Report

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On the anisotropy of mechanical properties in Grimsel Granodiorite

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ABSTRACT

This report discusses the degree of anisotropy in the mechanical properties of Grimsel Granodiorite. These properties include the elastic and seismic behaviour, tensile strength, mode I fracture toughness and the size of the fracture process zone. The results show that all these properties exhibit a large degree of anisotropy in Grimsel Granodiorite. This anisotropy must to be taken into account when interpreting ISC experiments conducted in the Grimsel underground laboratory.

Introduction

The elastic and inelastic deformations of many rock types are anisotropic, due to the complex micro-structures of these rocks, stemming from a complex geological history. Taking rock anisotropy into account allows more accurate predictions of the rock mass deformation, stability and failure. Determining the elastic constants as well as inelastic properties such as tensile strength and fracture toughness is of crucial importance in a wide range of fields related to geomechanics and geophysics. An important application is related to so-called enhanced geothermal systems (EGS) or reservoirs, normally developed in the crystalline basement, where anisotropic rocks, such as granite or gneiss, are likely to be present. Recent studies have demonstrated the importance of rock anisotropy in the in-situ stimulation and circulation project in the deep underground laboratory at the Grimsel test site in Switzerland (Amann et al., 2018; Gischig et al., 2018; Jalali et al., 2018; Krietsch et al., 2018b; Wenning et al., 2018).

Transversely isotropic constitutive law provides a suitable model for predicting the deformational behaviour of many types of rocks. This is the case, because most sedimentary and metamorphic rocks exhibit formation processes, such as bedding and foliation, which result in preferred orientations of the constituent minerals, pores, and cracks (Jaeger et al., 2007). These processes result in an axis of symmetry normal to the foliation and bedding planes, often referred to as transverse isotropy. The transverse isotropy elasticity model requires five independent material constants that need to be measured through experiments. In addition, the orientation of the isotropy plane, defined by one unit normal or two angles, needs to be identified (Dambly et al., 2018). When the elasticity of the rock is anisotropic, the failure parameters such as strength and toughness are also expected to be anisotropic. This report aims to demonstrate the strength of anisotropy in Grimsel Granodiorite based on the recent laboratory measurements on the rock samples obtained from the boreholes drilled for the ISC experiments (Amann et al., 2018; Gischig et al., 2018; Jalali et al., 2018).

Transverse isotropy model

Anisotropic elasticity indicates the directional dependency of the material deformability. Depending on the number of symmetry planes, describing the response of anisotropic materials requires different numbers of material constants. Due to the presence of foliation or bedding, many rock types exhibit a geometrical micro-structural axis of symmetry, which makes the transverse isotropy with five constants a suitable model to describe their response. This model defines an isotropy plane, often assumed to coincide with the features such as foliation and bedding, and infinite number of symmetry planes parallel to the axis of symmetry. Consider the Cartesian coordinate system $x'y'z'$ is the material coordinate system, with the isotropy plane coinciding with the plane $x'y'$ while $z'$ denoting the axis of symmetry. The well-known generalized Hooke’s law defines the constitutive law by Eq. (1). Here, $\varepsilon'$ and $\sigma'$ are the vectors of strain and stress, respectively, and $S'$ is the well-known compliance matrix. Note that the Vigot’s notation is used for the order of the components in the vectors. Due to the strain energy requirements, $S'$ must be a symmetric positive-definite matrix.
When the calculation of stresses in terms of strains is desired, Eq. (1) can be inverted to give the stresses in terms of strains, \( \sigma' = C' \epsilon' \), by defining the stiffness matrix as

\[
C' = S'^{-1} = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & 0 & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix},
\]

(2)

where the elements of \( C' \) are defined in terms of engineering constants, given as

\[
C_{11} = \frac{E(1 + 2v) - E'}{(v^2 - 1)E' + 2E(1 + v)}v^2
\]

\[
C_{12} = -\frac{2E'v}{v^2 - 1} - \frac{2E(1 + v)}{v^2 - 1}E'v^2
\]

\[
C_{13} = -\frac{E}{v^2 - 1}(v^2 - 1)E' + 2E(1 + v)v^2
\]

\[
C_{33} = \frac{(v - 1)E'^2}{(v - 1)E' + 2Ev^2}
\]

\[
C_{44} = G'
\]

\[
C_{66} = G
\]

It is worth noting that Eq. (1) is mainly employed to determine the static elastic constants from the results of a quasi-static experiment, while Eq. (2) is helpful to obtain the dynamic values of the elastic constants from an elastodynamic measurement. In addition to the five constants of the elasticity model, the orientation of the isotropy plane is also required for assigning the material coordinate system. A plane in space can be defined by a unit normal vector or equivalently by two angles in space. In this report, the angles \( \theta \) and \( \beta \) refer to the dip direction and the dip of the isotropy plane in a cylindrical sample, respectively. A full characterization of a transversely isotropic model, therefore, requires seven parameters: two define the geometry of the isotropy plane and five define the independent elastic constants.
Young's moduli

\[ E = E_x' = \frac{\sigma_x'}{\varepsilon_x'} \]
\[ E = E_y' = \frac{\sigma_y'}{\varepsilon_y'} \]
\[ E' = E_z' = \frac{\sigma_z'}{\varepsilon_z'} \]

Poisson's ratios

\[ \nu = \nu_{xy}' = -\frac{\varepsilon_y'}{\varepsilon_x'} \]
\[ \nu = \nu_{xz}' = -\frac{\varepsilon_z'}{\varepsilon_x'} \]
\[ \nu = \nu_{yz}' = -\frac{\varepsilon_z'}{\varepsilon_y'} \]

Shear moduli

\[ G = G_{xy}' = \frac{\tau_{xy}'}{\gamma_{xy}'} \]
\[ G = G_{xz}' = \frac{\tau_{xz}'}{\gamma_{xz}'} \]
\[ G = G_{yz}' = \frac{\tau_{yz}'}{\gamma_{yz}'} \]

Figure 1. Schematic definition of the elastic constants in transversely isotropic rocks.

Elastic constants

The experimental results are presented in three parts: 1) The orientation of the isotropy plane is measured from different methods. 2) The static elasticity constants, including both secant and tangent values are obtained from uniaxial compression tests. The tangent values of the elastic constants are determined to analyse the nonlinearity of the rock behaviour and the load-dependency of the elastic constants. 3) The dynamic values of elastic constants are obtained from the P-wave velocity variation under zero-confinement, and are compared to the static ones.

Rock samples and test setup

Three cylindrical samples were obtained from cores extracted from the Grimsel test site (GTS) in the central Swiss Alps, Switzerland. This underground laboratory is located in the Aare massif at a depth of about 480 m underneath the Juchlistock. The deformation history in this region caused a reorientation of sheet silicates forming a pervasive foliation in both lithologies, with a prevailing strike of N50°E and a dip of 80° towards SE (Krietsch et al., 2018a). The rock foliation is clearly visible in all three samples. To ensure comparability, all three rock core samples are taken from the borehole PRP16.001 at depths of 15.2-15.44 m (Sample 1 referred to as S1) and 21.3-21.54 m (Sample 3 referred to as S3) and 21.54-21.78 m (Sample 2 referred to as S2). The samples are of \( d = 10.8 \) cm diameter and \( l = 24 \) cm length, and have an average density of \( \rho = 2.7 \) g/cm³. With respect to the base of the cylinder, the foliation plane is oriented at an angle of \( \beta = 40^\circ \) for Sample 1 and \( \beta = 35^\circ \) for Samples 2 and 3.

Uniaxial compression tests were conducted to obtain the static elastic constants of the rock samples. In order to ensure that a uniform axial stress is applied, a ball-bearing plate was designed and built. This plate was placed on the top of the cylindrical samples to allow lateral displacement. Strain gauges with a grid length of 20 mm were found to be compatible with the size of specimens and grains, and were, therefore, used for local strain measurements. The cylinders were axially loaded up to...
σ_z = 35 MPa and then unloaded back to zero load. The reader is referred to Dambly et al. (2018) for more details on the uniaxial compression setup and the strain measurement results.

P-wave velocity measurements were conducted to obtain quantitative information regarding the orientation of the isotropy plane and to obtain the dynamic values of the elastic constants. The ultrasonic tests were carried out using the ultrasonic pulse transmission technique. The least-squares fit to the P-wave velocity variation enables the calculation of the orientation of the isotropy plane, characterized by \( \theta \) and \( \beta \). These values can be compared to those obtained from visually inspecting the foliation plane. The specifics of these tests and detailed results are given in Dambly et al. (2018). All ultrasonic measurements in this study are conducted under zero-confinement conditions.

**Orientation of isotropy plane**

Three different methods to determine the symmetry plane orientation, \( \theta_s \), were employed. The angle \( \beta \) was also measured using the ultrasonic P-wave velocity measurements. More details on these methods are given in Dambly et al. (2018). All these data are summarized in Table 1 and compared to the angles obtained from the orientation of the foliation plane. The cylindrical coordinate system used to report the angles is set up in a way that the \( \theta \)-axis is aligned with the dip direction of the foliation plane for all samples. Therefore, all samples hold the value of \( \theta_s = 0 \) for the foliation plane. These results shows that the isotropy plane coincides with foliation plane with a good approximation in the samples studied. Therefore, the foliation plane can be considered as the isotropy plane of the transverse isotropy model. The isotropy plane orientation from the P-wave velocity measurements is used for the determination of the elastic constants in the next sections.

**Table 1.** Results for the orientation of the isotropy plane, \( \theta_s \) and \( \beta \), from three different methods, in comparison with the orientation of foliation plane.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( V_p ) (m/s)</th>
<th>Zero of ( u_z )</th>
<th>Max. of ( u_z )</th>
<th>Foliation plane</th>
<th>( V_p ) (m/s)</th>
<th>Foliation plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-18.6</td>
<td>-22.2</td>
<td>-17.0</td>
<td>0</td>
<td>47.2</td>
<td>40</td>
</tr>
<tr>
<td>S2</td>
<td>0.5</td>
<td>-24.0</td>
<td>-23.5</td>
<td>0</td>
<td>31.4</td>
<td>35</td>
</tr>
<tr>
<td>S3</td>
<td>17.6</td>
<td>-7.2</td>
<td>-30.8</td>
<td>0</td>
<td>39.0</td>
<td>35</td>
</tr>
</tbody>
</table>

**Table 2.** Secant values of the elasticity constants at the load of \( \sigma_z = 35 \text{ MPa} \) obtained from different setups.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( E_x ) (GPa)</th>
<th>( E'_x ) (GPa)</th>
<th>( \nu_x )</th>
<th>( \nu'_x )</th>
<th>( G_x ) (GPa)</th>
<th>( G'_x ) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>38.0</td>
<td>19.5</td>
<td>0.11</td>
<td>0.07</td>
<td>17.1</td>
<td>11.8</td>
</tr>
<tr>
<td>S2</td>
<td>52.2</td>
<td>25.3</td>
<td>0.12</td>
<td>0.08</td>
<td>22.8</td>
<td>15.4</td>
</tr>
<tr>
<td>S3</td>
<td>39.7</td>
<td>23.3</td>
<td>0.22</td>
<td>0.07</td>
<td>16.2</td>
<td>13.5</td>
</tr>
<tr>
<td>Average</td>
<td>43.3</td>
<td>22.8</td>
<td>0.15</td>
<td>0.07</td>
<td>18.7</td>
<td>13.6</td>
</tr>
</tbody>
</table>

**Static elastic constants: Secant method**

Table 2 presents the secant values of the elastic constants calculated from the suggested setup SG8, at the maximum load of \( \sigma_z = 35 \text{ MPa} \) (Nejati et al., 2018). The results of S2 are slightly different from the ones of S1 and S3, which can be explained by the fact that the behaviour of S2 is furthest from an ideal transverse isotropy model. This is mainly caused by local heterogeneities and a shift of the isotropy plane orientation along the cylinder axis, as observed in the ultrasonic measurements (Dambly et al., 2018). Our results yield the following averages for the anisotropy ratios: \( E_x/E'_x \approx \nu_x/\nu'_x \approx 2 \) and \( G_x/G'_x \approx 1.4 \).

**Static elastic constants: Tangent method**

Nejati et al. (2018) suggested a method to obtain the tangent values of the elastic constants from a uniaxial compression test. The tangent elastic constants are obtained, using the derivatives of the stresses with respect to their corresponding strain for moduli and strain normal to the load direction, with respect to strain along the loading direction for Poisson’s ratios. The details of the determination of tangent constants are given in Nejati et al. (2018). Figure 2 shows the variation of the tangent elastic constants against the applied load for S1. The strain gauge setup SG8 is employed to calculate the tangent elastic constants. These results show that the Grimsel Granodiorite exhibits a significant nonlinear behaviour, with the moduli and Poisson’s ratios increasing with an increase in stress.
It is seen that both Young’s and shear moduli tangent values depend on stress, with a stronger nonlinear dependency at low stress levels, i.e. up to 5 MPa, and a somewhat linear dependency at higher stresses, i.e. 5 MPa up to 20 Mpa. This behaviour can be attributed to the presence of a large number of micro-cracks and voids that close due to applied stresses and leads to a higher material stiffness. It is expected, however, that the majority of micro-cracks close at high stress levels and, therefore, the moduli are expected to stabilize and become stress-independent at high confining stresses. The Poisson’s ratios also exhibit a strong stress-dependency. Poisson’s ratios increase with the stress level, and it is expected that they approach a constant stress-independent value at high stress levels.

Table 6 presents the tangent values of the elastic constants, calculated at the beginning of the loading stage. These results provide static values of elastic constants under zero-confinement conditions, which will be used later for comparison with the dynamic values. A comparison of these values with the secant values, given in Table 2, illustrates the significant stress-induced nonlinearity of elasticity in the samples.

Table 3. Tangent values of the elastic constants at the beginning of the loading stage i.e. under zero-confinement (no axial stress, $\sigma_z = 0$) condition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$E_t$ (GPa)</th>
<th>$E'_t$ (GPa)</th>
<th>$\nu_t$</th>
<th>$\nu'_t$</th>
<th>$G_t$ (GPa)</th>
<th>$G'_t$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>19.8</td>
<td>6.3</td>
<td>0.07</td>
<td>-0.01</td>
<td>9.6</td>
<td>5.7</td>
</tr>
<tr>
<td>S2</td>
<td>40.4</td>
<td>9.5</td>
<td>0.28</td>
<td>-0.06</td>
<td>15.0</td>
<td>11.0</td>
</tr>
<tr>
<td>S3</td>
<td>27.2</td>
<td>6.9</td>
<td>0.17</td>
<td>-0.04</td>
<td>11.7</td>
<td>7.9</td>
</tr>
<tr>
<td>Average</td>
<td>29.1</td>
<td>7.6</td>
<td>0.17</td>
<td>-0.04</td>
<td>12.1</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Dynamic elastic constants

Through the least-squares fit of P-wave velocity variations versus the polar angle, the four elastic constants, $C_{11}, C_{13}, C_{33},$ and $C_{44},$ can be determined, as described in Dambly et al. (2018). While $G'$ is directly obtained from the inverse of $C_{44},$ the other elastic parameters, $E, E', \nu,$ and $\nu'$, cannot be calculated from the three constants $C_{11}, C_{13},$ and $C_{33},$ since the system is under-determined. Assuming knowledge of one parameter, for example $\nu,$ enables us to solve for $E, E',$ and $\nu'$ from the constants $C_{11}, C_{13},$ and $C_{33},$ employing Eq. (3). This nonlinear system of equations is then solved, using the Newton-Raphson scheme in order to obtain the dynamic values of elastic constants. Table 4 presents these results, using the assumption of $\nu = 0.2$ for the in-plane Poisson’s ratio. It is noteworthy that only trivial changes of the values of the Young’s moduli and the transverse Poisson’s ratio occur when a different in-plane Poisson’s ratio is assumed (Dambly et al., 2018).

Table 4. Dynamic values of elastic constants under zero-confinement condition.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$E_d$ (GPa)</th>
<th>$E'_d$ (GPa)</th>
<th>$\nu_d$ (assumed)</th>
<th>$\nu'_d$</th>
<th>$G_d$ (GPa)</th>
<th>$G'_d$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.0</td>
<td>19.7</td>
<td>0.2</td>
<td>0.04</td>
<td>16.7</td>
<td>10.8</td>
</tr>
<tr>
<td>2</td>
<td>41.4</td>
<td>19.9</td>
<td>0.2</td>
<td>0.04</td>
<td>17.2</td>
<td>11.0</td>
</tr>
<tr>
<td>3</td>
<td>41.1</td>
<td>20.2</td>
<td>0.2</td>
<td>0.04</td>
<td>17.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Average</td>
<td>40.8</td>
<td>19.9</td>
<td>0.2</td>
<td>0.04</td>
<td>17.0</td>
<td>11.1</td>
</tr>
</tbody>
</table>
Comparison of static and dynamic constants
There is a significant difference in the rock deformation magnitude, when it is induced dynamically, by ultrasonic or seismic wave propagation, compared to the case when it is induced by a static test, such as a uniaxial compression test. Dynamically induced deformation is extremely small, compared to the one induced statically (Schön, 2015). High values of strains in static tests result in considerable inelastic processes such as frictional sliding of micro-cracks and grain-boundaries, whereas the small dynamically induced strains are mainly affected by the elastic response of the rock. The elastic constants are independent of test type only for an ideal elastic material. Rocks often exhibit complex micro-structures with high densities of micro-cracks and pores, so that their inelastic deformation can be significant during static tests. For this reason, the dynamic moduli are expected to be larger than the static moduli.

Table 5 compares the static and dynamic values of the elastic constants under zero-confinement condition. It is seen that the dynamic moduli are significantly larger than the static values. In particular, the dynamic transverse Young’s moduli are two to three times larger than the static ones. This is explained by the fact that the micro-cracks are dominantly oriented along the isotropy plane (foliation). Due to small strain values, the micro-cracks cannot often influence the P-wave velocity. On the other hand, the statically induced strains are high enough to be influenced by micro-cracks oriented normal to the loading direction. This difference is reduced within the isotropy plane, as there is a lower density of micro-cracks. The anisotropy ratio of the Young’s moduli is also significantly larger for static values than for dynamic values. This is explained by the fact that the micro-cracks are mainly oriented along the isotropy plane, which is one of the main reasons for elasticity anisotropy in this granite. Since the static tests are more likely to be influenced by micro-cracks than the dynamic values, we expect to see a more anisotropic response (larger anisotropy ratios) during the static tests.

Table 5. Comparison of the static and dynamic elastic constants under zero-confinement conditions.

<table>
<thead>
<tr>
<th>Value</th>
<th>$E$ (GPa)</th>
<th>$E'$ (GPa)</th>
<th>$G$ (GPa)</th>
<th>$G'$ (GPa)</th>
<th>$E/E'$</th>
<th>$G/G'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>40.8</td>
<td>19.9</td>
<td>17.0</td>
<td>11.1</td>
<td>2.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Static</td>
<td>29.1</td>
<td>7.6</td>
<td>12.1</td>
<td>8.2</td>
<td>3.8</td>
<td>1.5</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.4</td>
<td>2.6</td>
<td>1.4</td>
<td>1.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tensile strength and fracture toughness
Figure 3 shows schematically the geometrical configuration of the Brazilian disk (BD) and semi-circular bend (SCB) specimens used for tensile strength and fracture toughness measurements. The isotropy plane makes angle $\phi$ with the load axis in both SCB and BD tests. The fracture toughness and tensile strength tests were conducted using two configurations $\phi = 0^\circ, 90^\circ$. The geometrical details of the samples are given in Dutler et al. (2018). The results of the strength, fracture toughness and the size of the fracture process zone are given in Table 6. These results show that the fracture toughness and strength are both much higher in the direction normal to the foliation compared to the direction along the foliation.

Table 6. Tensile strength, mode I fracture toughness, and the length ($L_{FPZ}$) and the width ($W_{FPZ}$) of the fracture process zone at the two principal directions.

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\sigma_t$ (MPa)</th>
<th>$K_Ic$ (MPa $\sqrt{m}$)</th>
<th>$L_{FPZ}$ (mm)</th>
<th>$W_{FPZ}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>5.6</td>
<td>0.7</td>
<td>10.8</td>
<td>5.4</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>14.7</td>
<td>1.7</td>
<td>8.8</td>
<td>4.7</td>
</tr>
<tr>
<td>Ratio</td>
<td>2.6</td>
<td>2.4</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>

It is evident that the strength is strongly anisotropic, with the value in the direction normal to the foliation being 2.6 times the one along the foliation. This indicates the principal role of micro-cracks dominantly aligned with the foliation on the strength of rock. The failure mechanism in two main directions also shows significant differences. The failure normal to the direction of foliation exhibits a more sudden and instantaneous behaviour than the one along the foliation. In fact, the analyses of strains obtained from digital image correlation (DIC) measurement show the development of a band of failure along the foliation before the final rupture. This may indicate that the fracturing process is mainly due to the gradual activation of micro-cracks, which are mainly aligned with foliation, followed by their coalescence to form a macro-crack that splits the specimen. On the other hand, when the direction of final rupture is normal to the foliation, the existing micro-cracks cannot simply connect to form the fracture, and a more complex mechanism is required in the failure process perhaps including the development of new micro-cracks to connect the existing ones.
Figure 3. Schematics of (a) Semi-circular bending and (b) Brazilian disk specimens, with their two end members $\varphi = 0^\circ, 90^\circ$ where $\varphi$ is the angle between isotropy plane and the loading direction. A picture of the Brazilian disk with the apparent direction of isotropy plane (foliation) is also shown.

The ratio of the maximum fracture toughness to its minimum is 2.4, which indicates a strong anisotropy in fracture toughness. The fracture toughness is the largest for crack propagating normal to the foliation, and is the minimum when the crack grows along the foliation. Also related to the inelasticity of the material is the size of the fracture process zone (FPZ) which develops at the tip of fracture and dissipates energy before the fracture propagation. The detailed results given in Dutler et al. (2018) demonstrate the development of a semi-elliptical FPZ region with the width of $W$ and the length of $L$. These two length parameters seem to be independent, and are expected to be only material properties provided that the boundary of the FPZ is fully formed (no load dependency of the FPZ boundary) and the crack ligament is large enough (no boundary influence). Table 6 reports the width and length of the FPZ along the two principal orientations, normal and along the foliation.

Conclusions

The laboratory measurement of the elastic and inelastic properties of Grimsel Granodiorite given in this report indicate a strong anisotropy of these mechanical properties. Any geomechanical, and geophysical analysis of such rock type, therefore, strongly requires the anisotropy to be taken into account. The anisotropy of Grimsel Granodiorite seems to be due to foliation that happened during the rock formation process, which resulted in the formation of a set of micro-cracks that aligns predominantly along the foliation.

References


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