# The anisotropic nature of selected metamorphic rocks from Greece

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## Synopsis

**Anisotropy is a characteristic of intact foliated metamorphic rocks (slates, gneisses, phyllites, schists). Testing was used to establish the anisotropic behaviour of selected gneissic rocks. The effect of anisotropy on various mechanical properties (strength, deformation) and dynamic properties (wave velocity) was examined. The rock samples were also tested at successively higher confining pressures in order to evaluate the effect of anisotropic behaviour at high overburden pressures.**

## Introduction

The factors that influence the strength and deformation of the intact rock are the mineral composition, the fabric, the grain size and the degree of alteration and weathering.

The current paper deals with the pronounced effect of the fabric of anisotropic rocks on the strength and deformation characteristics of intact rocks. It is part of ongoing research in the Sector of Geotechnics, National Technical University of Athens.

## Experimental work

Two types of gneissic rocks were examined and were collected from rock exposures of slope cuts and tunnel portals of the Egnatia Highway, Veroia-Polymylos Section in Northern Greece.

Attention was given that the rocks blocks selected were from mechanically excavated slopes in order that minimum disturbance existed. Gneiss A is banded gneiss with fine-sized grains and light-coloured minerals. The petrographic composition is actinolithic gneiss.

Gneiss B is typical gneiss to schistous gneiss with medium-sized grains and dark-coloured minerals. It characterized as epidotitic, actinolithic schistous gneiss.

Both gneisses originate from low to medium metamorphic conditions.

The testing of numerous rock samples included: determination of physical properties (dry density, porosity), dynamic properties (longitudinal and transverse wave velocity on dry samples) and mechanical properties including point load tests, unconfined compression tests, indirect tensile tests and triaxial tests, according to ISRM (1981).

Large size blocks were cored at different inclinations, using a special frame fitted to the base of the conventional laboratory-drilling machine. About 60 specimens, of length to diameter of 2.0 to 2.5, having 5.4 cm diameter (NX-size) at different orientation angles $\beta$ (0°, 15°, 30°, 45°, 60°, 75°, and 90°) were cored from the rock blocks.

An attempt was made to drill cores with different values of $\beta$ from the same block to minimize the lithological differences. The specimens meeting the tolerance limits were first oven dried at 105°C for 24 h.

## Physical properties

Following the standard test procedures outlined in ISRM (1981), various physical properties such as density, porosity and void ratio were determined for both types of rocks.

The range of values obtained from eighty tests for each property is presented in Table I.

There is little difference in the values of porosity and dry density of the two gneisses.

## Wave velocity anisotropy

The ultrasonic pulse method was used to determine the anisotropy of P- and S-waves of intact schist. The correlation of these two follows the expression $V_p = 1.56 \cdot V_s$ with a correlation coefficient equal to $r = 0.91$ (Figure 1).

Due to the fact that the physical properties of the two gneisses are very similar, the effect of anisotropy on the ultrasonic wave velocity was examined irrespective of the rock type of the gneiss.

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*Table I*

**Physical properties**

| Rock type | | Dry density (kN/m³) | Saturated density (kN/m³) | Void ratio | Porosity (%) |
|---|---|---|---|---|---|
| Gneiss A | Min-Max | 25.55–27.12 | 25.77–27.30 | 0.013–0.025 | 1.3–2.7 |
| | Mean | 26.51 | 26.71 | 0.018 | 1.9 |
| Gneiss B | Min-Max | 19.65–27.39 | 19.75–27.50 | 0.010–0.020 | 1.0–2.2 |
| | Mean | 26.90 | 27.06 | 0.016 | 1.6 |

The variation of the wave velocity with the orientation of foliation planes, β (the angle between the wave propagation direction and the foliation plane), is shown in Figure 2 and the results are summarized in Table II.

It is obvious that the planes of foliation have a major effect on the wave velocity. The wave velocity perpendicular to the planes is approximately 40% lower than that parallel to them. Furthermore, the minimum longitudinal and transverse wave velocity is encountered when the foliation planes have an orientation of 75°.

The anisotropy degree (defined as the ratio of the maximum to the minimum wave velocity) is equal to 1.6 and 1.7 for the longitudinal and transverse wave velocity respectively.

The behaviour of this gneiss agrees well with observations made by Cvetkovic (1993) who tested a gneissic rock (from Prvonek dam in Yugoslavia) parallel and perpendicular to foliation. They determined a mean longitudinal and transverse velocity of $V_p$ = 4532 m/s and $V_s$ = 2362 m/s respectively, parallel to foliation, while perpendicular to it the velocity was $V_p$ = 2890 m/s and $V_s$ = 1570 m/s. This agrees very well with the findings of the current research.

The impact of the foliation on the dynamic Modulus of Elasticity ($E_0$) and the dynamic Poisson ratio ($v_0$) is proportional to that on the longitudinal and transverse wave velocity.

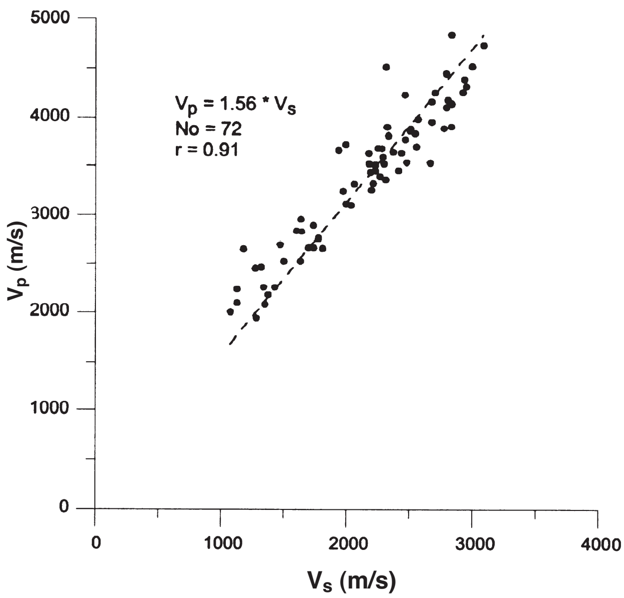


**Figure 1—Correlation between longitudinal and transverse wave velocity**

## Strength anisotropy

### *Uniaxial compression procedure*

The uniaxial compressive strength of the gneiss was determined as per ISRM test procedure.

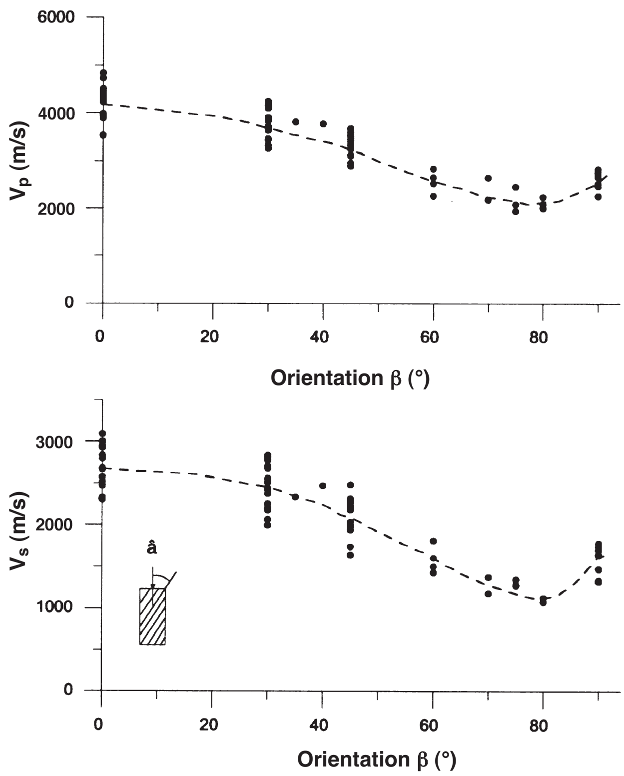


**Figure 2—Variation of longitudinal and transverse wave velocity with inclination of foliation**

*Table II*

**Geophysical properties**

| Orientation β (°) | 0 | 30 | 45 | 60 | 75 | 90 |
|---|---|---|---|---|---|---|
| | | | $V_p$ (m/s) | | | |
| Min | 3526 | 3259 | 2894 | 2263 | 1947 | 2263 |
| Max | 4839 | 4250 | 3683 | 2834 | 2454 | 2828 |
| Mean | 4182 | 3781 | 3359 | 2569 | 2162 | 2608 |
| | | | $V_s$ (m/s) | | | |
| Min | 2299 | 1995 | 1637 | 1429 | 1275 | 1321 |
| Max | 3091 | 2838 | 2480 | 1811 | 1350 | 1777 |
| Mean | 2668 | 2481 | 2121 | 1586 | 1302 | 1578 |
| No of tests | 16 | 19 | 15 | 4 | 3 | 8 |

The tests were carried out using a servo-controlled 2.5 MN capacity-loading frame. The stress rate was kept constant at 13 kN/s such that failure occurred within 5–10 min of loading. For measuring axial ($\varepsilon_\alpha$) and diametral ($\varepsilon_d$) strains under uniaxial compression, two LVDTs (one used to measure the axial and one for the diametral deformation) mounted appropriately on steel cylinder frames, were used measuring the deformation at the mid-height of the specimens.

The samples were cylindrical with a height to diameter ratio of about 2.5. Prior to testing, the samples were air-dried at room temperature.

The variation of the uniaxial compressive strength with the inclination of foliation planes is shown on Figure 3 and the results are summarized in Table III.

The minimum strength coincides with an angle of the foliation plane relevant to the load axis equal to 30°.

The strength anisotropy index (defined as the ratio of the maximum to the minimum uniaxial compressive strength) for Gneiss A is Ia = 2.1, while for Gneiss B it is quite high equal to Ia = 4.2 due to the high uniaxial compressive strength of this gneiss (perpendicular to foliation).

The results were compared with data from other studies on gneissic rocks (Broch, 1974, Berry *et al.*, 1974, Horino and Ellickson, 1970, Youash, 1966) and some of them are presented in Figure 4.

Broch (1974) has tested gneiss parallel and perpendicular to the foliation and determined that the uniaxial compressive strength is approximately the same in these two directions ($\sigma_{c0}$ = 179 MPa and $\sigma_{c90}$ = 184 MPa). Tests carried out by Horino *et al.* (1970) and Youash (1966) on gneissic rocks from Idaho Springs, Denver (Colorado) show that the strength parallel and perpendicular to the foliation is similar.

The gneisses tested within the current study have significant difference in the strength in these two orientations, possibly due to the well-developed nature of the foliation plane that assemble schist-like characteristics to the studied rock.

The minimum strength direction for the tests carried out by Horino *et al.* is 30° while the anisotropy index is Ia = 1.1. The minimum strength direction for the tests carried out by Youash is 60° while the anisotropy index is Ia = 1.55. The orientation of 60° is not consistent with the literature findings and is questionable.

The grain size difference of the gneisses tested, in the same orientation of the foliation planes, controls the ultimate strength of these two rocks in uniaxial compression.

Futher testing is commissioned in order to define the effect of the mean grain size of anisotropic rocks on the uniaxial compressive strength.

### Modulus anisotropy

The Young's modulus, E, calculated refers to the tangent modulus measured at the 50% of the uniaxial compressive strength, $E_{t50}$.

The deformability parameters for the various orientations are summarized in Table III.

The gneiss is classified according to Deere and Miller (1966) as a high modulus ratio rock with a low to medium strength. The uniaxial strength data from tests on samples having an orientation of foliation planes in the range between 30° and 45° belong in the low strength category, while the rest fall in the medium strength category.

*Table III*

**Strength and deformation properties**

| Orientation β (°) | 0 | 30 | 45 | 60 | 90 |
|---|---|---|---|---|---|
| | | | $\sigma_{ci}$ (MPa) | | |
| Gneiss A | 42.5 | 28.3 | 37.5 | 28.7 | 60.5 |
| Gneiss B | 40.9 | 20.1 | – | 31.6 | 85.3 |
| | | | $E_{t50}$ (GPa) | | |
| Gneiss A & B | 68 | 65 | 14 | 49 | 38 |

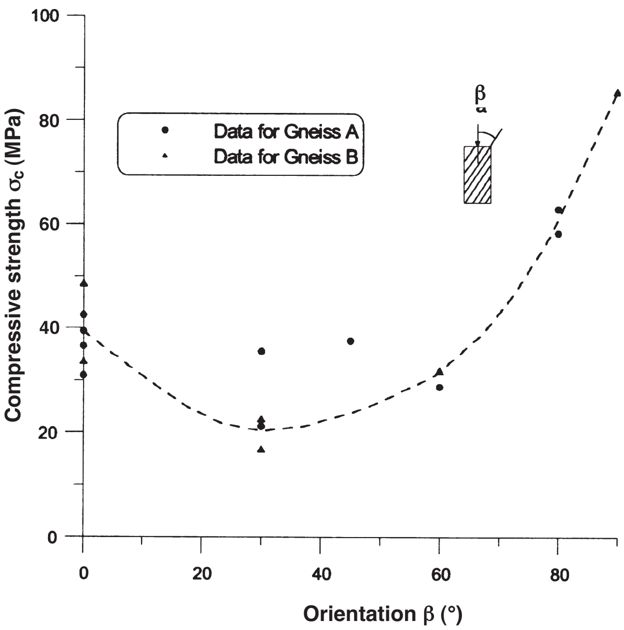


**Figure 3—Variation of uniaxial compressive strength with inclination of foliation**

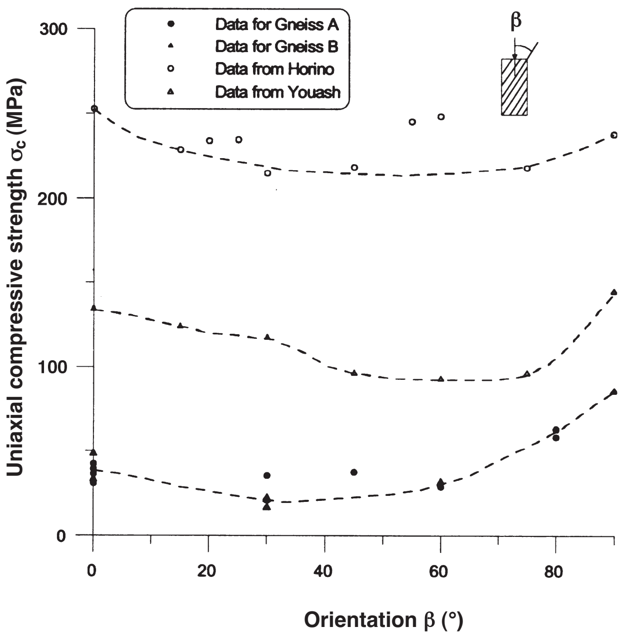


**Figure 4—Variation of uniaxial compressive strength with inclination of foliation**

The maximum value of Young's modulus is encountered when loading is parallel to the foliation planes ($E_{t50}$ = 68 GPa) and the minimum value when perpendicular to them ($E_{t50}$ = 38 GPa).

The degree of Young's modulus anisotropy as measured by the ratio $E_1/E_2$ has been extensively worked, where $E_1$ and $E_2$ are Young's moduli in the plane of transverse isotropy and in direction normal to it, respectively. In this study the ratio of $E_1/E_2$ equals 1.8.

### Tensile strength anisotropy

The effect of the planes of foliation on the indirect tensile strength was determined by testing cylindrical discs (Brazilian test) with reference to the axis of loading.

The pressure was applied parallel and perpendicular to the foliation planes up to failure of the rock discs.

The correlation of the indirect tensile test $\sigma_t$ with the anisotropy index $I_a$ is shown in Figure 5. The data used are summarized in Table IV.

The anisotropy index for the tensile strength ranges between Ia = 1.3 and Ia = 3.3, depending on the tensile strength of the rock, with a mean value of 2.3.

The mean tensile strength parallel to the foliation planes is 3.9 MPa, while normal to it is equal to 7.0 MPa.

Deklotz (1966), who tested fine-grained schistose gneiss in direct tension, found that a single plane of weakness is not indicated as the tensile strength increases gradually for increasing angular orientation of the failure plane with respect to the plane of schistosity.

### Strength anisotropy in triaxial condition

#### *Triaxial testing procedure*

Triaxial compressive tests were carried out using a 70 MPa capacity triaxial cell placed in a 1.5 MN capacity-loading frame. The triaxial cell is a Hoek-Franklin cell for specimens of between 1.5 and 54.74 mm diameter. Five different confining pressures applied during the triaxial tests were 1.8, 3.0–3.6, 4.2–6.0, 7.2–9.0, 10.2—12.0, 14.4–15.6 and 18.0–21.6 MPa.

Since the scope of this work is to comment on the parameters $\sigma_{ci}$ and $m_i$ of the Hoek-Brown criterion for use in anisotropic materials, the range of confining pressures of $0 < \sigma_3 < 0.5\ \sigma_{ci}$ proposed by Hoek and Brown (1980a) were used. The specimens were first subjected to the required confining pressure and then the axial load was applied until the specimen failed.

The plots of compressive strength between $\sigma_1$ and β at different confining pressures $\sigma_3$ for the two gneisses are presented in Figure 6.

The overall strength behaviour of the intact gneiss is similar as far as the shape of the anisotropy curve in the unconfined state is concerned. The shape of the anisotropy curves for these three rocks is towards 'U-shaped' over the entire range of $\sigma_3$ adopted.

The anisotropic trend in the lower range of confining pressures retains the same trend in the higher confining pressures. This agrees well with the triaxial data at similar pressures on gneisses published by Horino *et al.* (1970) and Youash (1966).

### Applicability of the Hoek and Brown criterion

Based on the results of 60 triaxial tests on intact rock samples of gneiss, the use of the Hoek and Brown criterion in a gneissic rock is discussed.

The triaxial data sets presented in Figure 7 were selected, in order to proceed with the determination of the Hoek and Brown criterion parameters, according to the following criteria:

- the range of confining pressures should lie within $0 < \sigma_3 < 0.5\ \sigma_{ci}$
- The data that didn't seem reliable, for instance samples that failed in decreased strength although the confining pressure was higher in comparison with previous sets, were excluded
- The mean uniaxial compressive strength was used for each orientation of foliation, as the range of the strength can have a significant effect upon the criterion parameters.

The data were then plotted irrespective of the orientation of foliation and are presented in Figure 8, while in the following paragraphs the effect of the orientation of the schistosity planes on the failure criterion is discussed in detail.

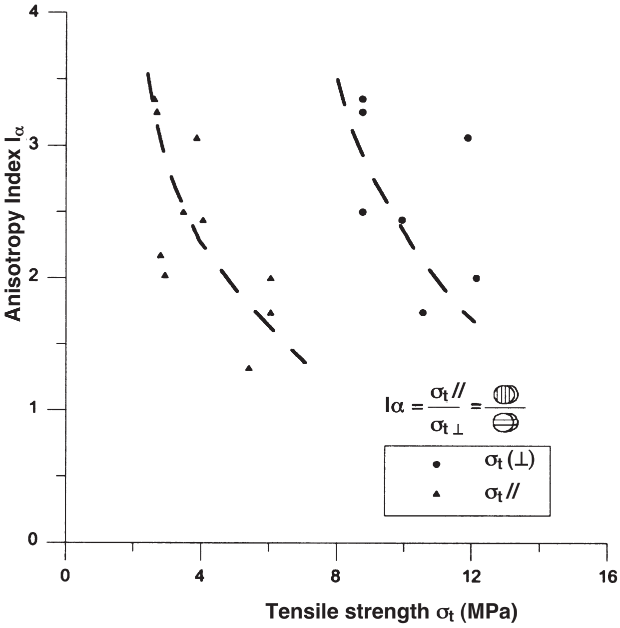


**Figure 5—Correlation of tensile strength anisotropy index with indirect tensile strength**

*Table IV*

**Indirect tensile test data (numbers in parenthesis are not plotted in Figure 6)**

| Ia | $\sigma_t$ parallel (MPa) | $\sigma_t$ normal (MPa) |
|---|---|---|
| 3.06 | 3.8 | 11.9 |
| 1.32 | 5.4 | (7.1) |
| 2.02 | 2.9 | (5.9) |
| 3.35 | 2.6 | 8.7 |
| 3.25 | 2.7 | 8.7 |
| 2.5 | 3.5 | 8.7 |
| 2.17 | 2.8 | (6.1) |
| 2.44 | 4.0 | 9.9 |
| 2.0 | 6.0 | 12.1 |
| 1.74 | 6.0 | 10.5 |
| Mean 2.3 | 3.9 | 7.0 |
| No. of tests | 10 | 10 |

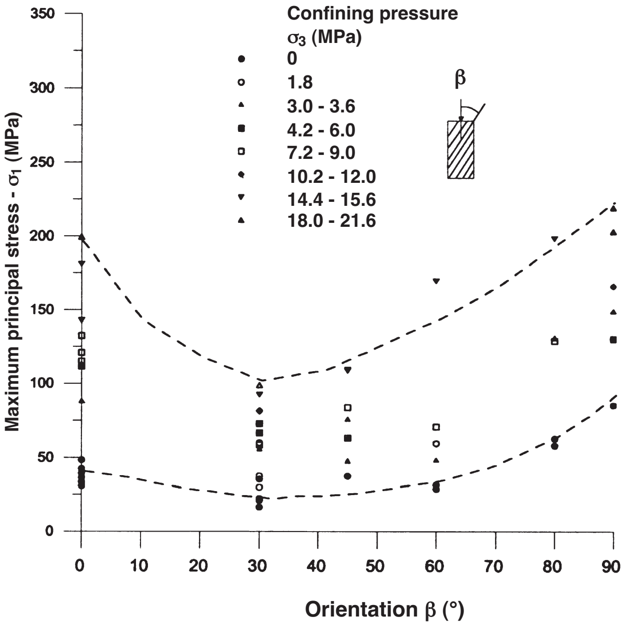


Figure 6—Compressive strength anisotropy

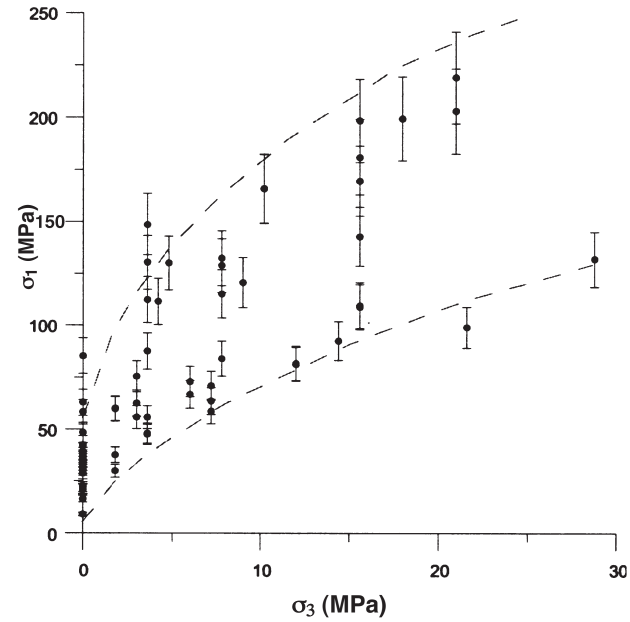


Figure 7—Triaxial data for gneiss type A and B

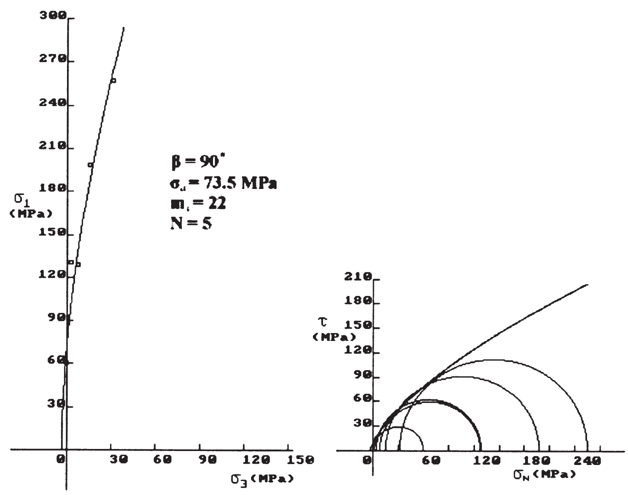


Figure 8—Hoek and Brown and Mohr-Coulomb failure envelopes for orientation of foliation 90°

The Hoek and Brown criterion parameters in respect to the orientation of the schistosity planes for Gneiss type A are summarized in Table V and for all samples in Table VI.

The value of $m_i$ normal to the foliation planes is equal to 22 and agrees well with the value proposed by Marinos and Hoek (2000) for gneisses ($m_i = 28 \pm 5$). The failure envelope is shown in Figure 8.

Hoek *et al.* (1980) proposed an average value to be used in the Hoek and Brown criterion.

The lowest value of the parameter $m_i$ is encountered when the inclination of the foliation planes is 30° to the major loading axis. For the Gneiss of type A the value of $m_i$ in that direction is $m_i = 11$, while for all the data it is found equal to $m_i = 7$. The failure envelope is shown in Figure 9. The decrease of the value is in the order of 50% to 70%.

The maximum value is found for specimens loaded parallel to the foliation planes, where $m_i$ is $m_i = 37$ for Gneiss A, while for all the data it is found equal to $m_i = 22$.

The uniaxial compressive strength predicted by the criterion shows significant difference from the average laboratory value, especially when loading takes place parallel and at 30° to the foliation planes, and is very similar for the case of loading normal to them.

The variation of the uniaxial compressive strength in the same orientation β has a crucial impact on the determination of $m_i$. It was found that increasing uniaxial strength in the criterion for the same triaxial data set decreases the parameter of $m_i$ to as much as 40%.

Using the average from a number of uniaxial tests at the same orientation seems appropriate in such cases.

## Conclusions

The mechanical properties of the gneissic rocks studied found to be greatly influenced by the prevailing foliation planes.

The longitudinal and transverse wave velocity perpendicular to the planes is approximately 40% lower than that parallel to them.

The anisotropy degree of the wave velocity is equal to 1.6 and 1.7 for the longitudinal and transverse wave velocity respectively.

*Table V*

**Hoek and Brown criterion parameters for Gneiss type A**

| Orientation β (°) | 0 | 30 | 45 | 80 |
|---|---|---|---|---|
| $\sigma_{ci}$ (MPa) | 45.1 | 37 | 40 | 73.5 |
| $m_i$ | 37 | 11 | 11 | 22 |
| No. of tests | 10 | 10 | 5 | 5 |

*Table VI*

**Hoek and Brown criterion parameters for all samples**

| Orientation β (°) | 0 | 30 | 45 | 80* |
|---|---|---|---|---|
| $\sigma_{ci}$ (MPa) | 57 | 38 | 35 | 73.5 |
| $m_i$ | 22 | 7 | 12 | 22 |
| No. of tests | 14 | 17 | 9 | 5 |

* Taken from Gneiss type A only

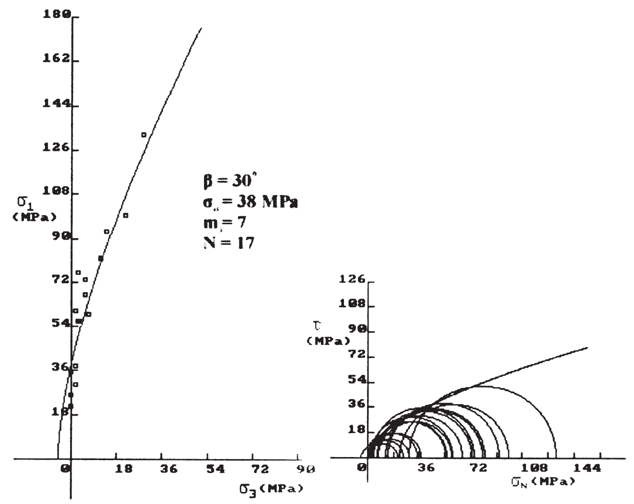


**Figure 9—Hoek and Brown and Mohr-Coulomb failure envelopes for orientation of foliation 30°**

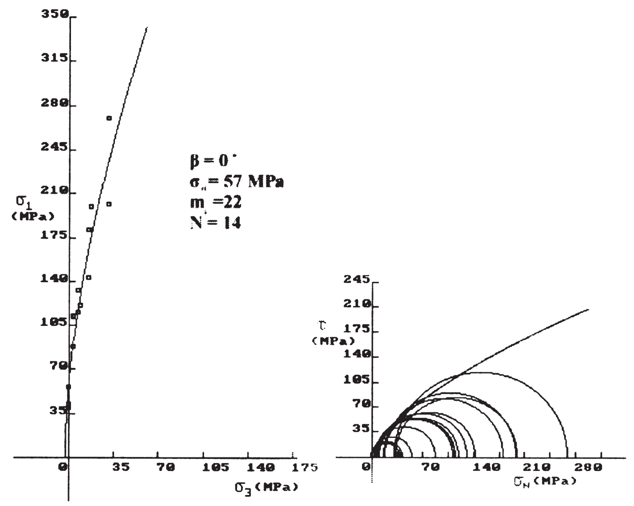


**Figure 10—Hoek and Brown and Mohr-Coulomb failure envelopes for orientation of foliation 0°**

The impact of the foliation on the dynamic Modulus of Elasticity ($E_0$) and the dynamic Poisson ratio ($v_0$) is proportional to that on the longitudinal and transverse wave velocity.

The minimum uniaxial compressive strength is encountered at 30° of inclination of the foliation planes to the loading axis. The uniaxial compressive strength anisotropy index for Gneiss type A is Ia = 2.1 and is expected to be directly related to the grain size, while the tensile strength ranges between Ia = 1.3 and Ia = 3.3, depending on the tensile strength of the rock having an average value of 2.3.

The anisotropic trend in the lower range of confining pressures retains the same trend in the higher confining pressures.

The results of the triaxial testing programme, designed to accommodate the effect of foliation planes on confined strength, prove that an isotropic criterion as proposed by Hoek and Brown (1980a), should be used with extreme care in cases of anisotropic intact rocks.

This is mainly due to the fact that the uniaxial compressive strength predicted by the criterion, as well as the parameter $m_i$ defined normal to bedding or foliation, can vary significantly in these rocks. The uniaxial compressive strength $\sigma_{ci}$ predicted by the criterion was found to vary between 35 MPa and 73 MPa, while the parameter $m_i$, varied between 7 and 22

The gneiss examined in the present study proves that the selection of parameters based on the criterion has to follow a procedure that accounts for anisotropy effect.

It is proposed that the Hoek and Brown criterion is used for the metamorphic rock formations by taking into account lower values of uniaxial compressive strength and $m_i$ when anisotropy, due to the presence of closely spaced foliation planes, is predominant.

Further studying of the effect of the confining pressure on the behaviour of anisotropic rocks and the determination of a suitable empirical criterion needs to be done.

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