.*, 1983). This is believed to be due to proper consideration not being given to the factors influencing the seismic velocities of rocks and the propagation mechanism of the seismic waves. Table 2 gives a summary of the suggested methods of rock mass characterization in terms of seismic velocities. It is clear from the table that,

Tableau 2 : Suggested methods for rock material and mass characterization in terms of seismic velocities.

Conditions of Rock Material and Mass	Characterization Methods Laboratory and Field Seismic Velocities	Applicable Equations	
		Laboratory	Field
Dry	Seismic fissuration Index P and S wave velocities	$\frac{1}{V_d} = \frac{1+K}{V_0}$ $K_p \neq K_s$	$\frac{1}{V_f} = \frac{(1+N)(1+t)}{V_0}$
Partially Saturated	Seismic fissuration Index S wave velocity	$\frac{1}{V_d} = \frac{1+K_s}{V_0}$	$\frac{1}{V_f} = \frac{(1+N)(1+t)}{V_0}$
Saturated	Seismic fissuration Index S wave velocity Time Average Equation P wave velocity	$\frac{1}{V_d} = \frac{1+K_s}{V_0}$ $\frac{1}{V_f} = \frac{1-F}{V_0} + \frac{F}{V_w}$	$\frac{1}{V_f} = \frac{(1+N)(1+t)}{V_0}$ $\frac{1}{V_f} = \frac{1-F}{V'_0} + \frac{F}{V_w}$
Grouted	Time Average Equation P and S wave velocities	$\frac{1}{V_f} = \frac{1-F}{V_0} + \frac{F}{V_g}$	$\frac{1}{V_f} = \frac{1-F}{V''_0} + \frac{F}{V_g}$ $F_p \neq F_s$, $V'_0 = \frac{V_0 \cdot V_w}{(1-n)V_w + nV_0}$ $V''_0 = \frac{V_0 \cdot V_g}{(1-n)V_g + nV_0}$

V_0 = Intact rock seismic velocity
V'_0 = Intact, saturated rock velocity at a pressure equal to the depth of the rock mass concerned
V''_0 = Intact grouted rock velocity at a pressure equal to the depth of the rock mass concerned
V_d = Dry seismic velocity of rock mass
V_f = Field seismic velocity of rock mass
V_w = Seismic velocity of water
V_g = Seismic velocity of grout
K = Seismic fissuration index
K_p = P wave seismic fissuration index
K_s = S wave seismic fissuration index
F = Seismic fracture index
F_p = P wave seismic fracture index
F_s = S wave seismic fracture index
N = Field seismic fracture index
n = Open rock porosity under field pressure
t = Intact rock specimen sonic fissuration index under pressure equal to the field pressure.

depending on the ground saturation condition and seismic wave type, the rock mass characterization equation or parameter should be different. While for dry rock mass characterization it is suggested that the seismic fissuration index (K) should be used, the seismic fracture index (F) should be used for characterizing the saturated and grouted rock mass. Therefore, the relation between (K) and (F) should be known or established in order to assess the influence of grouting on the seismic velocities of the dry rock mass. Additionally, K and F indices are expected to be different for P and S wave velocities due to their differing propagation modes.

Since Knill's (1970) data include different rock types, the established relation between the seismic fissuration index and seismic P wave velocity of rocks in Fig. 2 should be applicable to all rock types. This also means that all rocks can be represented by a single seismic fissuration index versus seismic velocity curve. Also rocks can be regarded as having a maximum seismic velocity and any change in the seismic velocity is due to a change in F of rocks. Additionally, the difference between the best fitted line to Knill's (1970) data and the time average equation for the same F value in Fig. 2 indicates that the fractures are not always filled with water, and there must also be low velocity materials present in the fractures i.e. clays. Besides, the propagation direction of the seismic waves in relation to the rock mass fractures and refraction and reflection of the seismic wave would also give a lower rock mass velocity than theoretical relations.

Even though the saturated sonic velocity values were used instead of V_0, in analyzing Knill's (1970) field seismic data, this is not expected to have introduced major errors to the seismic field fracture index calculations, as the seismic velocity measured in rock masses in dam foundations were not expected to be under high pressures.

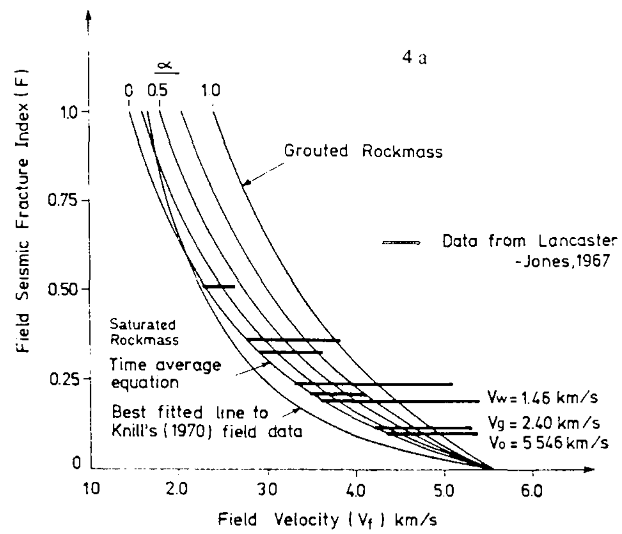
Table 3 gives the seismic velocity of the rock mass from different dam sites obtained before and after grout injection (Lancaster-Jones, 1967). When the table is compared with Fig. 3, though the majority of the seismic velocity values fall below the grouted rock mass curve, four seismic velocity values for quartz phyllite gave high increases after grouting and fall beyond the grouted rock mass curve (Fig. 4a). This discrepancy must have resulted from using grouts having greater seismic velocity than 2.40 km and/or the fact that the ground was dry before the grouting.

Table 3 : Improvements in the seismic velocity of the rock mass of some dam foundations by grouting (Lancaster-Jones, 1967).

Dam Site	Observations	V_{before} km/s	V_{after} km/s	Rock Type
Farahnaz Pahlavi	2	2.30	2.62	Hard sandstone
Roseland	—	2.75	3.80	Schist
Roseland	10	2.92	3.62	Mica Schist
Alcantara	30	3.50	4.09	Palaeozoic sediments
Frera, right bank	7	3.32	5.09	Quartz Phyllite
Frera, left bank (Horizontal)	3	3.60	5.40	Quartz Phyllite
Frera, valley bottom	9	4.22	5.33	Quartz Phyllite
Frera, left bank (vertical)	4	4.35	5.38	Quartz Phyllite

However, when the seismic field P wave velocities from the Passante dam in Italy (Fig. 5) and the Cabril dam in Spain (Table 4) are compared with Fig. 3, the majority of the grouted rock mass velocities fall below the fully grouted rock mass curve, as shown in Fig. 4b.

Figure 6 shows the seismic velocity measurements in granite using the uphole technique before and after grouting in a borehole drilled in granite (Blinde *et al.*, 1983 a). Though grouting increased the seismic velocity



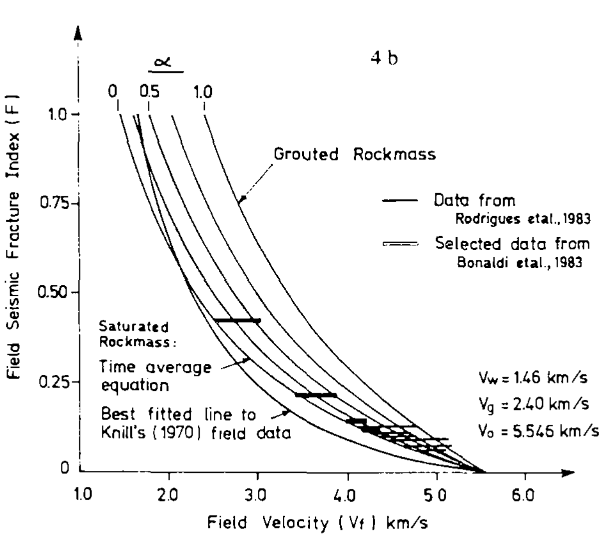


Fig. 4 a : Seismic velocity increase in the field velocity of the rock mass due to grout injection, from different dam sites (Data from Lancester-Jones, 1967, Table 3).

Fig. 4 b : Seismic velocity increase in the field velocity of the rock mass due to grout injection from the Passante dam-Italy (Bonaldi *et al.*, 1983, Fig. 5), and the Cabril dam Spain (Rodrigues *et al.*, 1983, Table 4).

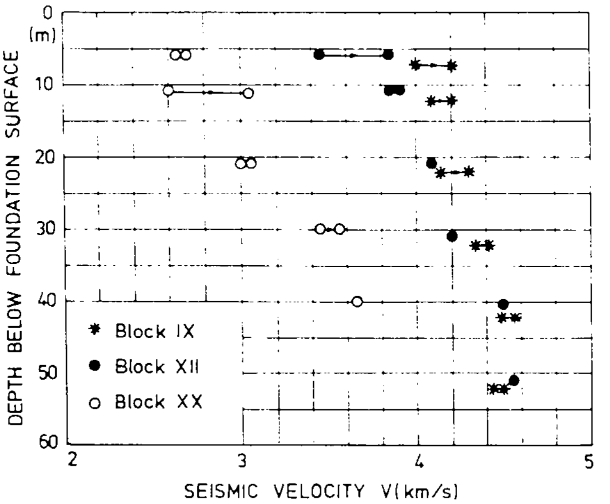


Fig. 5 : Average seismic velocities at various depths below the foundation surface of the Passante Dam-Italy. The velocity increases measured after the construction of the dam are indicated by arrows. The velocity values measured along the valley side (Block XX), are markedly lower than those on the valley bottom (Blocks IX and XII). (Bonaldi *et al.*, 1983).

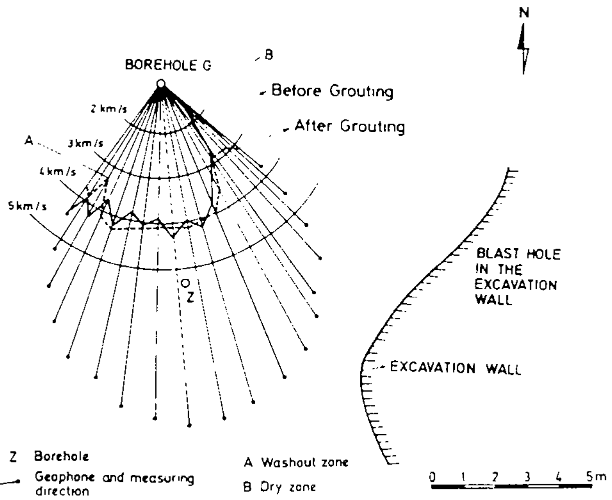


Fig. 6 : Results of "Up hole" seismic velocity measurements in a borehole, before and after grout injection into the granite rock mass (Blinde *et al.*, 1983 a). A = Washout zone, B = Dry zone.

of granite in most parts, there are two zones which need closer study. In zone A, the seismic velocity decreased after grouting, indicating that this may be caused by a wash out or refraction of the seismic waves. In zone B, the seismic velocity increased by more than 50 per cent indicating that the ground was dry before grouting was carried out. This emphasizes the fact that it is not always practical to rely on comparison of the seismic velocities alone to assess grouting efficiency in the rock mass.

Figure 7 shows the curve obtained by plotting the seismic fracture index F versus the different seismic velocity ratio of field velocity to water and/or grout velocity. Figure 7 can be used to assess the grout efficiency in the rock mass. First find F, from the V_{fw}/V_w and V_o/V_w ratios, following the path 1, 2 an 3 in Figure 6, then knowing F, V_g and V_o/V_g, V_{fg}/V_g ratio can be determined following the path 4, 5 and 6 in the

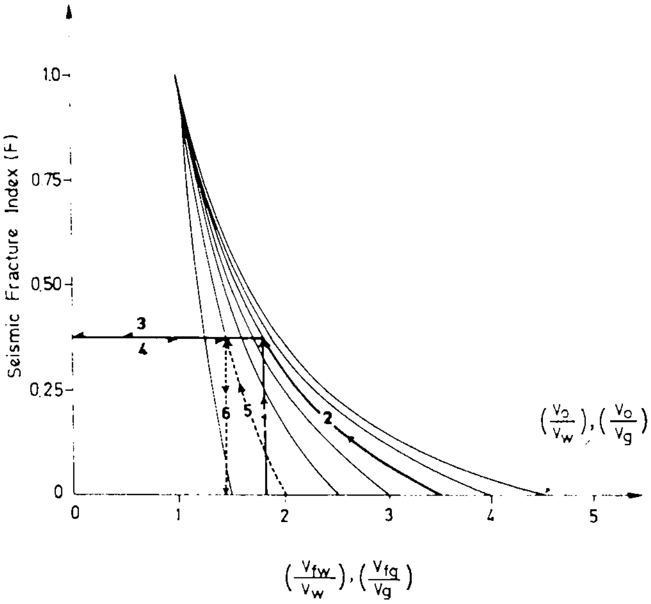


Fig. 7 : Dimensionless seismic fracture index (F) versus V_o/V_w and V_{fg}/V_g ratios for assessing the grout efficiency in a rock mass. V_w = Seismic velocity of grout and V_{fg} = Seismic velocity of grouted rock mass.

Table 4 : P wave velocity values measured in the Cabril dam foundation before and after grouting (Rodrigues *et al.*, 1983).

Consolidation block	Longitudinal wave velocity, (m/s)		Number of tests
	Before grouting	After grouting	
II	3650 – 4520 x̄ = 4120 SD = 419	4600 – 5200 x̄ = 4938 SD = 220	20
III	4100 – 5100 x̄ = 4637 SD = 374	4800 – 5450 x̄ = 5173 SD = 172	10
IV	3840 – 5470 x̄ = 4773 SD = 256	3950 – 5600 x̄ = 5103 SD = 302	90
V	4890 – 5500 x̄ = 5330 SD = 203	5010 – 5650 x̄ = 5410 SD = 213	30
VI	4810 – 5420 x̄ = 5270 SD = 183	4890 – 5600 x̄ = 5440 SD = 288	44
VII	4240 – 5370 x̄ = 4450 SD = 445	4780 – 5800 x̄ = 5153 SD = 468	6
VIII	3440 – 5450 x̄ = 4369 SD = 535	3760 – 5650 x̄ = 4780 SD = 503	50
IX	3220 – 5110 x̄ = 4256 SD = 517	3800 – 5430 x̄ = 4618 SD = 515	43

3220 – 5110 – extreme values
x – mean value
SD – standard deviation

same diagram. Then, by comparing the estimated V_{fg} and measured V_{fg} from the known F value, the grouting efficiency in the rock mass can be determined.

A similar diagram to Figure 2 can also be produced for the rock mass having higher (lower) seismic P wave velocity than 5.65 km/s and also having the grout seismic velocity higher (lower) than 2.40 km/s, for special rock mass conditions that may be met in practice. Additionally, such a diagram can also be produced for S wave seismic velocities which would be much more reliable for the assessment of the partially saturated and dry rock mass grout efficiency than using P wave velocities.

Conclusion

The effect of grouting on rock mass properties can be assessed by analyzing the seismic velocities of the rock mass obtained before and after the grouting operation. The rock mass can be characterized either by the seismic fissuration index (K) or a seismic fracture index (F) depending on the saturation state of the rock mass. Thus, any increase in seismic velocities due to grouting will also be apparent in these indices. Although the saturated ground grouting efficiency can be determined by applying the time average equation and finding the changes in the seismic fracture index, the same is not so for grout efficiency determination in dry ground. The latter requires the relation between (K) and (F) to be established and any apparent changes in F value due to grouting to be noted.

The time average analysis of Knill's (1970) seismic field velocity data from dam sites in the U.K. has given a relation between the seismic fracture index and the field velocity of a rock mass best represented by a curve. This relation is extended to include water saturated and grouted rock mass cases. It is also found that while the water saturated rock mass curve gives an upperbound value for Knill's (1970) data, the grouted rock mass curve gives a similar upperbound curve envelope when compared with published seismic field velocities from different dam sites. Thus, it is suggested that the relation between the seismic fracture index and field velocity can be used as a reference diagram for grout efficiency determination.

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