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ISRM Suggested Methods for rock stress estimation—Part 1: Strategy for rock stress estimation☆

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Contents

1. Introduction

1. This is Part 1 of four new ISRM Suggested Methods (SMs) for rock stress estimation:

Part 1: Strategy for rock stress estimation.
Part 2: Overcoring methods.
Part 3: Hydraulic fracturing and/or hydraulic testing of pre-existing fractures (HTPF) methods and
Part 4: Quality control of rock stress estimation.

These SMs are published together in a Rock Stress Estimation Special Issue of the International Journal of Rock Mechanics and Mining Sciences, 2003, Volume 40, Issue 7–8, together with a suite of supporting contributions describing various aspects of rock stress estimation. It is strongly recommended that the new SMs are studied in association with the supporting contributions in the 2003 Special Issue—because these contributions provide a wealth of further detail and measurement case examples.

2. This Part 1 of the new ISRM SMs on Rock Stress Estimation[1] concerns the recommended strategy of approach for estimating the state of stress in a rock mass within the context of rock mechanics modelling and rock engineering design. There are many aspects to rock stress estimation and it is important to be aware of these and to approach the subject in a coherent and practical way. Accordingly, Part 1 outlines the relevant issues relating to building up a knowledge of the stress tensor while utilizing a full understanding of the nature of stress and all the evidence available. The points covered in Part 1 paragraphs are summarized in Table 1.

☆Please send any written comments on this ISRM Suggested Method to Prof. J.A. Hudson, President of the ISRM Testing Methods Commission, 7 The Quadrangle, Welwyn Garden City, Herts AL8 6SG, UK.

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[1] These new ISRM SMs for Rock Stress Estimation replace the earlier ones prepared by Kim K and Franklin J A in 1987 [1]. Note that an SM on the Japanese CCBO overcoring device was also published in 1999 [2].

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Table 1
Content of the 30 paragraphs in this Part 1 ISRM Suggested Methods for rock stress estimation

1. 4 SMs and Special Issue	11. Laboratory tests	21. Several measurements
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9. Trend and plunge	19. Scale	29. Integrating estimates
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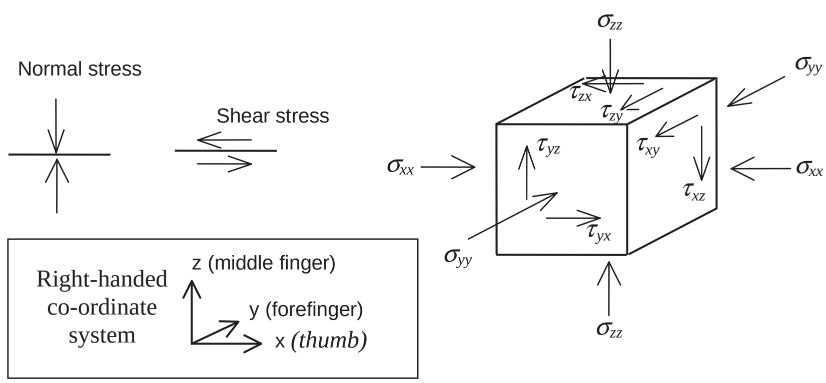

Fig. 1. The components of the stress tensor acting on an infinitesimal cube within the rock mass.

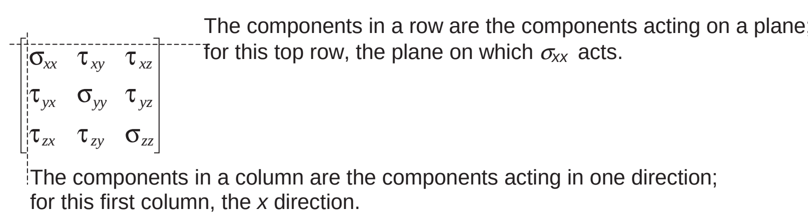

Fig. 2. The components of the stress matrix referred to given x, y and z axes (see also Fig. 1).

2. The concept and occurrence of rock stress

3. For a rock stress estimation campaign, it is essential to understand the concept of stress. Stress is not the same type of quantity as pressure or force because stress is neither a scalar nor a vector quantity: it is a tensor quantity. The stress at a point within a rock mass has three normal stress components acting perpendicular to the faces of a small cube, and six shear stress components acting along the faces (see Fig. 1), a total of nine stress components. The individual stress components are listed in the stress matrix in Fig. 2.

4. The elemental cube shown in Fig. 1 is in equilibrium and, by taking moments about the axes, the complementary shear stresses are found to be equal, as indicated in Fig. 3. This means that the nine component stress tensor has six independent components. Hence, whenever the rock stress is specified, six independent pieces of information must be given. A statement concerning stress which contains less information, and is expressed without further qualification, has no meaning, e.g. a statement such as "The stress is 30 MPa". The stress state is specified either by: (a) the three normal stresses and the three shear stresses acting on the three specified orthogonal planes determined by a set of x, y and z axes; or (b) the magnitudes and directions of the three principal stresses (see Paragraph 5).

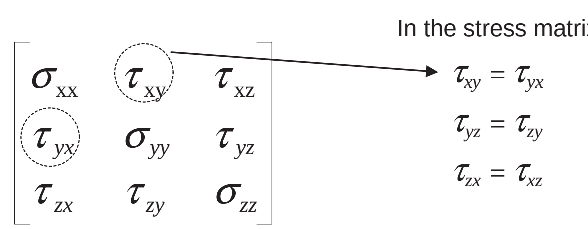

Fig. 3. The complementary pairs of shear stresses are equal, so the stress tensor has six independent components.

5. When the elemental cube shown in Fig. 1 is rotated, the stress components on the faces change in value.

There is always one, and only one, cube orientation at which all the shear stress component values are zero. When this occurs, the cube faces represent the principal stress planes. The normal stresses on these planes are the principal stresses, see Fig. 4.

6. Stress is a tensor quantity because the rules which govern the changes in the stress components as the reference axes are changed are those of a tensor. A tensor quantity is defined not only by magnitude (as for a scalar), or by magnitude and direction (as for a vector), but also by the orientations of the planes on which the stress components are acting. More mathematically [3], a tensor is a "multilinear differential form invariant with respect to a group of permissible co-ordinate transformations in *n*-space".

7. The units of the stress components are newtons per metre squared, $\mathrm{N\,m^{-2}}$, known as pascals, Pa, (or pounds force per inch squared, $\mathrm{lbf\,in^{-2}}$), with dimensions $\mathrm{L^{-1}MT^{-2}}$.

8. Remember that, although compressive stresses are usually reckoned as positive in rock mechanics, computer programs for numerical analysis are often developed from structural engineering codes in which tensile stresses are positive. Always check the sign convention.

9. The orientations of stress components, e.g. the principal stresses, are specified by the 'trend' and the 'plunge'. These are the parameters used for the orientation of a line: the 'trend' is the compass bearing or azimuth of the line; the 'plunge' is the angle between the line and the horizontal. (The terms 'dip direction' and 'dip angle' are used for the orientation of a plane: the 'dip angle' is the angle between the steepest line in the plane and the horizontal; the 'dip direction' is the compass bearing or azimuth of the dip line.)

10. There is no internationally agreed terminology for words describing the state of stress in a rock mass. However, the usage in Table 2 (and see Fig. 5) is recommended, from Hyett et al. and Harrison and Hudson [4,5].

11. The terms used for laboratory testing are clearly defined and are sometimes used to describe aspects of natural and perturbed rock stress as follows:

Uniaxial stress: one principal stress acting, i.e. one principal stress has a non-zero value, $\sigma_1 \neq 0$, $\sigma_2 = \sigma_3 = 0$.

Biaxial stress: two principal stresses acting, i.e. two principal stresses have non-zero values, $\sigma_1 \neq 0$, $\sigma_2 \neq 0$, $\sigma_3 = 0$.

Triaxial stress: three principal stresses are acting *but two have the same value*. This term came into use during the history of laboratory testing: a cylinder of rock is compressed by one principal stress along its axis and a fluid pressure is applied to the sides—equivalent to a stress state $\sigma_1 \neq 0$, $\sigma_2 = \sigma_3 \neq 0$. The term is correct in that three stress components are applied along three axes, but somewhat misleading because two of the components have the same value.

Polyaxial or true triaxial stress: three principal stresses are acting, i.e. the three principal stresses have non-zero values, $\sigma_1 \neq 0$, $\sigma_2 \neq 0$, $\sigma_3 \neq 0$. These three stresses are usually unequal.

12. A key point concerning the stress tensor in relation to rock engineering is that all unsupported rock

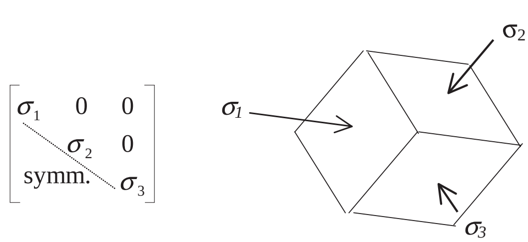

Fig. 4. The principal stresses are the normal stresses acting perpendicular to planes on which there are no shear stresses.

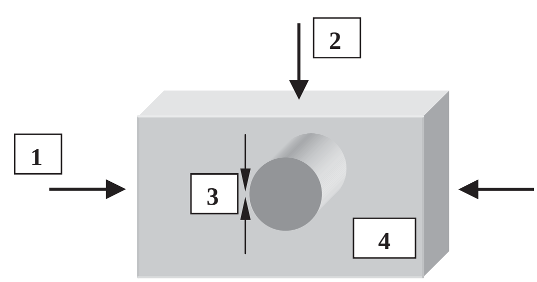

Fig. 5. Types of stress field (see Table 2 for the list of terms).

Table 2
Explanation of terms in current usage (as referring to the numbers in Fig. 5)

1	Tectonic stress	The stress state caused by tectonic plate movement
2	Gravitational stress	The stress state caused by the weight of the rock above
1 and 2	Natural stress	The in situ stress that exists prior to engineering
1 and 2	Regional stress	The stress state in a relatively large geological domain
1 and 2	Far-field stress	The stress state beyond the near-field
3	Local stress	The stress state in a small domain
3	Near-field stress	The stress state in the region of an engineering perturbation
3	Induced stress	The natural stress state as perturbed by engineering
4	Residual stress	A locked-in stress state caused by previous tectonic activity but currently acting
4	Thermal stress	The stress state caused by temperature change
—	Palaeostress	A previous natural stress that is no longer acting

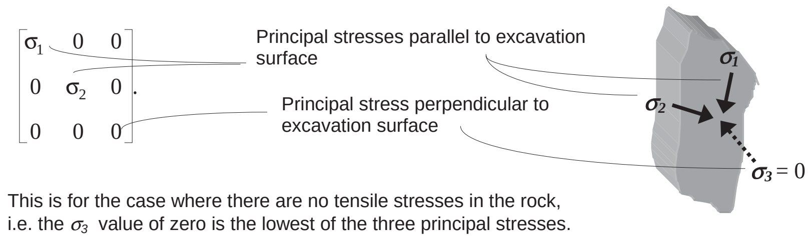

Fig. 6. The local influence of an unsupported excavation surface on the principal stresses.

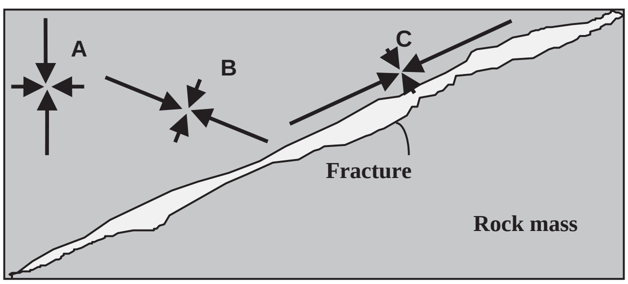

Fig. 7. An open fracture will perturb the stress field and cause the principal stresses to be locally parallel and perpendicular to the fracture surface.

excavation surfaces are principal stress planes—because there are no shear stresses acting on them (Newton's third law). Thus, one of the effects of excavation is to define locally the orientations of the principal stresses, i.e. they will be parallel and perpendicular to unsupported excavation surfaces. Moreover, the magnitude of the principal stress component acting normal to unsupported excavation surfaces is also zero or, more strictly, the value of atmospheric pressure (also by Newton's third law). When the principal stresses at an excavation surface are listed in the stress matrix (with the z-axis perpendicular to the excavation surface), most of the terms have zero value, see Fig. 6. It is much easier to understand underground deformations and excavation-induced fracturing if this is borne in mind.

13. A similar phenomenon occurs naturally at an open fracture, as illustrated in Fig. 7 for the 2-D case. The stress state A indicates two components of the pervasive stress state in the rock. Nearer the fracture, states B and C, the principal stress directions are rotated and the magnitudes of the principal stresses change. In the case of an open fracture, no normal or shear stress can be sustained respectively perpendicular and parallel to the fracture surface, so the fracture surface becomes a principal stress plane with a principal stress value of zero. When the fracture is partially closed or filled, the stress trajectories will be perturbed, but less severely. Imagining this effect adjacent to many fractures at all scales in a rock mass leads to the expectation that local values of in situ stress, and site investigation measured values, are likely to be variable, possibly highly variable.

3. Mathematical expression and continuum aspects of stress

14. The stress, as described in the previous paragraphs, can be expressed more formally as follows.[2] Consider a small surface $\mathrm{d}\underline{\mathbf{s}}$ with normal $\underline{\mathbf{n}}$ and area $\mathrm{d}a$ ($\mathrm{d}\underline{\mathbf{s}} = \underline{\mathbf{n}}\,\mathrm{d}a$) centered on any point $\underline{\mathbf{X}}$ of a continuum. When the continuum is submitted to surface and/or body forces, the surface $\mathrm{d}\underline{\mathbf{s}}$ supports a surface traction $\mathrm{d}\underline{\mathbf{t}}$ which depends on the stress tensor $\boldsymbol{\sigma}$ acting over $\mathrm{d}\underline{\mathbf{s}}$: $\mathrm{d}\underline{\mathbf{t}} = \boldsymbol{\sigma}\underline{\mathbf{n}}\,\mathrm{d}a$. The stress tensor is defined from the limit of the force $\mathrm{d}\underline{\mathbf{t}}$ when area $\mathrm{d}a$ decreases to zero for three orthogonal surface elements. In the absence of distributed body couples and distributed surface couples, the balance of momentum implies that the second-order stress tensor is symmetrical. It exhibits six independent components, which depend on the frame of reference chosen for the analysis. It is customary to consider surfaces of unit area so that the correlative surface traction $\underline{\mathbf{t}}$($\mathrm{d}\underline{\mathbf{t}} = \underline{\mathbf{t}}\,\mathrm{d}a$) is: $\underline{\mathbf{t}} = \boldsymbol{\sigma}\,\underline{\mathbf{n}}$.

15. Because the stress tensor $\boldsymbol{\sigma}$ is symmetrical, it exhibits three real eigenvalues, referred to as the principal stress components. They are associated with three eigenvectors the directions of which are called principal stress directions. The orientation of the principal stress directions with respect to the geometrical frame of reference is characterized by the three Euler angles. Hence, the matrix of the stress tensor includes either six independent coefficients in any frame of reference, or the three principal values in the frame of reference of the three eigenvectors and the three Euler angles characterizing the orientation of the three eigenvectors in the geometrical frame of reference.

16. The concept of stress is associated with that of a continuum and therefore is of value only at a scale at which the continuum concept is valid. The minimum volume for which an equivalent continuum can be

[2] Notation: second-order tensors ($\mathbf{t}$) are denoted by bold characters; vectors ($\underline{\mathbf{v}}$) are denoted by bold underlined characters; scalars (s) are denoted by normal characters.

defined is termed the representative elementary volume (REV). Generally, the continuum concept is of interest when the volume under investigation is at least two orders of magnitudes larger than that of the REV. The REV represents the volume of the physical point, as opposed to the mathematical point which, by definition, has zero volume.

17. With the present definition, a stress tensor exists only if the body of interest is subjected to surface and/or body forces. Stresses that exist in an equivalent continuum in the absence of surface and body forces are termed residual stresses (see Table 2). Residual stresses are such that their net resulting force is zero, as well as their resultant momentum.

4. The stress estimation approach strategy

18. Before listing the steps in estimating rock stress, we first note key factors that must be satisfied for the stress concept to be applicable. The first question to be addressed concerns the relevance of the concept of stress for the circumstances being considered, i.e. whether it is possible to define a REV of interest for the given problem. Indeed, in a heterogeneous and/or fractured rock mass, continuum mechanics may not be appropriate and the concept of stress may be inappropriate. This is particularly the case when deformation primarily results from displacements at block boundaries, while the blocks themselves may be considered as essentially rigid, i.e. structurally controlled displacements. In such circumstances, a continuum approach will be useful only if it addresses volumes significantly larger than those of the constitutive blocks. However, in that case, the large REV size may be incompatible with that of stress measurements made over a much smaller volume. Thus, stress measurement should involve volumes or areas larger than those of the REV. If this cannot be avoided and stress measurements are conducted at scales smaller than the REV, statistical methods must be devised to identify the stress components of interest at the proper scale—and the validity of the method must be demonstrated. It is important to understand any geological heterogeneity in the vicinity of the measuring points. Also, numerical modelling can assist in indicating possible perturbations to the stress field caused by geological features.

19. A second question is raised when stress measurements are conducted at scales larger than the REV and concerns must be given to stress gradients, i.e. the volume over which stress variations may be neglected must be specified. When the various measurements may not be considered as sampling the same stress tensor, interpolation rules must be formulated and their validity must be assessed a posteriori. This is also critical for establishing the scale at which heterogeneity, or discontinuity, is to be considered.

20. Once the validity of the continuum mechanics approach has been established, the next step is to identify the objectives of the stress estimation campaign. A useful way to proceed is simply to list the components that must be accurately estimated (with a specification of the associated confidence level), and those which may be simply assigned values from general considerations. A critical evaluation of the results, a posteriori, may help validate the continuity and homogeneity hypothesis formulated a priori, as well as hypotheses on the constitutive equations of the rock mass.

21. A stress estimation procedure cannot rely on one single set of measurements: it is always advantageous to combine measurements conducted at various locations. As already mentioned, when the distance between the various measurement locations is small in relation to the stress gradients, then simple statistical procedures may be adopted. When the various measurements have been conducted in different locations where the stress variations are significant, then interpolation rules must be proposed. The reliability of these interpolation rules with respect to the hypothesis of continuity must be established. Once, the interpolation rules have been validated, they may be applied to extrapolate the results. Domains of validity for a simple extrapolation procedure should be defined. Various techniques may be designed to extrapolate the results to much larger domains by integration of different stress data. In such instances, efforts should be undertaken to characterize the confidence level of the extrapolation. These extrapolation procedures may help identify zones of heterogeneity and/or discontinuity. Because these are of utmost importance to the mechanical and hydrological properties, they should be outlined in the Final Report. It should be remembered that topographical, geological, and lithological changes can all affect the stress tensor in ways that only direct measurements can establish.

22. Given the cautions in Paragraphs 18–21, the objective of the stress estimation programme must be established, plus the ramifications of the objective. What information is required? Principal stress directions? The magnitude of one or more principal stress components? The complete stress tensor? The variation of the stress state across the site? Are general estimates required, or determination via actual measurements? Are the values required with an interpretation of the site context? What accuracy is required? How are uncertainty and spatial variability to be assessed? Is a confirmatory procedure required? Is a multiple complementary approach required with a final quantitative harmonization? Do the results need to be supported by subsequent numerical modelling? How are the results to be presented? Is strict quality control required, or is an informal approach satisfactory?

5. Assessing existing information and the geological evidence

23. An early step must be to gather all available information on rock stress in the rock mass volume under consideration. This includes an understanding of the geological setting, data from the World Stress Map (http://www-wsm.physik.uni-karlsruhe.de),[3] and reports and papers on stress measurements previously made in the region. An early assessment of the magnitudes and directions of the principal stresses provides a hypothesis against which the results of the new stress estimation campaign can be compared.

24. A preliminary geological investigation should indicate the rock formations, the structural geology setting, the presence of fractures, and the petrofabric description of the rock formation in which the stress measurements are to be conducted. This is essential information for establishing the stress estimation strategy and whether the rock is likely to exhibit elastic brittle behavior or whether plastic deformation or visco-elastic effects may be significant. It is also useful to obtain evidence on the potential role of pore pressure. Further, both geological and geomorphological considerations are always helpful in providing some a priori knowledge of the stress field. They help in establishing whether the principal stresses may be assumed to be vertical and horizontal via topography plus the possibility of any lateral geological variation. They can also provide some information on the local tectonics and therefore on the relative magnitudes of the horizontal principal stresses with respect to the vertical stress [6].

25. At the ground surface, the stress component normal to the surface has a magnitude of zero, i.e. it is the lowest principal stress (assuming no tension). In fact, the vertical stress component is generally the lowest principal stress, independently of the local tectonics, for the first few 100 m depth in hard rock. However, where topographic or geomorphological effects are significant, postulating principal stress directions and magnitudes is not so easy. However, these effects should inform the selection of stress measurement sites, as well as the methodology for interpolation procedures. Also, the existence of major faults or other sources of stress heterogeneity should be identified. These may be located by geological observation at surface exposures and from underground access or from geophysical logs in boreholes. Areas close to fault zones may be avoided in the stress estimation campaign or may be selected for local measurements—depending on the purpose of the measurements.

[3] Much of the World Stress Map data is based on deep data from stress indicators and thus mainly indicates principal stress directions at depth. The data have, therefore, to be used with caution when applied to shallow civil engineering applications.

26. In concluding the literature survey and preliminary geological investigation, an a priori evaluation of the stress field is formulated, with error bars. The latter are included to indicate the level of confidence in the proposed model. For example, if it is known that the rock relative density is not going to be less than 2.0 and not larger than 3.0, then the relative density may be set to 2.5 with error bars of 0.5, and similarly for the other parameters. These considerations will be helpful for selecting the measurement technique, the measurement sites, and in the interpretation process.

27. As already noted, stress is a tensor quantity; therefore, data reduction must acknowledge this fact. When N stress tensors have been specified by the magnitudes and directions of their three principal stresses, σ_{1i}, σ_{2i}, σ_{3i}, for $i = 1$ to N, in order to obtain the mean stress tensor it is not correct to just take the mean of the principal stress values and the mean of their directions. For example, if one stress state has the maximum principal stress acting due north with a value of 5 MPa and a second stress state has the maximum principal stress acting due west with a value of 10 MPa, the mean stress state is not a stress state with the maximum principal stress acting north-west with a value of 7.5 MPa. The separate tensor components must be averaged first and then the magnitudes and directions of the average principal stresses established. For example, if the mean of two stress tensors is required, e.g. for stress states A and B, specified with respect to x, y and z axes, the means of their corresponding components should be obtained first, as

$$\text{Mean} = \left\{ \begin{bmatrix} \sigma_{xx}^{A} & \tau_{xy}^{A} & \tau_{xz}^{A} \\ \tau_{yx}^{A} & \sigma_{yy}^{A} & \tau_{yz}^{A} \\ \tau_{zx}^{A} & \tau_{zy}^{A} & \sigma_{zz}^{A} \end{bmatrix} + \begin{bmatrix} \sigma_{xx}^{B} & \tau_{xy}^{B} & \tau_{xz}^{B} \\ \tau_{yx}^{B} & \sigma_{yy}^{B} & \tau_{yz}^{B} \\ \tau_{zx}^{B} & \tau_{zy}^{B} & \sigma_{zz}^{B} \end{bmatrix} \right\} / 2$$

$$= \left\{ \begin{bmatrix} \sigma_{xx}^{(A+B)} & \tau_{xy}^{(A+B)} & \tau_{xz}^{(A+B)} \\ \tau_{yx}^{(A+B)} & \sigma_{yy}^{(A+B)} & \tau_{yz}^{(A+B)} \\ \tau_{zx}^{(A+B)} & \tau_{zy}^{(A+B)} & \sigma_{zz}^{(A+B)} \end{bmatrix} \right\} / 2,$$

where $\sigma_{xx}^{(A+B)} = \sigma_{xx}^{A} + \sigma_{xx}^{B}$, and so on, and then the principal stresses calculated.

6. Progressive generation of the rock stress tensor and the overall rock stress state

28. A recommended approach strategy is to progressively build up a knowledge of the rock stress tensor. This allows a commensurate enhancement of confidence in the results—because of the sequential confirmation of the stress tensor components. The steps in the progression are summarized in Table 3. Note that Parts 2 and 3 of these ISRMs SMs provides guidance on the specific

Table 3
Steps in developing a knowledge of the rock stress tensor components

<table>
<tr><td colspan="2">Use pre-existing information on the rock stress state at the site</td></tr>
<tr><td colspan="2">Consider whether the vertical direction is a principal stress direction (from topography, geological evidence and other information)</td></tr>
<tr><td colspan="2">Estimate the vertical stress component magnitude (from the rock density and overburden depth)</td></tr>
<tr><td colspan="2">Consider indications of the principal stress directions and the ratio of stress differences (from focal plane solutions inversion or seismic shear wave anisotropy)</td></tr>
<tr><td colspan="2">Establish the minimum principal stress orientation (whether actual or minimum horizontal stress) from hydraulic or drilling induced fractures and borehole breakout orientations</td></tr>
<tr><td colspan="2">Find components of the stress tensor using indirect methods on borehole core (such as the Kaiser effect and differential strain analysis)</td></tr>
<tr><td rowspan="3">Establish the complete stress state at one or more locations by overcoring tests</td><td>Establish the minimum principal stress (from hydraulic fracturing tests in boreholes)</td></tr>
<tr><td>Establish the maximum principal stress magnitude (from hydraulic fracturing tests in boreholes and from borehole failure analysis)</td></tr>
<tr><td>Establish the complete state of stress at one or more locations (by hydraulic testing of pre-existing fractures (HTPF))</td></tr>
<tr><td colspan="2">Establish the variation of the stress state across the site due to different geological strata and fractures (as estimated through numerical analyses and further measurements)</td></tr>
</table>

The table breaks into two columns, the left column is for overcoring and the right column is for hydraulic fracturing.

overcoring and hydraulic fracturing techniques, respectively (see Paragraph 1).

29. The extent to which the steps in this progressive generation of the rock stress state can be incorporated in a site investigation will be a function of the objective, the practicality of their implementation (including length, dip and stability of access borehole, role of water, etc.) and the resources available. Integrating stress estimates obtained with various techniques is always highly recommended. The integration must explicitly take into account uncertainties in the various estimates. The number of estimates for each corresponding technique must also be considered with care to avoid giving any inappropriate weight to the more numerous data set.

30. Before commencing a stress estimation campaign, a plan of action should be prepared based on the objective and the local circumstances. This will lead to a report, which must include a characterization of the confidence level of the estimation. It should separate, when possible, the variation associated with instrumental observations from that associated with the rock mass continuity and homogeneity factors. It should discuss the role of large-scale fractures when these have been identified. It should discuss the validity of constitutive equations assumed for numerical analyses and the stress interpretation, when utilized. Further, results from the stress estimation may be commented upon in terms of their regional significance (topographical effects, existence of a tectonic component, etc.) and should be compared with the a priori assessments.

See the Special Issue in which this ISRM SM is published for a suite of supporting papers on the many facets of rock stress estimation. Also, the book by Amadei and Stephansson [7] is particularly useful.

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