Integrating rock mechanics and structural geology in rock engineering

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Abstract. One of the major challenges facing rock engineers is that of establishing the bulk properties of the fractured rock mass on which or in which they are working. These are controlled principally by the geometry of the fracture network and the properties of the individual fractures. The network is built up by the superposition of separate fracture sets, each related to a geological event (burial tectonism and exhumation). In structural geology ‘fracture analysis’ is used to determine the order in which the sets are superimposed and knowing this, the 3D geometry of the network can be determined. Examination of the fracture surfaces can also reveal whether they are shear or extensional. Provided with this information the rock engineer can then combine it with site specific tests on the properties of the individual fracture sets and begin to quantify the likely physical behaviour of rock masses on an engineering scale. This paper presents a brief introduction to the concepts of fracture analysis, and goes on to show how these can usefully be integrated with typical rock mechanics analyses to give improved data for rock engineering design.

1. Introduction
The rock masses in which rock engineering takes place are the result of various geological processes. Such processes and their products are well understood by geologists, and they use this understanding to interpret the genesis of a rock mass. Here, we explore how such understanding can bring benefits to rock engineering.

We begin with a brief discussion of the geological processes that generate fractures in a rock during its cycle within the crust from (for sedimentary rocks) deposition, through burial and diagenesis, possible deformation linked to plate motion (orogenesis, i.e. mountain building) and finally exhumation to its present position at the Earth’s surface. Each of these processes is likely to result in the formation of a fracture set whose orientation and type (shear or extensional) will be determined by the stress field acting at the time. Crucially, the different types are likely to possess different mechanical properties.

A succession of processes generates superimposed fracture sets that lead to a fracture network that is characteristic of the structural history. Furthermore, this network dissects the intact rock to form the rock mass in which engineering takes place. The intrinsic properties of the intact rock are largely unaffected by structural processes, but the bulk properties of the rock mass are generally controlled by the fracture network and thus intimately related to its structural history. So how does an appreciation of this history help with rock engineering?

As the scale of the engineering relative to the spacing of the fractures increases, so the bulk properties become dominant in controlling the physical behaviour of the rock mass. In rock engineering, analytical or numerical models that explicitly use properties of the fracture network are often used to predict the
bulk properties of rock masses. By understanding the structural history of a rock mass we can determine the 3D geometry of the resulting fracture network and identify the types of fractures present, and use this to constrain the properties of the fractures used in the engineering analyses and modelling. This enables a realistic estimate of the bulk properties of the rock mass to be determined. Using examples chosen for their clarity, we show how such integration of structural geology and rock mechanics can lead to improved predictions of rock mass behaviour and thus rock engineering performance.

2. Fractures and geological processes

We begin with a brief discussion of the geological processes that generate fractures in a rock during its cycle within the crust from (for sedimentary rocks) deposition, through burial and diagenesis, possible deformation linked to plate motion (orogenesis, i.e., mountain building) and finally exhumation to its present position at the Earth’s surface.

Each of these processes is likely to result in the formation of a fracture set whose orientation and type (shear or extensional) will be determined by the stress field acting at the time. Crucially, the different types are likely to possess different mechanical properties. Over geological time, as a result of these processes, several sets of fractures develop in a rock and these combine to form a fracture network the geometry of which has a major impact on the bulk geo-mechanical properties of the rock mass. In this paper we show how an understanding of the formation of fracture sets within the crust and the understanding of how later fractures interact with earlier fractures – the basis of fracture analysis – can be used to complement a detailed field study of a fractured rock mass in order to generate a realistic 3D model of the fracture network. This will be of use to rock engineers in the siting of engineering projects on and in the rock mass, and in determining its bulk properties such as permeability and strength.

Two major groups of fractures are encountered in the Earth’s crust namely, joints and faults. These correspond to the two types of fractures that are predicted from the theory of brittle failure, namely extensional fractures and shear fractures. Figure 1 shows the complete brittle failure envelope which is the graphical expression of the linear shear failure criterion, \( \tau = C + \mu \sigma \) where \( \tau \) is the shear stress, \( C \) the cohesive strength (the shear strength) of the rock, \( \mu \) the coefficient of sliding friction and \( \sigma \) the normal stress acting on the shear fracture plane), developed by Navier and Coulomb, and the parabolic, extensional failure criterion, \( \tau^2 + 4T\sigma - 4T = 0 \) where \( T \) is the tensile strength of the rock), developed by Griffith [1, 2]. The discussion of the theories of brittle failure on which this figure is based is given in detail in Cosgrove & Hudson [3] to which the interested reader is referred.

The figure shows two stress states represented by the two Mohr circles. The smaller satisfies the conditions for extensional failure (i.e., touches the failure envelope for extensional failure) and the larger satisfies the condition of shear failure (i.e., it touches the shear failure envelope). The relationship between these two types of fractures and their causative stress field is shown in figure 1b and 1c.
respectively. The extensional fracture forms at right angles to the least principal compressive stress, \( \sigma_3 \), and therefore coincides with the \( \sigma_1-\sigma_3 \) plane, and the shear fractures form in two sets (a ‘conjugate’ set), symmetrically disposed about the maximum principal compressive stress, \( \sigma_1 \). For many rocks the angle between them, \( 20^\circ \), is \( \sim 60^\circ \).

It can be seen from the figure that in order for shear failure to occur the diameter of the Mohr circle \((\sigma_1-\sigma_3)\) must be relatively large and for the formation of extensional fractures, it must be relatively small. This can be quantified from the geometry of figure 1a. For many rocks the shear strength of the rock, \( C \), is approximately twice the tensile strength, \( T \). If the differential stress (i.e., the diameter of the Mohr circle) is less than \( 4T \), it is small enough to touch the extensional failure criterion, and if it is greater than \( 4T \) the circle is too large to satisfy the extensional failure criterion and will intersect the failure envelope in the shear failure region.

The intimate relationship between the fractures and the stresses that generate them can be used to either predict the orientation of the fractures that will form in response to a particular stress field or allows the stress regime responsible for the formation of a particular fracture to be determined. These key relationships, combined with ‘fracture analysis’ discussed later in the paper, enable the stress history experienced by a rock mass over geological time, to be determined.

Fractures in the Earth’s crust form in response to stress, and the principal causes of stress are the overburden stress and the stress linked to plate motion. The simplest stress regime is that linked to an overburden and such a stress will characterise the conditions in the crust during the burial and diagenesis of a sediment in a non-tectonic environment. This stress regime is illustrated in figure 2, which shows the overburden stress \( \sigma_3 \) (the vertical stress) increasing linearly with depth. It is given by \( \sigma_3 = z \cdot \rho \cdot g \) where \( z \) is the depth, \( \rho \) the average density of the overlying rocks, and \( g \) the acceleration due to gravity. Assuming the density remains constant with depth, the vertical stress increases linearly with depth as shown in figure 2. The overburden stress attempts to cause a lateral expansion of the rock which is prevented by the confinement of the surrounding rocks which, in order to prevent this expansion, must apply a stress. The magnitude of this stress relates to the compressibility of the rock i.e., to its Poisson’s ratio (the ratio between the axial contraction and lateral extension that would be produced in an unconfined specimen), and can be shown to be \( \sigma_h = \sigma_v (m - 1) \) (see e.g., Cosgrove & Hudson [3]) where \( m \) is Poisson’s number, the reciprocal of Poisson’s ratio. Assuming Poisson’s ratio and the density of the rock remains constant with depth the induced horizontal stress will increase linearly with depth as shown in figure 2.

Using figure 1 the type and orientation of fractures that can develop in the crust under this stress regime can be determined. The differential stress, \( \delta \sigma = \sigma_3 - \sigma_1 \) i.e., \((\sigma_1-\sigma_3)\), increases with depth. In the upper section of the crust where it is less than \( 4T \), extensional fractures can form, and at depths where it exceeds \( 4T \), any fractures that form will be shear fractures. The extensional fractures form normal to \( \sigma_3 \) and will therefore be vertical, and the shear fractures will form in two sets dipping at \( \sim 60^\circ \) each side of the vertical stress i.e., \( \sigma_1 \), figure 2.

There are other factors that will affect the stress state in the crust e.g., the geothermal gradient. The temperature increases with depth and the rock therefore attempts to expand. Any lateral expansion is inhibited by the confining effect of the surrounding rocks which have to apply a horizontal stress to prevent this. This can be quantified. The expansion, i.e., the strain \( \varepsilon \), is given by the change in temperature \( \Delta T \), from the Earth’s surface to the depth of interest and the coefficient of thermal expansion \( \alpha \), \((\varepsilon = \Delta T \cdot \alpha)\) and, by assuming that the rocks behave as a linear elastic materials, Hooke’s law \((\sigma = E \cdot \varepsilon)\), where \( \sigma \) is the stress, \( \varepsilon \) the strain and \( E \) the Young’s modulus) can be used to determine the stress needed to prevent this expansion. By taking into account the impact of the geothermal gradient, the equation for the horizontal stress now incorporates elements linked to both the rock’s compressibility (i.e. \( \sigma_v / (m - 1) \)) and its coefficient of thermal expansion \((E \cdot \Delta T \cdot \alpha)\). The expression for the horizontal stress becomes

\[
\sigma_h = [\sigma_v / (m - 1)] + E \cdot \Delta T \cdot \alpha.
\]
The dependence of the horizontal stress on the intrinsic properties of the rock (the density, Young’s modulus, Poisson’s ratio and coefficient of thermal expansion), means that at any particular depth the state of stress in adjacent layers can be different. This is illustrated schematically in figure 3a which shows the stress states in four adjacent layers. Each layer has the same vertical stress but because of their different properties, has different horizontal stresses.

Figure 2. The variation of the principal stresses $\sigma_1$ ($\sigma_v$) and $\sigma_3$ ($\sigma_h$) in the crust when the only stress it experiences is the result of an overburden. The differential stress, $(\sigma_1 - \sigma_3)$, increases with depth and divides the crust into an upper zone where $(\sigma_1 - \sigma_3) < 4T$ ($T =$ the tensile strength of the rock) and where extensional failure occurs and a lower zone in which shear fractures develop.

Figure 3. (a) The state of stress ($1 - 4$) in four different rocks at a particular depth in the crust corresponding to a vertical stress $\sigma_1$. (b) The effect on the lithostatic stress, $\sigma_1$ and $\sigma_3$, of a fluid pressure $p$. (c) The impact of fluid pressure on the stress states shown in (b).

The state of the principal stresses in the crust during burial and diagenesis under a simple overburden stress, is one of compression, figure 2. It can be seen from figure 3a that none of the four stress states touches either of the failure envelopes and that therefore no fractures will occur. However, in situations where the overburden stress is thought to be the only important stress regime to affect the rocks, the
upper crust is generally permeated with well-developed extensional fractures. This apparent anomaly can be explained when the impact of fluid pressure on the stress states is considered.

Below the water table, the Earth’s crust is saturated with water and the water pressure increases linearly with depth as a consequence of the increasing hydrostatic head, figure 2. However, this hydrostatic fluid gradient is only applicable to a system when the water in the pores of the rock is in contact and can move freely. If as a result of burial, compaction and cementation, the pores become isolated from each other, the rock becomes less permeable, and the fluid pressure builds-up more rapidly as shown by the dashed line in figure 2. The effect of the fluid pressure on the lithostatic stress (i.e., the stress caused by the overburden) is illustrated in figure 3c. The lithostatic stress is shown by the stress ellipse in which both the principal stresses are compressive, and the fluid pressure \( p \), which is represented by the circle, acts to oppose the lithostatic stress. The two stresses combine, and the resultant or effective stress is represented by the stress ellipse with axes \( (\sigma_1 - p) \) and \( (\sigma_3 - p) \). The differential stress, \( (\sigma_1 - \sigma_3) \), i.e., the diameter of the Mohr circle representing the stress state, remains unchanged but the circle is moved to the left, i.e., towards the failure envelope, by an amount \( p \), the fluid pressure. If this pressure is sufficiently high the circle will come into contact with the failure envelope and failure will occur. The magnitude of the differential stress will determine whether shear failure or extensional failure will occur, figure 3b. Thus, stress state 1 will lead to shear failure and states 2–4 to extensional failure.

As noted above, in order for extensional failure to occur the differential stress must be less than four times the tensile strength of the rock. Four Mohr circles are shown in figure 4 all of which will produce extensional failure, which it will be recalled forms normal to the least principal stress \( \sigma_3 \). Although the differential stress in stress state 1 is less than \( 4T \) there is still a significant difference between \( \sigma_1 \) and \( \sigma_3 \), and therefore a clear direction of relatively easy opening for the fractures. They will therefore display a marked preferred orientation, figure 4b(i). In contrast, in stress state iv, the Mohr circle is reduced to a point and represents a hydrostatic stress in which \( \sigma_1 = \sigma_2 = \sigma_3 \), the differential stress is zero and the normal stress is the same in all directions. The fractures form in all directions with equal ease and there is no tendency for them to be aligned. The result is the formation of a polygonal fracture array, figure 4b(iv). As the differential stress of a stress field reduces from \( \sim 4T \) to zero, so the tendency for the fractures to align decreases (figure 4b(ii) & b(iii)). Thus, depending on the value of the differential stress, extensional fractures can range from randomly oriented fractures to a well organised fracture set in which all the fractures are aligned. How this concept may be used in rock mechanics is outlined later in this paper, at the discussion associated with figure 16.

2.1 Possible fracture patterns in a layered crust
As discussed above, even under the simplest of stress regimes i.e., an overburden stress, the stress state in adjacent rock layers at any particular depth \( z \) in the crust, can be significantly different, figure 3a. The depth at which extensional failure changes to shear failure is the depth where the differential stress is \( 4T \) (dashed line in figure 2), and because the tensile strength of different rocks is different the depths at which this change occurs will be different for different rocks. It is therefore possible that fluid induced failure at a particular depth could produce extensional fractures in some layers and shear fractures in others.

The magnitude of the fluid pressure at any particular depth in the crust will depend on both the depth and the permeability of the rock layer. Beds with a low permeability are likely to develop high fluid pressures and are therefore more likely to produce fractures than more permeable strata. It follows that at a particular depth in the crust, some beds may remain unfractured whilst other, less permeable beds, in which the fluid pressure is likely to rise more rapidly, will fail and develop either extensional or shear fractures depending upon their Poisson’s ratio which controls the differential stress. Thus, the expression of brittle failure in a rock can be extremely varied even when generated by the simplest of stress fields acting on flat-lying beds. Figure 5a shows the fractures that could develop at a particular depth in four adjacent layers of different rock types (1 – 4), whose stress states are shown by the four Mohr circles,
Layers of rock type 1 have a high differential stress and will, if the fluid pressure becomes sufficiently high, develop conjugate shear fractures.

Figure 5b. Layers of rock type 1 have a high differential stress and will, if the fluid pressure becomes sufficiently high, develop conjugate shear fractures.

Figure 4. (a) Four stress states (i – iv) represented by Mohr circles, all of which have a differential stress of less than 4T and which touch the extensional part of the brittle failure envelope. (b) shows the organisation of the extensional fractures that form in response to these stresses.

Layers of rock type 2 have a high permeability which prevents the fluid pressure building up sufficiently for the formation of any fractures. Layers of rock type 3 have a differential stress just less than 4T and will therefore develop extensional fractures that are well aligned, see figure 4b(i). Note that the spacing of the fractures is linearly related to the layer thickness, beds 3a & 3b, figure 5, see e.g., Price [4] and Hobbs [5]. Layers of rock type 4 have a very low differential stress and the extensional fractures that form are therefore poorly aligned.

3. Fracture networks and rock masses

3.1 Fracture development in response to several geological stress regimes.

The above discussion has shown how the simplest of stress regimes can generate a complex variety of fracturing at any depth within the crust. Rocks are generally subjected to multiple stress fields during their history and therefore contain multiple fracture sets. These combine to form fracture networks and it is the geometry of these that controls the bulk properties of fractured rock masses.

An understanding of the way in which one set of fractures mechanically interacts with another forms the basis of ‘fracture analysis’, a technique used by structural geologists to determine the stress history of a geological region and also to reveal the 3D geometry of the fracture network. The technique is described briefly below and a detailed discussion of it is given in Cosgrove & Hudson [3], chapter 2 section 12, to which the interested reader is referred.

As noted in figure 1 and the related discussion, extensional fractures form normal to σ3 and contain the σ1 – σ2 plane, figure 1b. Figure 6a shows the disturbed principal stress trajectories around the tip of an early open extensional fracture. The free surfaces which define the two walls of the fracture cannot support a shear stress and as a consequence the principal stresses within the material must rotate as they approach them into an orientation that is either normal or parallel to the walls. The later fracture, approaching from the left, has to track the stress trajectories and so it too rotates into an orientation normal to the wall of the early fracture. It can be seen that the later fracture curves into the earlier fracture and stops propagating. This curving and abutting of late fractures when they encounter earlier fractures provides the basis for fracture analysis and can be used for determining the relative ages of two fracture sets. The value in a rock mechanics context of knowing this is seen later in figure 16.
In the limestone bed shown in figure 6b, a fracture to the SW of the coin, when traced SE, rotates into an orientation normal to, and stops against, the fracture that cuts EW across the lower third of the photograph, indicating that the EW fracture is an earlier fracture. If the later fracture is traced towards the left-hand side of the photograph it is seen to rotate and intersect a NS fracture at 90°. It also stops against this fracture. This NS fracture when traced south terminates against the main EW fracture. Two other NS trending fractures, propagating from the south, also abut against the main EW fracture.

The relative age of the fractures is therefore earliest EW, followed by the NS fractures followed by the NW–SE trending fractures. They represent the $\sigma_1$–$\sigma_2$ planes of three different stress fields in which the minimum principal compressive stresses were oriented NS, EW and NE–SW respectively.

Figure 5. (a) The possible variability of the type and organisation of fractures in a sequence of beds at some depth $z$ in the crust. The rocks 1–4 have the stress states represented by the four Mohr circles shown in (b).

The fracture network shown in figure 7 consists of three fracture sets, and their relative ages and the stress fields under which they formed can be determined from their orientation and the curving and abutting relationships that they display with each other. This is shown in the left-hand panel (i.e., A first, then B and finally C) and it is apparent that there has been an anticlockwise rotation of the stress field during the geological time interval over which these three fracture sets were formed.

Armed with the knowledge that the spacing of extensional fractures tends to be uniform and linearly related to the bed thickness [4, 5], and that later fractures tend to curve towards and stop against earlier fractures, it is possible to produce a geologically realistic diagram of the fracture network if presented with the orientations of the individual fracture sets and their relative age. Figure 8 shows two fracture networks made up of identical fractures. In the first, no consideration is given to spacing or interaction,
and the fractures are distributed in a stochastic manner. In the second the fractures are distributed according to the understanding outlined above where care is taken to respect the relative age of the fracture sets and to ensure that there is a reasonably uniform spacing. The results are profoundly different and the bulk properties of the material such as permeability and strength are very different.

Figure 6. (a) The maximum principal stress ($\sigma_1$) trajectories around the tip of an extensional fracture, far right, and a later fracture whose path is controlled by the deviated stress trajectories. (b) A fractured limestone bed containing an early set of EW trending fractures and later NS and NW–SE trending fractures which curve into and abut against them. Lilstock, North Somerset, UK. Coin for scale.

Figure 7. A schematic fracture network made up of three fracture sets. Their relative age and associated stress regimes can be determined from their curving and abutting relationships and their orientation, see right hand panel.

Even when the orientation and spacing of natural fracture sets is known, an error in the order of their superposition can have a major effect on the geometry of the fracture network and upon the bulk properties it induces in the rock mass. This is illustrated in figure 9 in which the two fracture networks consisting of two identical fracture sets are shown.

In figure 9a, the EW trending fractures are assumed to be the earlier of the two sets and the later, NS set are therefore impeded by and abut against them. If the order of formation of the two fracture sets is reversed, then the NS fractures will be long and continuous and the EW fractures will be shorter and abut against them, figure 9b. The impact on the geometry of the fracture network on the order in which the two sets of fractures are developed is clear and will affect the bulk properties. For example, in model (a) the permeability is greatest in the EW direction and in model (b) in a NS direction.
3.2 Field study to determine the geometry of the fracture network in a rock mass
In this section a field study of a fractured rock mass is described with the aim of providing the rock engineer with a model that they can use to (i) site an engineering structure on or in the rock mass and (ii) obtain an insight into the likely bulk properties of the rock. It is carried out using the understanding of fracture development and interaction described above which provides constrains that are used to check and refine the model.

The Cadomian Granites of Jersey
A detailed field study of the fractures in the Cadomian granites of Jersey has been carried out by Covers [6] in an attempt to explain the geometry of the cave system that has developed in the sea cliffs.

Prior to the field study the geological history of the granites was considered in order to determine the events that had occurred over their lifetime which could have generated fractures. These include cooling, the impact of tectonism and exhumation.

Fortunately, the history of the study area is well known. After the intrusion and cooling of the granites linked to the final stages of the Cadomian tectonism which occurred between 650-550 mya i.e., at the end of the Precambrian, the rocks were subjected to three more major tectonic events. These are;

- The Hercynian orogeny, the mountain-building event caused by Late Palaeozoic (350mya) continental collision between Laurussia and Gondwana to form the supercontinent of Pangaea.
The maximum principal compression in the study area during this event is thought to have been oriented NS (see e.g., Matte [7], Plant et al. [8]).

- The break-up of Pangea. This occurred over the Mesozoic period (250-60mya). The stress regime operating in the study area during this time was one of extension with the least principal stress being oriented EW (see e.g., [8]).
- The Alpine orogeny, caused by the collision of the African and European plates during the Late Cretaceous and Tertiary periods (65mya to the present day). In the study area, the stress regime linked to this event was one in which the maximum principal stress was oriented approximately NW–SE (see e.g., Bevan & Hancock [9]).

Knowing the stress orientation, it is possible to predict the orientation of the fractures that it could generate. Because the main causes of stress operating in the earth’s crust act either vertically (i.e., the overburden stress) or horizontally (i.e., the stresses linked to horizontal plate motion), the stress fields that characterise the crust tend to have principal stresses either vertically or horizontally oriented. The three possible options are shown in figure 10, together with the orientation of the fractures that they could cause.

Figure 10. The three stress regimes which occur when the principal stresses are constrained to being either normal or parallel to the Earth’s surface. The orientation of the shear fractures (solid lines) and extensional fractures (dashed lines) linked to these three configurations is also given.

It can be seen that the three main classes of faults, normal, wrench (strike-slip) and thrust, correspond to the three stress configurations shown in figure 10. Normal faults form when the maximum principal compression is vertical, strike-slip faults when the intermediate principal compression is vertical, and thrusts when the minimum principal compression is vertical.

**Predicting the geometry of the fracture network in the granite**

Based on the knowledge of the tectonic history of the granite (see Helm [10]), it is possible to predict the orientation of the fractures that will form in response to each episode of tectonism and to build up the fracture network that would be expected to form. Field inspection of the granite in the study area shows that on the scale of the outcrops being studied along the coast, the fractures are dominantly extensional fractures with virtually no shear fractures (faults) observed. As a result, in the construction of the fracture network that will develop in the rock mass, only the extensional fractures linked to each tectonic event are considered. The fractures predicted for these tectonic regimes are given in table 1, and block diagrams containing these predicted fractures are shown in figure 11. Figure 11a shows the fractures drawn when no consideration is given either to the order in which the different sets were added or of their mechanical interaction. In figure 11b the chronology of fracture set development is taken into account with late fractures being made to terminate against earlier fractures. This generates a more realistic fracture network than that shown in figure 11a. Figure 11b is the model of the fracture network predicted to form in the granite, based solely on the tectonic history of the region. Thus, in engineering...
sites that are remote or in poorly exposed terrain, then, if the tectonic history of the region is known, it is possible to produce such a model. However, if a detailed study of the fracture system of a potential engineering site is possible, a much more accurate model of the fracture network can be constructed. An example of where this has been done is described in the following section.

Table 1. The four major tectonic events to affect the study area together with the orientation of the principal stresses linked to each and the extensional fractures that will form in response to them.

| Tectonic Event       | Orientation | Fracture Type                          |
|----------------------|-------------|----------------------------------------|
| Alpine Orogeny       | NW-SE or NW-SSE Compression | Vertical extensional fractures associated with a strike-slip regime, Horizontal extensional fractures associated with a thrust regime |
| Mesozoic Extension   | E-W Extension | Vertical extensional fractures associated with an extensional regime |
| Hercynian Orogeny    | N-S Compression | Vertical extensional fractures associated with a strike-slip regime, Horizontal extensional fractures associated with a thrust regime |
| Cadomian Orogeny     | NE-SW Compression | Vertical extensional fractures associated with a strike-slip regime, Horizontal extensional fractures associated with a thrust regime |

Figure 11. (a) A fracture network made up of the extensional fractures predicted for the four tectonic events listed in table 1. (b) A fracture network that has been constructed, taking into account the interaction of later fractures with earlier fractures. After Covers [6].

Determining the geometry of the fracture network in the granites based on a detailed field study

A detailed field study of the fractures in a granite has been carried out and used to construct a model of the fractured rock mass. The study area is in the granite of the St. Brelade’s Bay region of SW Jersey,
figure 12. Data on the extensional fractures collected from various sites are shown in figure 12c. Analysis of these data show that there are 12 discernible fracture sets and field examination of their interaction enables their relative ages to be established using the technique of fracture analysis described earlier and illustrated in Figs. 6 & 7. The 12 fracture sets are represented on the stereographic projection of figure 13 and the accompanying table gives the orientation of the fracture sets, the number of fractures observed for each set, and the variance of each set. The data have been used to construct the model shown in figure 14.

During the field work it was recorded that two of the vertical fracture sets, those trending NS and EW, often developed in clusters forming fracture corridors (see Olson [11]), and these features have been included in the model.

During the exhumation of a rock to the Earth’s surface, the reduction of the lateral constraint and the removal of the overburden produces a relaxation of the stress which is accompanied by the generation of fractures. These generally form parallel to the Earth’s surface and are known as exfoliation fractures. They occur in the top few 100m of the crust and their spacing decreases as the surface is approached. They have not been included in the model because two of the tectonic stress regimes (those linked to the Cadomian and Alpine events, see table 1) are both likely to have generated horizontal fracture sets. It is thought that the sub-horizontal fractures in the granites (set No 9, table 2, figure 13) are linked to these events. It follows that during exhumation, stress release could be achieved by the opening of these fractures and that it would be unnecessary to generate new ones.

 Appropriately oriented blocks, that would fall naturally from the model shown in figure 14c, have been removed. The caves and arches (i.e., the negative topographic features) that have formed along the sea cliff, figure 14a & 14b, and the rock pillars the (positive features), left on the foreshore by the retreating cliff line, figure 14d & 14e, have geometries that are compatible with being derived by the erosion of the model.

![Figure 12. A geological map of SW Jersey and stereographic projections of planes and poles of extensional fractures from seven sites. Based on Covers [6].](image-url)
Figure 13. A stereographic projection showing the mean orientation of the 12 extensional fracture sets formed in the granite. The table gives the mean orientation of each set, the number of fractures recorded for each set and the variance in their orientation. S-H = Sub-Horizontal.

From Covers [6].

This correlation between the model generated and the topographic features in the landscape indicates that the fracture network of the model is a good approximation to that in the granite. Having established this, it can now be used in numerical simulations to explore the bulk properties of the rock. A sensitivity analysis can be carried out using different values of fracture properties, to obtain an insight into the bulk strength and permeability of the system.

Summary

The model of the fractured rock mass based on a general knowledge of the geological history of the study area, (the cooling of the granite, the four tectonic events that have affected it and the exhumation), understandably, does not represent the fractured rock mass as accurately as a model based on field data. Nevertheless, it does capture some of the important features of the fractured granite and when constructing engineering projects in areas that are inaccessible or have poor exposure, such a model could be used as a first approximation and one which could be improved as data generated by the site investigation is accrued.

In engineering sites where a detailed study of the bed rock is possible, an accurate model of the rock mass can be generated, i.e., a model of the type shown in figure 14c. It is based on field mapping combined with an understanding of the processes of fracture generation and fracture interaction.

The rock engineer provided with such a model will know the shape and orientation of the main intact blocks of the rock mass and the likely directions of high permeability, information which, when combined with site specific observations, will facilitate the location and orientation of any construction or excavation. How such information can be used to assist rock mechanics analysis and rock engineering design is the subject of the following section of the paper.
Figure 14. (a) and (b) caves and arches carved by the sea into the granite cliffs. (c) A model of the fractured granite, based on detailed field observations and a sound understanding of the formation of fracture sets and the interaction of fractures. The numbers relate to the fracture sets numbered in Table 2, figure 13. (d) and (e) are rock pillars left by the retreating cliff. The shapes of the caves and the pillars are dominated by the fracture network. From Covers [6].

4. Rock masses in an engineering context

4.1 Integration of structural geology and rock mechanics

The preceding material clearly indicates how the fundamentals of structural geology allow interpretation of fracture patterns in rock masses. In rock engineering, it is recognised that the physical behaviour of rock masses on an engineering scale is significantly controlled by the geometric and mechanical properties of the fractures, and hence measurement and assessment of these properties forms a key part of all ground investigation in rock (figure 15). The links between these rock mechanics properties and structural geological attributes is summarised in Table 3. It is important to recognise that the various rock mechanics attributes presented in this table combine to dictate the engineering behaviour of a rock mass: for example, rock mass hydraulic conductivity is a function of the fracture network, fracture surface morphology and in situ stress. Similarly, rock mass stiffness is related to fracture stiffness and extent, block size and shape, and in situ stress in addition to intact rock stiffness. As all of these
properties are related to structural geology, it is clear that an appreciation of the fundamentals of structural geology will allow rock engineers to better understand the properties and thus behaviour of any rock mass they are working with.

![Diagram of rock mechanics properties]

Figure 15. Typical rock mechanics properties of a rock mass.

Table 3. Rock mechanics properties related to structural geological attribute.

| Rock mechanics property                                        | Structural geological attribute                              |
|----------------------------------------------------------------|--------------------------------------------------------------|
| Fracture strength, stiffness and hydraulic conductivity (all related to fracture surface morphology) | Fracture type (shear, normal)                                 |
| Block shape                                                    | Fracture pattern                                             |
| Block size                                                     | Fracture density (related to permeability during diagenesis) |
| Fracture extent                                                 | Structural history (early fractures, large extent; later fractures, shorter extent and often terminating at earlier fractures) |
| Fracture network                                                | Stress history                                               |
| In situ stress                                                  | Principal stress orientations constrained by fracture orientations |

An example of the benefit that can accrue from such integration is illustrated in the photographs presented in figure 16. The rock mass in these images is a sedimentary sequence comprising cyclic beds of limestone and shale exposed at Lyme Regis, UK. The rock face in figure 16a clearly shows the cyclic sequence, but examination of the limestone beds indicates that this material seems to be broken into blocks. Assessment of block size and shape forms part of a rock mechanics ground investigation, and application of structural geological principles can help with this. Obviously, the blocks are delimited by the upper and lower bedding planes, but what about the shape within each stratum? Reference to Figs. 6 and 7 given above helps here: block edges are likely to be formed of features from different episodes of fracturing, with the early features being of greatest extent and more recent fractures terminating at these. In all cases the orientation of these features will be largely controlled by the stress state that was operating at the time of their formation. This suggests there will be some regularity to the block shape, and we should attempt to determine this. This particular rock face happens to be a sea cliff, and as a result the limestone beds are exposed as wave-cut platforms – as seen in Figure 16b.
The relative ages of the fractures are clear from the photograph of figure 16b, as is the resulting block shape. The fractures that run from left to right are regular and continuous, indicating that they formed before the fractures oriented at right angles to them which terminate (i.e., abut) against them. By reference to figure 4, the geometry of these fracture sets allows an indication of the stress state acting at the time of their formation to be obtained. Similarly, comparing figure 16b with figures 8, 9 and 11b suggests how bulk properties such as strength and permeability of this rock mass will be a function of these earlier stress states and episodes of fracture formation. Turning now to a typical scheme used in geotechnical engineering for block shape description, Table 4 indicates that we would want to describe these blocks as either tabular, prismatic or equidimensional. Although none seem to fit these particular blocks well, a modification of the tabular description is clearly what exists here: these are tabular blocks that are largely rectangular in shape, with one set of block faces (those running from left-to-right of figure 16b) being much less irregular than the other set. Furthermore, rather than simply describing these blocks in this way it is important draw attention to the extensive nature of the left-to-right fractures: these are likely to significantly affect the stability of the rock mass at an engineering scale.

For the rock mass shown in figure 16 it is fortuitous that observations could be made on both a face through the sequence and a particular bedding plane. In the common case of observations being only available on borehole core, identifying spatial relationships between fractures is difficult. In these circumstances it is critical to use expert fracture analysis to obtain information regarding block shape.

The importance of recognising relative timing of fracture formation is vividly illustrated by the quarry face shown in figure 17. This photograph, taken in a quarry on Hong Kong Island, shows a series of parallel sub-vertical fractures, with the camera position being co-linear with the strike of the feature just to the right of centre. Reference to figure 7 indicates that, of the various fractures seen in this photograph, these are the oldest. These features are strikingly planar and extensive, and have low strength and high hydraulic conductivity. Although they have been used to good effect here to form the permanent side slope to the quarry, in general features like this have significant potential to cause excavation instability both above and below ground. Once again, when such features are encountered in borehole core it is critical that their planar extent is correctly identified, and this can only be done by application of the structural geology techniques presented above.
4.2 Engineering design properties

Engineering geologists and rock engineers are familiar with the inherent variability of rock masses and hence uncertainty in engineering design properties. A simple classification of this is given in Table 5. This table shows that tectonic activity and structural history have a strong influence on the confidence with which design properties can be determined.

Table 4. Terms to describe rock mass structures and block shapes
(excerpt from Table C.1 of ISO 14689:2017, ISO [12]).

| Term                 | Figure | Description                                                                 |
|----------------------|--------|-----------------------------------------------------------------------------|
| Tabular blocks       | ![Figure](image1.png) | One dominant set of parallel discontinuities (1), for example bedding planes, with other non-continuous joints; thickness of blocks much less than length or width. |
| Prismatic blocks     | ![Figure](image2.png) | Two dominant sets of discontinuities (1 and 2), approximately orthogonal and parallel, with a third irregular set; thickness of blocks much less than length or width. |
| Equidimensional blocks | ![Figure](image3.png) | Three dominant sets of discontinuities (1, 2 and 3), approximately orthogonal, with occasional irregular joints, giving equidimensional blocks. |

Table 5. Predictability and complexity of geological conditions (from Keaton, [13]).

| Level | Confidence | Geological Characteristics and Conditions                                      |
|-------|------------|------------------------------------------------------------------------------|
| I     | High       | Conditions are massive, homogeneous, vertically and laterally extensive. Site geology has a history of low tectonic activity. |
| II    | Intermediate | Conditions are generally predictable, with lateral and vertical variability. Structural features produced by tectonic activity tend to have systematic orientation and spacing. |
| III   | Low        | Conditions are extremely variable because of complex depositional or structural history, mass movements, or landscape evolution. Significant variability is widespread in lateral and vertical continuity. |
Such complexity and variability has led rock engineering to develop an ethos of subjective assessments of rock mass properties (e.g., components of rock mass classification schemes) and qualitative descriptions of structural behaviour (e.g. definitions of failure). This is quite different from that seen in other engineering disciplines, where rigorous statistical characterisation of material properties and strict quantified definitions of failure are the norm. In geotechnical engineering this more formal approach appears as limit state design, and is beginning to form the basis of geotechnical design codes and standards worldwide. This probabilistic design philosophy is summarised in simplified form by Figure 18, and indicates clearly that both strength and load – referred to as resistance and effect of actions, respectively – are both required to be characterised as statistical distributions, and that failure is defined in terms of probability (not factor of safety). Although this approach is standard in structural engineering, it is currently used only rarely in rock engineering. Although there may be many reasons for this, without doubt one may be the difficulty of determining the strength of a rock mass in the form of a distribution.

As the strength of a rock mass is largely a function of the properties of the fractures within it, can structural geology assist in developing statistical distributions of fracture properties? Also, given that in situ stress is what loads underground openings, can structural geology assist in developing a statistical distribution of this? Well, the structural geologist can certainly provide the rock engineer with an understanding of the 3D geometry of the fracture network in a fractured rock mass, and can indicate which of the fracture sets making up the network are shear fractures, and which are extensional fractures. This information can then be used by the rock engineer (see the following section) to begin to quantify the impact of the fracture network on the bulk strength of the rock mass and to determine its impact on the in situ stress. Crucially, the structural geologist brings specialist knowledge: rather than the rock engineer blindly attempting to fit statistical distributions to data without insight, the expert input of a
structural geologist can guide and constrain any analysis, leading to improved quantification of rock mass properties and behaviour. Three examples of this follow.

Fracture orientation

Most rock engineering projects collect a large amount of fracture orientation data, for the simple reason that borehole core is generally available and orientation is usually determined as part of the standard logging process. These data can then be subject to statistical analysis, and distributions fitted. However, in the situation when quantitative data are limited they can be augmented with expert knowledge. In the context of figure 18 such knowledge needs to be quantitative, and the augmentation formally undertaken via Bayes’ theorem. This profound theorem is based on conditional probability, which many geotechnical engineers are not familiar with, but can be represented graphically as shown in figure 19.

![Figure 18: The basis of probabilistic design.](image)

![Figure 19. Graphical representation of Bayes’ theorem.](image)
Figure 20. Bayesian approach to analysis of structural orientations (after Thiele et al. [14]).

Figure 19 shows how the data, in the form of a distribution known as the likelihood, is augmented by existing knowledge in the form of a prior distribution to give an improved estimate of the data in the form of the posterior distribution. In general the integral in the denominator of Bayes’ theorem has to be evaluated computationally, and so practical application of Bayesian methods uses specialised software. An example of Bayesian analysis in the analysis of fracture orientation is shown in figure 20, and clearly illustrates how the prior distribution (i.e. expert knowledge of structural geology) is used with the likelihood (i.e. limited orientation data) to obtain a posterior distribution (an improved estimate of the distribution of fracture orientation).

In situ stress

Turning to in situ stress, a multivariate model that allows frequentist statistical analysis of this has recently been developed (Gao & Harrison, [15]). Figure 21 shows the model applied to the analysis of stress measurement data obtained at an underground research laboratory. The stress measurement locations at the 240 Level can be separated into two groups as shown in Figure 21: one proximal to and affected by the Room 209 Fracture Zone, and another distant from and hence unaffected by the zone. Although the major principal stress trends shown in the figure seem generally similar in these two groups, analysis using the multivariate stress model shows that the measured stresses in the group affected by the fracture zone are more variable than those in the second. The increased variability of stress proximal to the fracture zone is to be expected on the basis of structural geology, but engineers who are not aware of this may, on the basis of visual similarity, incorrectly assume the stress state to be uniform at the site.

The frequentist statistical model requires a data sample that is large enough to approximate the population. In the case of the analysis of figure 21 there are sufficient data for this approximation to hold, but in general this will not be the case as for most rock engineering projects only a small number of stress measurement tests will be conducted. In such circumstances a Bayesian model is appropriate, and for this analysis uses prior knowledge of stress states in similar geology to augment the limited data (Feng et al., [16]). Once again it is structural geology that will provide this prior knowledge, but at the time of writing this is a new research topic.

Determining the strength of fractures

Interpreting laboratory shear strength data in order to develop design strength criteria is often challenging, as such data often display large variability. An example of such a situation in illustrated in figure 22a, the data in which represent the strength of fractures in limestone (Hencher & Richards, [17]). Although a subjective lower bound could be drawn to these data, doing so has two drawbacks: it would
not characterise strength in the form shown in figure 18, and it would be inefficient as many of the results indicate much higher strength than given by a lower bound.

Now, these data comprise results from two different type of fracture, as shown in figure 22b. The saw-cut surfaces are essentially planar and hence can be thought of as being representative of natural fractures that have undergone significant shear deformation, thereby sustaining brittle surface damage. These are fractures of type (c) indicated in figure 1. Such shearing leads to smoothing of the surface, and so once a structural geologist has identified fractures as being of this origin the rock engineer can immediately predict low fracture surface roughness with little variability. Figure 22b qualitatively confirms this. Conversely, the split and natural joints are tensile in origin (i.e. type (a) of figure 1), and will have surfaces that are both more irregular and variable. Again, identification of such fractures allows an immediate prediction of these conditions, and figure 22b confirms this.

Rather than adopt a simple lower bound for the entire data set, the two groups can be analysed separately and improved estimates obtained. Bayesian regression (Bozorgzadeh et al. [18]) gives the results shown in figure 22c, clearly indicating that the natural (i.e. tensile) fractures are, indeed, rougher and more variable than the saw-cut (i.e. shear fracture) surfaces. The credible intervals shown in figure 22c and the histograms of figure 22d are the ranges in which the shear strength criterion can fall with 95% probability, and such an interpretation fits directly with the requirements of the design approach illustrated in figure 18. Importantly, the friction angles associated with the lower bound of the 95% credible interval can directly be used in probabilistic design as objectively-determined design values, in place of mean values and subjective factors of safety as is customarily the case at the moment. This simple analysis shows how an integration of concepts from structural geology with rock mechanics analyses leads to improved rock engineering design values.

Figure 21. Variability of in situ stress at the 240 Level of the AECL URL (after Gao & Harrison [19]).
Figure 22. Variability in shear strength of natural and artificial fractures (data from Hencher & Richards [17]).

4.3 Summary
The three examples given above – assessment of fracture orientation, interpretation of in situ stress state and determination of fracture strength – are procedures that are routinely undertaken as part of rock engineering projects. In the context of the first part of this paper, we see that such procedures are significantly helped by incorporating expert structural geological knowledge: in general, a robust understanding the conditions under which natural fractures form and the fracture patterns that are likely to develop. In particular, we see that formally incorporating such knowledge via Bayes’ theorem allows generation of statistical distributions suitable for use in modern rock engineering design techniques.

5. Conclusions
Structural geology and rock engineering have traditionally been considered separate disciplines. In This paper has shown how the fundamentals of structural geology, particularly fracture analysis, allows the genesis of fracture patterns in rock masses to be interpreted and a sound understanding of rock mass geometry to be developed. An example using the Cadomian granites of Jersey shows the value of the approach. The value of the improved appreciation for rock mechanics properties of rock masses this approach generates is shown via examples of fracture orientation and strength, and variability of in situ stress. When used in conjunction with Bayesian data analysis this integration of structural geology and rock mechanics is seen to produce improved rock engineering design properties.
Although currently in its infancy, as illustrated by the publication only five years ago of the first book combining structural geology and rock mechanics (Cosgrove & Hudson [3]), this paper has shown how the integration of these two disciplines has the potential to radically improve rock engineering design.

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