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### A step-by-step analytical procedure to estimate the in-situ stress state from borehole data

- $_{3}$  G. Scelsi · M.L. De Bellis · A. Pandolfi ·
- 4 G. Musso · G. Della Vecchia

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 $_{7}$  Abstract Knowledge of the in situ stress state of rock mass is fundamental

 $_{\rm 8}~$  for engineering, geological and geophysical applications. In situ stress state de-

<sup>9</sup> termination requires in principle the evaluation of the three principal stresses

 $_{10}$   $\,$  and the related principal directions, but it is widely recognized in the liter-

11 ature that the maximum horizontal stress is the most difficult component to

<sup>12</sup> accurately estimate. In the context of borehole methods, this paper proposes

<sup>13</sup> a step-by-step analytical procedure to estimate some bounds to the maximum

<sup>14</sup> horizontal stress, starting from a geomechanical description of the rock and

<sup>15</sup> relying on information generally available in the engineering practice. The pro-

<sup>16</sup> cedure is divided in substeps, each one requiring additional information about

<sup>17</sup> the mechanical properties of the rock and on the geometrical properties of the <sup>18</sup> failed portion of rock: more information available implies a lower uncertainty

#### Giulia Scelsi

Department of Civil and Environmental Engineering Politecnico di Milano, Milano, Italy E-mail: giulia.scelsi@polimi.it

Gabriele Della Vecchia Department of Civil and Environmental Engineering Politecnico di Milano, Milano, Italy E-mail: gabriele.dellavecchia@polimi.it

Anna Pandolfi Department of Civil and Environmental Engineering Politecnico di Milano, Milano, Italy E-mail: anna.pandolfi@polimi.it

Guido Musso Department of Structural, Geotechnical and Building Engineering Politecnico di Torino, Torino, Italy E-mail: guido.musso@polito.it

Maria Laura De Bellis Department of Innovation Università del Salento E-mail: maria.laura.debellis@unisalento.it  $_{19}$   $\,$  on in situ stress estimate. Furthermore, since the proposed procedure is analyt-

<sub>20</sub> ical, it allows a complete and very easy implementation in a spreadsheet. The

 $_{21}$  aim of the work is thus to provide a rigourous but simple analytical tool that

 $_{22}$  can be used in engineering practice to estimate some bounds to the maximum

<sup>23</sup> horizontal in situ stress state. The approach is finally validated by means of

<sup>24</sup> both numerical simulations, performed with a sophisticated numerical tool,

<sup>25</sup> and experimental field data coming from the literature.

Keywords In situ stress · borehole · breakout failure · tensile failure · rock
 mechanics · analytical procedure

#### 28 1 Introduction

Knowledge of in situ stress state is fundamental for the solution of many prob-29 lems not only in the field of civil, mining and petroleum engineering, but also 30 for geological and geophysical applications. For instance, stress concentration 31 around underground openings is significantly affected by the in situ original 32 stress state, and its knowledge is mandatory for any deformation and instabil-33 ity evaluation of tunells and shafts. When dealing with oil and gas applications 34 (e.g. borehole excavations, sand production management and stimulation in-35 terventions), the knowledge of the stress state and its variation is required 36 before and during reservoir depletion, as well as to predict the distribution 37 and the propagation of cracks as a consequence of hydraulic fracturing jobs. 38 39

In situ stress state evaluation implies the determination of six independent 40 quantities, namely the components of the Cauchy second order tensor with re-41 spect to a given coordinate system. However, it is most common in engineering 42 practice to determine the three principal stresses and to identify the related 43 principal directions. The initial stress state of horizontal and homogeneous 44 soil layers, which are commonly originated by deposition, is generally evalu-45 ated by assuming that the vertical and the horizontal directions are principal 46 ones: the vertical stress is considered coincident with the overburden, while the 47 horizontal one is evaluated by means of the  $K_0$  concept (Jaky, 1944, Schmidt, 48 1966). When the geometric configuration is more complex, numerical simula-49 tions of the deposition process are usually performed by increasing the unit 50 weight of the material. When dealing with rock formations at large depths, the 51 problem of identifying the initial stress state is much more complicated, being 52 the result of many processes and mechanisms, involving tectonic, gravity and 53 residual stresses. At a smaller scale, the in situ state of stress is also locally 54 influenced by the presence of cavities and discontinuities. Uncertainties related 55 to the exact geological history, the constitutive laws and the detailed structure 56 of the rock mass imply that no numerical computations can be performed to 57 reliably simulate the whole geological history and thus to estimate the in situ 58 stress field (Zang and Stephansson, 2010). Nowadays, it is widely accepted in 59 the engineering practice that the in situ stress state can be estimated by means 60 of techniques that disturb the rock itself, evaluating the induced mechanical 61

<sup>62</sup> response, which in turn depends on the initial stress state itself.

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According to Amadei and Stephansson (1997), classical crustal in-situ mea-64 surement techniques require either a well bore (e.g. breakout analysis, hy-65 drofrac) or core materials (e.g. overcoring, strain relief). Despite coring meth-66 ods are widely used techniques for stress measurement in the engineering prac-67 tice, they suffer of some limitations related to the maximum depth allowed and 68 to the small volume involved. Borehole methods applicability is vice versa lim-69 ited just by the maximum borehole depth. Zoback et al (2003) evidenced the 70 advantages and the reliability of borehole methods to determine both stress 71 magnitude and orientation in deep wells, highlighting the role of a sound ge-72 omechanical model of the subsurface and of wellbore imaging devices, like 73 ultrasonic televiewers and electrical imaging tools, to yield detailed informa-74 tion about wellbore failure. 75

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The classical strategy that is employed to characterize the stress field (see, 77 e.g. Zoback et al, 2003 and Zoback, 2007) is based on the following steps: 78 i) The vertical equilibrium, i.e. integrating density logs, enables the determi-79 nation of the vertical stress; ii) Wellbore and recent geologic observations as 80 well as earthquake focal mechanisms allow the determination of the principal 81 stresses directions; iii) The analysis of hydraulic fracturing and leak-off tests 82 (see, e.g. Zoback and Healy (1992) and Haimson et al (2009)) permits the esti-83 mation of the minimum principal stress; iv) Direct measurements or a cautious 84 estimation from geophysical logs or seismic data are used to determine pore 85 pressure magnitude. Generally, it is assumed that the vertical stress is princi-86 pal: as a consequence, the two other principal directions lie in the horizontal 87 plane. This assumption is widely accepted for non-active regions from the tec-88 tonics point of view, or for regions where the tectonical stress has already re-89 laxed. In fact, according to Bell (2003), the free surfaces of sedimentary basins 90 are generally horizontal, implying that the principal stress directions can be 91 considered vertical and horizontal. From this picture, it is evident that most 92 difficult component to estimate is the maximum horizontal principal stress. 93 Some bounds to the maximum horizontal stress can be provided by the appli-94 cation of the Anderson faulting theory together with Mohr-Coulomb failure. 95 For any given depth of a rock mass, some limiting values of the difference 96 between the maximum and the minimum principal stresses can be argued, 97 relying on the assumption that the stresses in the earth crust cannot exceed 98 the frictional strength of pre-existing faults. Of course, this argument is valid 99 at a broad scale and, locally, exceptions can exist. Furthermore, an estimate 100 of fault friction angle is needed. Applications are shown in Moos and Zoback 101 (1990), Wiprut and Zoback (2000) and Zoback et al (2003). Shear failure data 102 registered on circular well bores, induced by excavation and pressurization 103 processes, provide other bounds to the maximum horizontal principal stress. 104 Such bounds derive from the shear strength of the material. As a matter of 105 fact, when a well bore is drilled, some material is removed form the original 106 rock mass: the exhumed material is no more able to carry the stress, that is 107

transferred to rock around the well. This process implies a stress concentra-108 tion in the rock surrounding the well. According to the linear elasticity theory, 109 this stress redistribution amplifies the difference between the virgin principal 110 stresses and thus the maximum shear stress in the rock mass. The so-called 111 breakout failure is in fact the consequence of the increase in shear stress on 112 the borehole wall due to the excavation-induced increase of the hoop stress 113 around the wall. Breakout failure can also provide information about the prin-114 cipal stress directions: when either the borehole and the principal stress are 115 vertical, the azimuth of breakout failures coincides with the minimum hori-116 zontal stress direction. The reliability of breakout data as a tool to estimate 117 the in situ stress state is justified also by the possibility of having multiple de-118 termination of stress in single well and by the possibility to check for regional 119 consistency among numerous wells. Breakout failures have been exploited to 120 determine some limiting values of the maximum horizontal principal stress in 121 Leeman (1964), Bell and Gough (1979), Zoback et al (1986). A relevant role in 122 breakout failure analysis is provided by the failure criterion used to describe 123 rock behaviour: Moos and Zoback (1990) provided solutions by considering a 124 Galileo-Rankine criterion for the compressive strength of the rock, character-125 ized by a constant value, while Vernik and Zoback (1992) provided estimates 126 via the Weibols and Cook (1968) strain energy failure criterion. Zoback et al 127 (1985) exploited the elastic Kirsch solution and Mohr-Coulomb failure crite-128 rion to highlight the role of breakout shape and inelastic deformation around 129 the borehole, as later evidenced by Barton et al (1988), Aadnoy et al (2013) 130 and Della Vecchia et al (2014). Important information about the magnitude 131 and the orientation of the horizontal maximum principal stress can be also 132 obtained by drilling induced tensile fractures: these fractures form on the wall 133 of the borehole with an azimuth coincident with the direction of the maximum 134 horizontal stress, when one principal stress is locally tensile. 135

According to this picture, it is evident that the estimate of in situ rock 137 stress state for engineering purposes suffers, as any other geomechanical ap-138 plication, of a relevant problem: due to the complex stress-strain behavior of 139 rocks, sophisticated theoretical and numerical tools are in principle needed to 140 obtain reliable predictions. The applicability of such models is, however, lim-141 ited by the effort needed in their calibration and in their numerical implemen-142 tation, which is generally unaffordable for common engineering applications. 143 In order to overcome this seeming insurmountable dichotomy between reliable 144 predictions and applicability for engineering purposes, this paper presents a 145 step-by-step analytical procedure to estimate the in situ maximum horizontal 146 stress exploiting borehole failure data. The procedure is divided in sub-steps, 147 each sub-step implying an increasing degree of detail about the knowledge of 148 the mechanical properties of the materials involved and on the geometrical 149 properties of the failed portions of rocks. Of course, the larger the quantity of 150 information available, the lower the uncertainty on the estimated stress: the 151 bounds identified by the application of the procedure plays the same role of 152 the classical error bars that are often presented in the literature about in-situ 153

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stress state. It is worth underlying that the procedure is purely analytical: it 154 is thought to be implemented in a simple spreadsheet and no programming or 155 dedicated software are required. In order for the procedure to be analytical, 156 some simplification are necessarily introduced: for example, the role of tem-157 perature changes is neglected, as well as the role of possible not axisymmetric 158 distribution of pore pressure near the well. Remarkably, all the parameters re-159 quired are easy to determine: in the proposed version of the procedure the rock 160 will be characterized in terms of uniaxial strength and friction angle, while the 161 only information needed from the field is the orientation of the faults (if any) 162 and the size of the breakout failure (if any). The procedure has been success-163 fully validated basing on both numerical analyses and case histories from the 164 literature. Numerical analysis has been performed by means of a Finite Ele-165 ment approach, capable of simulating the mechanical behaviour of the rock 166 surrounding the borehole by means of a brittle damage constitutive model for 167 geological media recently proposed in De Bellis et al (2016, 2017). The model 168 in fact proved able to simulate the mechanical behaviour of both sedimentary 169 and crystalline rocks, both in the pre- and the post-peak stages, showing to 170 be particularly suitable for materials characterized by a brittle behavior. The 171 approximation provided by the simplified analytical solution to the results ob-172 tained by means of such a sophisticated numerical tool is excellent, at least 173 for breakout opening lower than  $90^{\circ}$ , proving that the procedure is able to 174 provide reliable results also for non-circular and collapsed boreholes. Appre-175 ciable agreement has been also obtained by applying the procedure to in situ 176 experimental data presented in the literature. 177

#### <sup>178</sup> 2 Steps involved in the procedure: methodology

The procedure to estimate the maximum horizontal stress detailed below in-179 volves four sub-steps: Step 1 is based on Anderson faulting theory, and just a 180 broad estimate of the friction angle of the faults is required. Step 2 is based on 181 the application of the Kirsch elastic solution for the redistribution of stresses 182 around a borehole in plane strain conditions: depending on the azimuth and 183 the far-field stress state, the maximum and minimum principal stress on the 184 borehole wall coincides with different stress components, i.e. radial, hoop or 185 vertical. Stress distribution around the hole according to the Kirsch solution, 186 together with simple visual information obtained along borehole depth about 187 the orientation of drilling-induced failure, allows a refinement of the bounds 188 of the far field stress obtained in Step 1. It is worth noting that Step 2 does 189 not require any information about strength properties of the material at the 190 borehole scale, being based on an elastic solution. Step 3 takes advantage on 191 both the information about the presence of tensile and breakout failures on 192 borehole wall and the knowledge of rock failure criterion, further reducing the 193 bounds identified in Step 2. Finally, if also the size of the borehole breakout is 194 known, Step 4 will provide a unique value of the maximum horizontal stress. 195

In the following,  $S_v$  represents the total principal vertical virgin stress, 196  $S_H$  the total maximum horizontal virgin stress and  $S_h$  the total minimum 197 horizontal virgin stress. According to the Introduction,  $S_v$  and  $S_h$  are assumed 198 to be known in terms of both magnitude and direction. When dealing with 199 the mechanical behaviour of rocks, the stress to be used in the failure criteria 200 are effective stress, indicated as  $S'_v$ ,  $S'_h$  and  $S'_H$  for the vertical and the two horizontal stress directions, respectively. The effective stress tensor, in general 201 202 indicated as  $\sigma'_{ii}$  is evaluated according to the poroelastic theory proposed by 203 Biot as 204

$$\sigma'_{ij} = \sigma_{ij} - \alpha p_w \delta_{ij} \tag{1}$$

where  $\sigma_{ij}$  is the total Cauchy stress tensor,  $p_w$  is the pore fluid pressure,  $\alpha$  the 205 Biot coefficient and  $\delta_{ij}$  is the Kronecker delta. Experimental and theoretical 206 evidences (e.g. Boutéca and Guéguen, 1999) prove that, even for the same 207 material,  $\alpha$  is not a constant, but it depends on the phenomenon that has 208 to be modeled. A large amount of experimental evidence related to sedimen-209 tary rocks (Vincké et al. (1998), Espinoza et al. (2015), Sulem and Ouffroukh 210 (2006), Han et al. (2018)) shows that reproducing the elastic behaviour usually 211 requires  $\alpha$  to be smaller than one, while reproducing failure generally requires 212  $\alpha$  to be equal to one. Since all the following steps deal with failure condi-213 tions, in the following,  $\alpha = 1$  is assumed and the rock is always considered as 214 saturated. 215

216 2.1 Step 1: limits on the stress state from the tectonic regime

<sup>217</sup> The idea of using the Anderson (1951) faulting theory to estimate some broad

limits on the in situ stress state relies on the assumption that brittle frac-

 $_{\rm 219}$   $\,$  ture evidenced at the laboratory scale appears to be reproduced also in na-

<sup>220</sup> ture by geological structures (Zang and Stephansson, 2010): faults thus result

<sup>221</sup> from brittle failure, according to the Mohr-Coulomb failure criterion. Following

Anderson, tectonic stress near the Earth crust can be classified into normal, strike-slip and reverse, depending on the relative combination of the principal

stresses (Table 1).

224

| Regime         | $S_1$ | $S_2$ | $S_3$ |
|----------------|-------|-------|-------|
| Normal NF      | $S_v$ | $S_H$ | $S_h$ |
| Strike-slip SS | $S_H$ | $S_v$ | $S_h$ |
| Reverse RF     | $S_H$ | $S_h$ | $S_v$ |

Table 1 Principal stresses in the different tectonic regimes

At each depth, the Anderson faulting theory defines some relations between the values of stresses, according to the strength criterion of the material. Let us assume that the Mohr-Coulomb failure criterion holds in the form

$$\sigma_1' = C + N_\phi \sigma_3' \tag{2}$$

<sup>228</sup> being  $\sigma'_1$  and  $\sigma'_3$  the maximum and minimum principal effective stress, respec-<sup>229</sup> tively, C the uniaxial compressive strength and  $N_{\phi}$  a parameter dependent on <sup>230</sup> the friction angle  $\phi'$ , i.e.  $N_{\phi} = (1 + \sin \phi') / (1 - \sin \phi')$ .

For any tectonic regime, a relation between some of the in situ principal stresses can be identified, corresponding to the fulfilment of Equation 1:

233 – Normal fault (NF)  $S'_v > S'_H > S'_h$ 

$$\frac{\sigma_1'}{\sigma_3'} = \frac{S_v'}{S_h'} = \frac{C}{S_h'} + N_\phi \tag{3}$$

234 – Strike-slip fault (SS)  $S'_H > S'_v > S'_h$ 

$$\frac{\sigma_1'}{\sigma_3'} = \frac{S_H'}{S_h'} = \frac{C}{S_h'} + N_\phi \tag{4}$$

235 – Reverse fault (RF)  $S'_H > S'_v > S'_v$ 

$$\frac{\sigma_1'}{\sigma_3'} = \frac{S_H'}{S_v'} = \frac{C}{S_v'} + N_\phi$$
(5)

For a given depth (and thus a given overburden stress) and pore pressure, the equations above identify a region in the horizontal stresses plane: the in situ stress state of the material, that cannot support a shear stress greater than the one identified by the failure criterion, must lay inside the region or on its boundaries. For detailed information about this procedure see Zoback et al. [43] and Moos and Zoback [25].

This first step of the procedure needs just a broad estimate of the strength 242 parameters of the material involved: as it has been shown from laboratory 243 studies on a large variety of rock samples and from in situ experiments in 244 different fault regimes, the friction coefficient generally ranges between 0.6 245 and 1.0 (i.e.  $\phi'$  between 30° and 45°). In this case just literature data of 246 friction angle for the studied litotypes can be used, being not known a priori 247 if the major role in terms of failure is provided by the faults or by the core 248 material. As for the value of the uniaxial strength, it is worth evidencing that 249 in petroleum engineering applications the role of C in drawing stress polygons 250 is generally neglected. 251

In the following, each step of the procedure is applied to a well documented 252 case study from the literature, i.e. a 2-km-deep research borehole (Hole-B) 253 drilled in the context of the drilling project investigating the Chelungpu Fault 254 (Taiwan). Information about material properties and in situ stress state can be 255 found in different studies present in the literature (e.g. Wu et al., 2007, Hung 256 et al., 2007, Lin et al., 2009, Haimson et al., 2009); leak-off tests allowed the 257 determination of the variation of the minimum horizontal principal stress  $S_h$ 258 with depth, while from the interpretation of formation microscanner FMS 259 results breakout widths have been estimated for depths between 940 m and 260 1310 m. Figure 1 shows the stress state limits that can be identified for a depth 261 of 1000 m, where the rock mass is characterized by a a far-field minimum 262

<sup>263</sup> horizontal principal stress equal to  $S'_{h} = 10.8$  MPa and a far-field vertical <sup>264</sup> effective stress  $S'_{v} = 14.7$  MPa:  $S'_{H}$  is limited by a lower bound  $S'_{H} = S'_{h} = 10.8$ <sup>265</sup> MPa and by an upper bound  $S'_{H} = 39.8$  MPa, corresponding to a stress <sup>266</sup> anisotropy  $S'_{H}/S'_{h} = 3.7$  deriving from the limit corresponding to the strike-<sup>267</sup> slip regime. Values of  $\phi' = 35^{\circ}$  and saturated density  $\rho_{sat} = 2.5$  g/cm<sup>3</sup> have <sup>268</sup> been used, according to Haimson & Rudnicki (2009) and Wang (2011). Pore <sup>269</sup> pressure has been assumed to be hydrostatic.



Fig. 1 Admissible stress polygon and limits from tectonic regimes for the Chelungpu fault site.

270 2.2 Step 2: limits on the stress state from failure orientation

The estimate of the bounds on the value of the maximum horizontal stress 271 identified at Step 1 can be refined by means of a visual inspection of borehole 272 failure, performed, e.g., by ultrasonic televiewers. It is well known that a cir-273 cular hole in a isotropic linear elastic material induces a perturbation in the 274 stress field, which can be computed according to the Kirsch solution. In the 275 following, a is the internal radius of the circular hole, subjected to a uniform 276 internal pressure  $p_i$ ), r is the radial coordinate, i.e. the distance from borehole 277 center that varies between a and  $\infty$ , and  $\theta$ , positive counterclockwise, is the 278 angle between the radius considered and the direction of the maximum hori-279 zontal stress (see figure 2). Another useful variable is the so-called net pressure 280  $p_{\text{net}}$ , defined as the difference between  $p_i$  and the pressure of the pore fluid, 281  $p_w: p_{net} = p_i - p_w$ . The Kirsch solution, developed in plain strain conditions, 282 reads (see, e.g. Jaeger [21]): 283



Fig. 2 Radial coordinates for the circular hole

$$\begin{aligned} \sigma_{r}' &= \frac{1}{2} (S_{H}' + S_{h}') \left[ 1 - \left(\frac{a}{r}\right)^{2} \right] + p_{\text{net}} \left(\frac{a}{r}\right)^{2} + \frac{1}{2} (S_{H}' - S_{h}') \left[ 1 - 4 \left(\frac{a}{r}\right)^{2} + 3 \left(\frac{a}{r}\right)^{4} \right] \cos 2\theta \\ \sigma_{\theta}' &= \frac{1}{2} (S_{H}' + S_{h}') \left[ 1 + \left(\frac{a}{r}\right)^{2} \right] - p_{\text{net}} \left(\frac{a}{r}\right)^{2} - \frac{1}{2} (S_{H}' - S_{h}') \left[ 1 + 3 \left(\frac{a}{r}\right)^{4} \right] \cos 2\theta, \\ \tau_{r\theta} &= -\frac{1}{2} (S_{H}' - S_{h}') \left[ 1 + 2 \left(\frac{a}{r}\right)^{2} - 3 \left(\frac{a}{r}\right)^{4} \right] \sin 2\theta, \end{aligned}$$
(6)

where  $\sigma'_{\theta}$ ,  $\sigma'_{r}$  and  $\tau_{r\theta}$  are the effective hoop, radial and shear stress, respectively and  $S'_{H}$  and  $S'_{h}$  are maximum and the minimum horizontal effective far-field stresses.

<sup>287</sup> Under the assumption of drilling operations performed in plane strain con-<sup>288</sup> ditions in the vertical direction, the principal stresses on borehole wall (r = a)<sup>289</sup> and  $\theta = 0$  can be expressed, according to the Kirsch solution, as

$$\sigma'_r = p_{\text{net}}$$

$$\sigma'_\theta = 3S'_h - S'_H - p_{\text{net}},$$

$$\sigma'_z = S'_v + \Delta\sigma'_z = S'_v + 2\nu(S'_h - S'_H).$$
(7)

In accordance with the elastic solution introduced, the increment  $\Delta \sigma'_z$  due to borehole excavation follows from the assumption of null vertical strain increment ( $\Delta \varepsilon_z = 0$ ). The increments of radial and hoop stress can finally be calculated as  $\Delta \sigma'_r = p_{\rm net} - S'_h$  and  $\Delta \sigma'_\theta = \sigma'_\theta - S'_H = 2'S_H - S'_h - p_{\rm net}$ , so that  $\Delta \sigma'_z = 2\nu(S'_H - S'_h)$  (being  $\nu$  the Poisson coefficient of the rock).

If the stress components are divided by the minimum effective far-field horizontal stress  $S'_h$ , the role of the far-field stress anisotropy ratio  $S'_H/S'_h$  is highlighted:

$$\frac{\sigma'_r}{S'_h} = \frac{p_{net}}{S'_h} 
\frac{\sigma'_{\theta}}{S'_h} = 3 - \frac{S'_H}{S'_h} - \frac{p_{net}}{S'_h} 
\frac{\sigma'_z}{S'_h} = \frac{S'_v}{S'_h} + 2\nu \left(1 - \frac{S'_H}{S'_h}\right).$$
(8)

Equations (8) represent three lines in the  $\sigma'/S'_h$  vs.  $S'_H/S'_h$  plane, that can be easily drawn when the relevant information about  $S'_v$ ,  $S'_h$  and  $p_{net}$  are known: for example, plotting the three lines allows the visualization of the maximum, the intermediate and the minimum principal stresses on borehole wall for  $\theta = 0$ , i.e. when tensile failure is anticipated.

Figure 3(a) shows an example of the evolution of the stress state in  $\theta = 0$  as 303 a function of the horizontal anisotropy ratio for  $S'_v = 14.7$  MPa and  $p_{net} =$ 304 0 MPa. The maximum stress anisotropy considered in the example is the one 305 identified in Step 1, i.e.  $S'_H/S'_h \leq 3.7$  (see section 2.1). It is evident that for low 306 values of  $S'_H/S'_h$ , the minimum principal stress is the radial one, while for high values of  $S'_H/S'_h$  the hoop stress becomes the minimum one. If a visual infor-307 308 mation about tensile failure is provided, it is possible to determine what is the 309 direction of the minimum principal stress: vertical fractures are generally ob-310 tained if the hoop stress is minimum, horizontal fractures if the vertical stress 311 is minimum, concentric fractures if the radial stress is minimum (see, e.g Zang 312 and Stefansonn, 2010). Once the minimum principal stress is identified, the 313 relevant zone according to Equation (8) can be identified, and thus a further 314 limitation in stress anisotropy is obtained. According to the example, in the 315 presence of vertical fractures  $\sigma'_{\theta}$  has to be the minimum principal stress, and 316 so  $3 \leq S'_H/S'_h \leq 3.7$ ; if concentric fractures are detected,  $\sigma'_r$  is the minimum 317 principal stress, so that  $1 \leq S'_H/S'_h \leq 3$ . The limiting anisotropies separating 318 the different tensile failure orientation can be plotted in the stress polygon, as 319 shown in Figure 4, where the line  $S'_{H} = 3 \cdot S'_{h}$  divides vertical and concentric 320 fractures. 321

322

The same logical path can be applied on the borehole wall in  $\theta = \pi/2$ , when shear failure is anticipated: also in this case the failure pattern is dependent on which components are the maximum and the minimum ones. In this case the principal effective stresses on borehole wall (r = a) reads:

$$\sigma'_r = p_{net}$$
  

$$\sigma'_\theta = 3S'_H - S'_h - p_{net}$$
  

$$\sigma'_z = S'_v + 2\nu(S'_H - S'_h),$$
(9)



Fig. 3 Relation between normalized principal components as a function of horizontal stress anisotropy  $S'_H/S'_h$  ( $S'_v = 14.7$  MPa,  $\nu = 0.34$ ,  $p_{net} = 0$ ).



Fig. 4 Identification of the regions where the different tensile failure orientations can potentially take place.

327 and in non dimensional form

$$\frac{\sigma'_r}{S'_h} = \frac{p_{net}}{S'_h} 
\frac{\sigma'_{\theta}}{S'_h} = 3\frac{S'_H}{S'_h} - 1 - \frac{p_{net}}{S'_h} 
\frac{\sigma'_z}{S'_h} = \frac{S'_v}{S'_h} + 2\nu \left(\frac{S'_H}{S'_h} - 1\right).$$
(10)

Figure 3(b) shows the evolution of the stress components in  $\theta = \pi/2$  as a function of the horizontal anisotropy ratio and it clearly illustrates that in this specific case for all the admissible anisotropy ratios the radial effective stress is always the minimum principal stress and the hoop stress is always the maximum principal stress ( $\sigma'_r < \sigma'_z < \sigma'_{\theta}$ ). In this specific case, such an information cannot provide any further refinement of  $S'_H$  bounds, because just  $_{\rm 334}$   $\,$  a type of breakout failure is predicted. If viceversa also the lines predicted by

 $_{335}$  (10) would cross themselves, then the same logic of Figure 3(a) can be followed:

<sup>336</sup> depending on failure pattern in the breakout zone, the relevant region in term
<sup>337</sup> of stress anisotropy could be identified.

2.3 Step 3: limits on the stress state from rock failure criterion

According to Equation 6, under the assumption of plane strain conditions 339 during drilling operations, the complete effective state of stress can be written 340 on borehole wall (r = a), allowing to determine, once the strength parameters 341 of the materials are known, if failure conditions are met. According to the 342 literature, the evolution of the effective hoop stress on the borehole wall can 343 be considered as a proxy to determine which zones of the borehole can be 344 subjected to shear failure and which ones to tensile failures. Writing  $\sigma'_{\theta}$  as a 345 function of  $\theta$  in r = a leads to the expression 346

$$\sigma'_{\theta}(a,\theta) = (S'_H + S'_h) - p_{\text{net}} - 2(S'_H - S'_h)\cos 2\theta, \tag{11}$$

that shows that the minimum value  $3S'_{h} - S'_{H} - p_{\text{net}}$  is achieved for  $\theta = 0$  or  $\theta = \pi$ , while the maximum one,  $3S'_{H} - S'_{h} - p_{\text{net}}$ , for  $\theta = \pi/2$ , or  $\theta = 3/2\pi$ . If the elastic and strength parameters of the material, as well as the values of  $S_{v}$ ,  $S_{h}$ ,  $p_{\text{net}}$  and  $p_{w}$ , are known from previous determinations, it is possible to obtain some bounds for  $S_{H}$  depending on the occurrence of compression or tensile failure at the borehole wall.

#### $_{353}$ 2.3.1 Using breakout failure to estimate maximum horizontal stress $S_H$ $_{354}$ bounds

When a breakout failure occurs, Step 3 of the procedure allows the determination of a lower bound for the maximum horizontal stress  $S'_{H}^{\text{min}}$ . This step relies on the assumption that, as soon as breakout failure starts to develop, it involves just a single point of the borehole wall, rather than a finite volume of rock. Breakout failure generally starts at an azimuth  $\theta = \pi/2$ , i.e. where  $\sigma'_{\theta}$  is locally the maximum principal stress. Equation (10) shows the dependence of the principal stresses on the the far-field (virgin) stresses in  $\theta = \pi/2$ .

Because both the principal effective stresses on the borehole wall  $\sigma'_{\theta}$  and  $\sigma'_{z}$  depend on the only unknown of the problem  $S'_{H}$ , from the mathematical point of view the problem reduces to finding  $S'_{H}$  such that

$$f_C\left(\sigma'_z(S'_H), \sigma'_r, \sigma'_\theta(S'_H)\right) = f_C(S'_H) = 0,$$
(12)

where  $f_C(\sigma'_{ij}) = 0$  is a suitable shear failure criterion of the material. The methodology is intended to work for any failure criterion, and analytical solutions can be found for several failure criteria, e.g. Mohr-Coulomb, Hoek-Brown and Mogi-Coulomb (Hashemi et al, 2014, 2015). For the sake of simplicity, in the following just the Mohr-Coulomb (MC) criterion will be considered, being its parameters the easiest to determine.

The Mohr-Coulomb failure criterion can be expressed in terms of maximum and minimum principal effective stresses ( $\sigma'_1$  and  $\sigma'_3$  respectively) as:

$$\sigma_1' = C + N_\phi \sigma_3'. \tag{13}$$

where C is the uniaxial compression strength and  $N_{\phi} = \frac{1 + \sin \phi'}{1 - \sin \phi'}$ , being  $\phi'$ the internal friction angle. For  $\theta = \pi/2$ , where breakout failure are anticipated, the maximum principal stress is generally  $\sigma'_{\theta}$ . For the minimum principal stress two cases are possible, i.e.  $\sigma'_3 = \sigma'_r$  and  $\sigma'_3 = \sigma'_z$ :

- If the minimum principal stress is  $\sigma'_r$ , the value of  $S'_H$  corresponding to failure (for given  $S'_v$  and  $S'_h$ ) is

$$S'_{H}^{MC} = \frac{1}{3} \left[ S'_{h} + (1 + N_{\phi}) p_{\text{net}} + C \right] \text{ if } \sigma'_{3} = \sigma'_{r},$$
 (14)

<sup>379</sup> – If the minimum principal stress is  $\sigma'_z$ , it follows that

$$S'_{H}{}^{MC} = \frac{C + N_{\phi}S'_{v} + S'_{h}(1 - 2\nu N_{\phi}) + p_{\text{net}}}{3 - 2\nu N_{\phi}} \quad \text{if} \quad \sigma'_{3} = \sigma'_{z}.$$
(15)

If breakout failure occurs,  $S'_{H}^{MC}$  has to be considered as a lower bound for  $S'_{H}$ , because in order to have failure, a value of  $S'_{H} \ge S'_{H}^{MC}$  is needed. Viceversa, if breakout failure does not occur, then  $S'_{H}^{MC}$  has to be considered an upper bound for  $S'_{H}$ .

Figure 5(a) shows the line expressed by equation 14 taking C = 79.5 MPa 384 and  $\phi' = 35^{\circ}$ , representing a bound for the maximum horizontal stress  $S'_H$ , 385 thus identifying two possible domains for  $S'_H$  according to the detection of 386 breakout failures. Due to the presence of shear failures in the considered bore-387 hole section, it can be stated that  $S'_H$  has to be greater than  $S'_H > 30.1 \text{ MPa}$ 388 (therefore  $S'_H/S'_h > 2.8$ ) for the specified  $S'_h$  value. Step 3 of the procedure, 389 accounting for breakout failure, is shown in Figure 5(b): the admissible stress 390 state has to fall between the limits deriving from Anderson faulting theory 391 (Step 1) and from the detection of breakout. 392

#### $_{393}$ 2.3.2 Using tensile failure to estimate maximum horizontal stress $S_H$ bounds

Also when a tensile failure occurs, Step 3 of the procedure allows the determination of a lower bound for the maximum horizontal stress  $S_{H}^{'\min}$ , which is in general different from the one estimated for breakout failure. Also for tensile failure, the step relies on the assumption that, as soon as failure starts to develop, it involves just a single point of the borehole wall, rather than a finite volume of rock. Tensile failure in general starts at an azimuth  $\theta = 0$ , i.e. where  $\sigma'_{\theta}$  is locally the minimum principal stress. Equation (8) shows the dependence of the principal stresses on the the far-field (virgin) stresses in  $\theta = 0$ .



Fig. 5 Stress polygon with the dashed red line identifying the lower bounds for  $S'_H$  in order to have breakout failures according to the Mohr-Coulomb failure criterion.

<sup>402</sup> Also in this case the principal effective stresses  $\sigma'_{\theta}$  and  $\sigma'_{z}$  depends on the <sup>403</sup> unknown  $S'_{H}$ , that can be found by imposing

$$f_T\left(\sigma'_z(S'_H), \sigma'_r, \sigma'_\theta(S'_H)\right) = f_T(S'_H) = 0,$$
(16)

where  $f_T(\sigma'_{ij}) = 0$  is the chosen tensile failure criterion for the rock. Also in this case, the methodology is intended to work for any failure criterion. For the sake of simplicity, in the following part just the Galileo-Rankine (G) criterion will be considered, because it requires just one parameter to determine, i.e the tensile strength  $S_T$ .

The Galileo failure criterion depends only on the minimum principal stress  $(\sigma'_3)$ , so that

$$\sigma_3' = S_T. \tag{17}$$

For  $\theta = 0$ , where tensile failures are anticipated, the minimum principal stress is  $\sigma'_{\theta}$ . The value of  $S'_{H}$  corresponding to failure (for given  $S'_{h}$ ) is

$$S'_{H}{}^{G} = 3S'_{h} - S_{T} - p_{net}.$$
 (18)

<sup>413</sup> In the case that tensile failure occurs,  $S'_{H}{}^{G}$  has to be considered as a lower <sup>414</sup> bound for  $S'_{H}$ , i.e. in order to have failure, a value of  $S'_{H} \geq S'_{H}{}^{G}$  is needed. <sup>415</sup> Viceversa, if tensile failure does not occur, then  $S'_{H}{}^{G}$  has to be considered an <sup>416</sup> upper bound for  $S'_{H}$ .

Figure 6(a) shows the line expressed by equation 18, representing an upper 417 bound for the maximum horizontal stress  $S'_H$ , since no tensile fractures have 418 been registered in the section taken as example. Two possible domains for 419  $S'_{H}$  are identified according to the detection of tensile failures. A value  $S_{T} =$ 420 5.4 MPa, as reported by Haimson & Rudnicki (2009), has been considered. 421 Combining this information with that derived in 2.3.1, it can be stated that 422  $S'_H$  ranges between 30.1 MPa (Fig. 6(b)) and 37.8 MPa (corresponding to 2.8 <423  $S'_H/S'_h < 3.5$ ) for the specified  $S'_h$  value. 424



15

Fig. 6 Stress polygon with the blue dashed line identifying the lower bounds for  $S'_H$  in order to have tensile failures according to the Galileo strength criterion.

425 2.4 Step 4: accounting for breakout size

In order to further reduce the uncertainties related to the determination of  $S'_H$ , 426 an analytical solution was provided in Della Vecchia et al (2014), by exploiting 427 also the information about the breakout width. Step 4 thus not only need the 428 knowledge of the parameters characterizing the rock failure criterion, but also 429 detailed outputs from dipmeters or borehole televiewers during well loggings. 430 According to Barton et al. (1998), the angle  $\alpha_b$  subtending the breakout zone 431 from the center of the hole is introduced. The same information in terms of 432 azimuth is given by  $\theta_b$  ( $\theta_b = \pi/2 - \alpha_b/2$ ), which measures the angle between 433 the radius passing from the extremity of the breakout zone and the direction of 434 the  $S_H$ . The proposal of Della Vecchia et al (2014) is based on the assumption 435 that the experimental breakout size measured at the borehole wall coincides 436 with the size of the yield zone that would originate in the same conditions 437 if the material is elastic perfectly plastic. Accordingly, the principal effective 438 stresses on borehole wall in  $\theta = \theta_b$  can be expressed as 439

$$\sigma'_{\theta} = S'_{H} + S'_{h} - p_{\text{net}} - 2(S'_{H} - S'_{h})\cos 2\theta_{b},$$
  

$$\sigma'_{z} = S'_{v} + \Delta\sigma'_{z},$$
  

$$\sigma'_{r} = p_{\text{net}}.$$
(19)

Also in this case, the increment  $\Delta \sigma'_z$  has been estimated assuming plane strain conditions in the vertical direction, i.e.  $\Delta \varepsilon_z = 0$ . Assuming that in  $\theta = \theta_b$ both the elastic solution ((6)), and the Mohr-Coulomb yield condition ((13)) are fulfilled, i.e. the material is prone to yield, the effective stress distribution obtained depends both on the size of the yielded zone and on the chosen yield function. As for the elastic case, in  $\theta = \theta_b$  the hoop stress  $\sigma'_{\theta}$  is the maximum principal stress, while the minimum one is not know a priori: also in this case



Fig. 7 Stress polygon with green dotted line identifying the value of  $S'_H$  at  $\theta_b = 68^{\circ}$  (eq. 20).

two possibilities must be taken into account. If the minimum principal stress is  $\sigma'_r$ , then

$$S'_{H} = \frac{C - S'_{h}(1 + 2\cos 2\theta_{b}) + (1 + N_{\phi})p_{\text{net}}}{1 - 2\cos 2\theta_{b}}, \qquad \sigma'_{3} = \sigma'_{r}.$$
 (20)

449 If the minimum principal stress is  $\sigma'_z$ , then:

$$S'_{H} = \frac{C + N_{\phi}S'_{v} + S'_{h}\left[-1 - 2\cos 2\theta_{b}(1 - \nu N_{\phi})\right] + p_{\text{net}}}{1 + 2\cos 2\theta_{b}(\nu N_{\phi} - 1)}, \quad \sigma'_{3} = \sigma'_{z}.$$
 (21)

If the breakout size is known, a unique value of the maximum horizontal 450 stress  $S_H$  can be determined. In the example,  $\sigma'_r$  is taken as the minimum 451 principal stress, assuming the principal components in  $\theta = \theta_b$  to have the 452 same relations as those in  $\theta = \pi/2$ . Equation 20, plotted in Figure 7, identifies 453 a single value of  $S'_H$  for each minimum horizontal stress  $S'_h$ : it is evident that 454 the stress states with a known breakout width are larger than the stresses 455 deriving only from breakout failure starting at  $\theta = \pi/2$ . For the  $S'_h$  value at 456 1000 m depth, equal to 10.8 MPa, the maximum horizontal stress  $S'_H$  takes the value of 34.8 MPa (corresponding to  $S'_H/S'_h = 3.2$ ); this value falls between 457 458 the limits obtained in Step 3. 459

Table 2 summarises the bounds for  $S'_H$  obtained using the proposed approach for the Chelungpu site at 1000 m. It is evident that the greater the detail of the analysis and the larger the information available, the lower the uncertainty of  $S'_H$  estimate.

#### <sup>464</sup> 3 Numerical validation of the procedure

The procedure proposed is characterized by a continuous refinement of the bounds in which the real value of  $S'_H$  should lie. If information on the mechanical properties of the material and the size of the breakout failures is

| Step | $S'_H{}^{min}$ [MPa] | $S'_H{}^{max}$ [MPa] | Information needed             |
|------|----------------------|----------------------|--------------------------------|
| 1    | 10.8                 | 39.8                 | Broad estimate of $\phi'$      |
| 2    | Data not available   | Data not available   | Visual information of failures |
| 3    | 30.1                 | 37.8                 | $C, \phi', S_T$                |
| 4    | 34.8                 | 34.8                 | $C, \phi',$ breakout width     |

Table 2 Bounds for  $S'_H$  for each step using the proposed procedure for Chelungpu-Hole B at  $1000\,{\rm m}$ 

available, then Step 4 allows the determination of a unique value of  $S'_H$ . As 468 a consequence, a relevant issue is provided by the reliability of Equations 20 469 and 21. In Della Vecchia et al. (2014), FEM simulations were performed to 470 check if the analytical equations proposed were consistent with the mechan-471 ical behaviour of an elastic-perfectly plastic material at the borehole scale. 472 However, rocks hardly behave as perfectly plastic materials, often showing a 473 brittle stress-strain response under stress paths that lead the material to fail-474 ure: stress redistribution due to material failure and the consequent induced 475 anisotropy cannot be accounted for when perfect plasticity is assumed. In or-476 der to validate step 4 of the procedure with reference to issues related to the 477 loss of circularity of the hole, the outcome of equations 20 and 21 has been 478 compared with the results of numerical simulations performed by considering 479 the complex stress-strain behaviour of the rock, including the possibility of 480 brittle failure. In particular, borehole excavation has been simulated via the 481 Finite Element Method, assuming the stress-strain relation to be described by 482 the brittle-damage constitutive model presented in De Bellis et al (2016, 2017). 483 The model is based on an explicit kinematic description of rock behaviour by 484 means of connected patterns of parallel equi-spaced faults that exist at the 485 material level: this micro-mechanical description guarantees that the rock un-486 dergoes compatible deformations and remains in static equilibrium down to 487 the micro-mechanical level. Each family of faults is characterized by a spacing 488 L and a unit normal **N** to the plane of the faults. In the following, for the 489 sake simplicity, it is assumed that just one family of fault can develop in the 490 material. The deformation of the rock is due to the contribution of both the 491 deforming homogenous rock matrix,  $\varepsilon^m$ , and the opening faults,  $\varepsilon^f$ , according 492 to: 493

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^m + \boldsymbol{\varepsilon}^f = \boldsymbol{\varepsilon}^m + \frac{1}{2L} (\boldsymbol{\Delta} \otimes \mathbf{N} + \mathbf{N} \otimes \boldsymbol{\Delta})$$
(22)

being  $\Delta$  the displacement jump of the faults (i.e. the relative displacement of the two sides of the fault) and  $\otimes$  the dyadic product.

Remarkably, the fracture pattern predicted by the model follows from a thermodynamically consistent approach. Fault inception, orientation and spacing are evaluated under the assumption that an incremental work of deformation exits, capable of accounting for both the reversible and dissipative behaviour of the rock. Assuming that the material state at the representative elementary volume level at time  $t_n$  is known, a numerical solution strategy is <sup>502</sup> employed to calculate incrementally the fault pattern and the effective stress <sup>503</sup> at time  $t_{n+1} = t_n + \Delta t$  for a given total deformation  $\varepsilon_{n+1}$ . The incremental <sup>504</sup> work of deformation  $E_n(\varepsilon_n, \Delta, q)$  over the time interval  $\Delta t$  is defined as the <sup>505</sup> sum of elastic, cohesive and frictional contributions:

$$E_{n}(\boldsymbol{\varepsilon}_{n},\boldsymbol{\Delta},q) = W^{m}(\boldsymbol{\varepsilon}_{m}) + \frac{1}{L}\boldsymbol{\Phi}(\boldsymbol{\Delta},q) + \frac{\Delta t}{L}\psi^{*}\left(\frac{\boldsymbol{\Delta}-\boldsymbol{\Delta}_{n}}{\Delta t},\boldsymbol{\varepsilon},\boldsymbol{\Delta}\right), \quad (23)$$

where  $W^m$  is the elastic strain energy density per unit volume of the matrix, 506  $\Phi$  is the cohesive energy density per unit surface of the faults, the term includ-507 ing  $\psi^*$  represent the frictional dissipation in  $\Delta t$  and q is an internal variable 508 describing the state of the faults. The cohesive energy  $\Phi(\Delta, q)$  has been de-509 fined assuming a linear decreasing cohesive law, according to De Bellis et al 510 (2016, 2017). Just two parameters are thus needed to describe the cohesive 511 behaviour: the tensile strength  $S_T$  and the critical energy release rate  $G_c$ . The 512 tensile strength  $S_T$  corresponds to the maximum attainable effective traction 513 on the faults, while  $G_c$  is the area enclosed by the cohesive law. According to 514 standard cohesive theory, a critical opening displacement  $\Delta_c = 2G_c/S_T$  can 515 be defined: for opening larger than the critical one, cohesive forces vanishes. 516 Irreversibility is introduced in the damage law by means of the scalar internal 517 variable q, corresponding to the maximum opening attained by the fault. Upon 518 unloading, the cohesive behaviour of the fault is supposed to be linear elastic 519 up the origin. Frictional dissipation processes are finally accounted for via the 520 introduction of a dual dissipation potential per unit fault area  $\psi^*$ . According 521 to the Coulomb friction model, it reads: 522

$$\psi^* = \mu \max\left\{0, \left(\boldsymbol{\sigma}' \mathbf{N}\right) \cdot \mathbf{N}\right\} |\dot{\boldsymbol{\Delta}}|,\tag{24}$$

where  $\mu = \tan(\phi')$  is the friction coefficient,  $(\sigma' \mathbf{N}) \cdot \mathbf{N}$  is normal component of 523 the traction vector on fault plane and  $|\Delta|$  the norm of the displacement jump 524 rate. The model thus accounts for two types of material failure: in tension 525 (according to the Galileo-Rankine criterion) and in shear (according to the 526 Mohr-Coulomb criterion). The solution of the incremental problem is obtained 527 by the minimization of the incremental work of deformation, subjected to the 528 constrains provided by the impenetrability of the closed faults (i.e.  $\Delta_N \geq 0$ ) 529 and the irreversibility of damage (i.e.  $\Delta q \geq 0$ ). The minimization process 530 finally provides the solution in terms of fault spacing and orientation: further 531 details on the model equations and the numerical solution strategy can be 532 found in De Bellis et al. (2016). From the practical point of view, just 6 material 533 parameters are needed: 534

<sup>535</sup> – The Young modulus E and the Poisson ratio  $\nu$ , describing the elastic be-<sup>536</sup> haviour of the homogeneous matrix, i.e. the behaviour of the material in <sup>537</sup> the pre-failure stage;

- The friction angle  $\phi'$  and the tensile strength  $S_T$ , describing the failure

<sup>539</sup> properties of the rock according to the Mohr-Coulomb failure criterion;

540 – The critical energy release rate  $G_c$ ;

#### 541 – A scale parameter $L_0/\Delta_c$ .

The model proved able to reproduce the triaxial response of different type of rock, both in the pre- and post-peak stages, as shown in De Bellis et al (2016, 2017) and Della Vecchia et al (2016).

In the context of the determination of the in-situ stress state, numerical 545 simulations with the advanced model have been performed with the aim of 546 providing a validation of the simplified analytical model presented in Step 4. 547 The excavation of a vertical borehole within a horizontally bedded rock for-548 mation has been simulated via the Finite Element method, starting from a 549 computational domain that includes a 1 m thick, 40 m wide horizontal square 550 layer perpendicular to the borehole axis. The finite element mesh consists of 551 8,010 nodes and 36,086 tetrahedral elements. The simulation of the excava-552 tion is achieved numerically by removing (or deactivating) the elements that 553 fall at the interior of a cylindrical cavity, whose radius takes the value a = 1554 m. The model is able to predict the evolution of stress concentration around 555 the borehole, together with the development of shear-induced failures, in cor-556 respondence to the maximum deviatoric stress, and tensile fractures. In the 557 context of this paper, Figure 8 shows the elements (red spheres) characterized 558 by the presence of shear induced fractures for two different stress anisotropy 559 ratios  $S'_{H}/S'_{h}$ , equal to 4.0 and 4.5, for the Chelungpu example. The material 560 parameters used are listed in Table 3. As expected, the higher the anisotropy 561 ratio in the horizontal plane, the larger the amplitude of the failed zone. By a 562 visual evaluation of the amplitude of the failed zone, the relationship between 563  $\theta_b$  and  $S'_H$  can be estimated, according to the advanced constitutive model 564 proposed. It is worth noting that, due to the stress redistribution induced by 565 the failed elements, the numerical model has the built-in capability in account-566 ing for the variation in borehole shape (i.e. ovalization) induce by breakout 567 failures. 568

569

| E                | ν    | $\mu$ | $S_T$  | $G_c$  | $L_0/\Delta_c$ |
|------------------|------|-------|--------|--------|----------------|
| [kPa]            | [-]  | [-]   | [kPa]  | [kN/m] | [-]            |
| $13.7\cdot 10^9$ | 0.35 | 0.7   | 29,800 | 0.005  | 1              |

Table 3 Material parameters introduced in the numerical simulations for Chelungpu-B

Simulations have been carried out by varying the value of  $S'_H$  at a constant 570  $S'_h$ , measuring the resulting breakout amplitude, if any. Results of the simu-571 lation in terms of breakout amplitude for different  $S'_{H}$  values are indicated 572 with black points in Figure 9 for the Chelungpu site, while the continuous 573 line represents the outcome of the simplified analytical procedure (Equation 574 20). Despite the strong assumptions at the basis of the analytical procedure, 575 the accordance between the two prediction is remarkably good, at least for 576 breakout amplitudes not exceeding  $90^{\circ}$ . It is worth noting that, for parameter 577



Fig. 8 Evolution of the zones subjected to shear failures at varying far-field stress anisotropies

calibration, real data coming from the relevant literature have been used: how-578 ever, available information is generally limited to friction angle and uniaxial 579 compressive strength, which can be related to the tensile strength according 580 to the Mohr-Coulomb failure criterion. As for the elastic parameters, E and 581  $\nu$ , typical values for any kind of rock can be easily found in the literature. 582 The remaining parameters are more complex to determine: in order to avoid 583 to consider them as variables that can be used a posteriori to fit the analytical 584 equation, sensitivity analyses have been performed in order to highlight their 585 role for the problem at hand: as shown in Scelsi (2017), the evolution of  $\theta_b$ 586 with the far-field stress is not significantly influenced by  $G_c$  and  $L_0/\Delta_c$ . Values 587 of these parameters have just been taken from the literature (e.g. De Bellis et 588 al. (2016, 2017), Della Vecchia et al. (2016)), without any significant influence 589 on the numerical validation. 590

# <sup>591</sup> 4 Experimental and numerical validation of case histories from the <sup>592</sup> literature

<sup>593</sup> In this section, a further numerical and experimental validation of the proposed <sup>594</sup> simplified procedure is presented, basing on two case histories presented in the

<sup>595</sup> literature.

<sup>596</sup> 4.1 Basel 1 enhanced geothermal system

<sup>597</sup> In 2006 a 5-km-deep borehole has been drilled under the Swiss city of Basel <sup>598</sup> with the aim of developing an "Enhanced Geothermal System" EGS for a <sup>599</sup> geothermal power plant. The orientation of the maximum horizontal princi-<sup>600</sup> pal stress has been determined from the observations of failures derived from <sup>601</sup> ultrasonic televiewer images in 2two vertical boreholes. In the granite, tensile



Fig. 9 Chelungpu, Hole-B (1000 m depth); comparison between the simplified analytical model and numerical results.

fractures are present in intermittent way, while breakout are present almost 602 continually, except for the first 100 m where they are sparse. The mean orien-603 tation of  $S_H$  from tensile and breakout failures is N143°E±14°. Information 604 about material properties and in situ stress state can be found in different 605 studies presented in the literature (e.g. Valley and Evans, 2015, Haring et 606 al., 2008). The profile of the breakout width is also available along the whole 607 depth of borehole Basel-1. In the following, the stress state at  $4,632\,\mathrm{m}$  will be 608 analysed, where the measurement of  $S_h$  is available ( $S'_h = 74.4 \,\mathrm{MPa}$ ). Rock 609 properties and the known effective stress state, taken from Valley & Evans 610 (2015), are listed in Table 4. 611

| Property       | Value        |
|----------------|--------------|
| $S_v'$ [MPa]   | 69.6         |
| $S_h'$ [MPa]   | 28.9         |
| $\phi'$ [°]    | 44           |
| C $[MPa]$      | 167          |
| $\theta_b$ [°] | $\approx 60$ |

Table 4 Data used in the study of Basel-1 at 4.632 km depth (Valley & Evans, 2015).

The analytical procedure have been applied according to the following steps:

<sub>614</sub> – Step 1: limits on the stress state from the tectonic regime

The polygon of the admissible stress states in the plane  $S'_H - S'_h$  is represented considering all faulting regimes. Figure 10(a) allows to identify graphically the first limits on  $S'_H$ : this value has to be between  $S'_h = 28.96$ 

graphically the first limits on  $S'_{H}$ : this value has to be between  $S'_{h} = 28.96$ MPa by definition and 160.73 MPa  $(S'_{H}/S'_{h} = 5.6)$ , i.e. limit deriving from strike-slip regime. From the polygon it can be easily deduced that the tec tonic regime can be either normal or strike-slip.

<sub>621</sub> - Step 2: limits on the stress state from failure orientation

Principal stresses are computed using the relation defined by Equations (8) for  $\theta = 0$  and from Eq. (10) at  $\theta = \pi/2$ . The components corresponding to the minimum, intermediate and maximum principal stress can be seen in Figure 11 for admissible tensional anisotropies  $S'_H/S'_h$ , i.e.  $1 \leq S'_H/S'_h \leq$ 5.6. It can be observed that:

<sup>627</sup> -  $\sigma'_r < \sigma'_z < \sigma'_{\theta}$  in  $\theta = \pi/2$  for all the values of  $S'_H/S'_h$ , apart from <sup>628</sup> anisotropies  $S'_H/S'_h < 1.2$  for which the vertical stress is greater than <sup>629</sup> the hoop stress. The presence of visual observations of failure directions <sup>630</sup> could thus allow a further refinement of  $S'_H$  bounds;

<sup>631</sup> - in  $\theta = 0$ , since no tensile fractures are registered at the considered <sup>632</sup> depth, the relation between stress components cannot be used to further <sup>633</sup> limit the anisotropy  $S'_H/S'_h$ .



Fig. 10 (a) Admissible stress polygon. (b) Lines dividing stresses associated to different type of failures. The blue thin solid line represents tensile fractures, red dashed line the shear failures in  $\theta = \pi/2$ . The green dotted line indicates the value of  $S'_H$  at  $\theta_b = 60^\circ$ , according to Eq. 20.

<sub>634</sub> – Step 3: limits on the stress state from rock failure criterion

Breakout failures have been registered in the section taken into account, while tensile fractures are absent. The Mohr-Coulomb failure criterion with tension cut-off is assumed to hold ( $\phi' = 44^{\circ}$ , C = 167 MPa,  $S_T = 0$  MPa). The lines delimiting the presence or absence of fractures are drawn in the stress polygon (Figure 10(b)); the stress state has to lie below the line representing tensile fractures, and above the line delimiting breakout failures.

 $_{\rm 642}$  Considering the absence of tensile fractures, it can be stated that  $S'_{H}$  has to

be smaller than 86.88 MPa; for shear failures in  $\theta = \pi/2 S'_H > 65.32$  MPa. Therefore  $2.3 < S'_H/S'_h < 3.0$ .



Fig. 11 Visualization of the relation between normalized principal components as a function of  $S'_H/S'_h$ , limited between admissible values derived by tectonic limits;  $\nu = 0.22$ ,  $p_{net} = 0$ .

<sup>645</sup> - Step 4: accounting for breakout size

Being the breakout angle approximately known ( $\theta_b \approx 60^\circ$ , corresponding to an amplitude  $\alpha_b \approx 60^\circ$ ), a single value of the maximum horizontal *farfield* stress state can be determined. According to eq. 20,  $S'_H \simeq 83.50$  MPa (corresponding to  $S'_H/S'_h = 2.9$ ) and thus  $S_H = 128.94$  MPa. This value falls between the limits obtained in Step 3.

The tectonic regime is strike-slip, as it is clearly shown in Figure 10(b). The maximum horizontal stress ( $S_H = 128.94$  MPa) differs of about 10 MPa from the value estimated by Valley & Evans (2015) with their empirical interpolation  $S_H = 1.04z + 115$  MPa/km, which gives a result equal to 119.82 MPa.

| $\operatorname{Step}$ | $S'_H{}^{min}$ [MPa] | $S'_H{}^{max}$ [MPa] | Information needed             |
|-----------------------|----------------------|----------------------|--------------------------------|
| 1                     | 28.96                | 160.73               | Broad estimate of $\phi'$      |
| 2                     | Data not available   | Data not available   | Visual information of failures |
| 3                     | 65.32                | 86.88                | $C, \phi', S_T$                |
| 4                     | 83.50                | 83.50                | $C, \phi',$ breakout width     |

Table 5 Bounds for  $S_{H}^{\prime}$  for each step using the proposed procedure for Basel-1 at 4632 m

Table 5 summarises the bounds for  $S'_H$  for each step of the proposed approach for the Basel-1 borehole at 4632 m.

The maximum horizontal stress obtained via the analytical procedure has been also validated by means of the numerical model described in Section 3. Material parameters are listed in Table 6, while the principal stress components  $S'_v$ and  $S'_h$  and the breakout width have been introduced in Table 4.

662

| E              | $\nu$ | $\mu$ | $S_T$ | $G_c$  | $L_0/\Delta_c$ |
|----------------|-------|-------|-------|--------|----------------|
| [kPa]          | [-]   | [-]   | [kPa] | [kN/m] | [-]            |
| $65\cdot 10^6$ | 0.22  | 0.97  | 36700 | 0.005  | 1              |

Table 6 Material parameters introduced in the numerical simulations for Basel-1.

<sup>663</sup> Different simulations have been carried out by varying  $S'_H$  between 29 MPa <sup>664</sup> (corresponding to  $S'_H/S'_h = 1$ ) and 159 MPa (corresponding to  $S'_H/S'_h = 5.5$ ), <sup>665</sup> measuring for each simulation the predicted breakout width. The obtained re-<sup>666</sup> sults are plotted in Figure 12, together with the  $S'_H$  trend obtained at Step 4 <sup>667</sup> via eq. 20. The numerical and analytical predictions are substantially essen-<sup>668</sup> tially coincident up to an anisotropy ratio  $S'_H/S'_h = 4$  equal to 4 and to a <sup>669</sup> width  $\alpha_b \approx 90^\circ$ , the maximum relative error being lower than 15%.



Fig. 12 Basel-1; evaluation of  $S'_{H}$  through the Mohr-Coulomb failure criterion imposition in  $\theta = \theta_b$  and results of simulations with brittle damage model.

#### <sup>670</sup> 4.2 Cajon Pass Scientific Research Borehole

At the Cajon Pass site (California) a scientific research borehole was conducted 671 between 1986 and 1987, reaching a depth of 3500 m. In the literature several 672 publications (Zoback & Healy (1992), Vernik & Nur (1992), Vernik & Zoback 673 (1992)) provide information regarding the material characteristics and the in 674 situ stress state; some minimum horizontal principal stress  $S_h$  measurements 675 and the amplitude of the breakout for depths between 907 m and 3486 m have 676 been obtained respectively via hydraulic fracturing and borehole televiewer. 677 In this case a depth of 2048 m has been considered, where an estimate of the 678 maximum horizontal stress  $S_H$  is available in Zoback & Healy (1992). Rock 679 properties and the known stress state are listed in Table 7. 680

| Property       | Value        |
|----------------|--------------|
| $S_v'$ [MPa]   | 32.15        |
| $S_h'$ [MPa]   | 19.81        |
| $\phi'$ [°]    | 39           |
| C $[MPa]$      | 132          |
| $T_0$ [MPa]    | 13           |
| $\theta_b$ [°] | $\approx 73$ |

Table 7 Data used in the study of Cajon Pass at 2.048 km depth.

- <sup>681</sup> The analytical procedure was applied according to the following steps:
- 682 Step 1: limits on the stress state from the tectonic regime
- The polygon of the admissible stress states in the plane  $S'_H S'_h$  is represented considering all faulting regimes. Figure 13(a) allows the graphical identification of the first limits on  $S'_H$ : this value has to be between  $S'_h = 19.81$  MPa by definition and 85.75 MPa  $(S'_H/S'_h = 4.3)$ , i.e. limit deriving from strike-slip regime. From the polygon it can be deduced that the tectonic regime can be either normal or strike-slip.
- Step 2: limits on the stress state from failure orientation
- Principal stresses are computed using the relation defined by Equations (8) for  $\theta = 0$  and from Eq. (10) at  $\theta = \pi/2$ . The components corresponding to the minimum, intermediate and maximum principal stress can be seen in Figure 14 for admissible tensional anisotropies  $S'_H/S'_h$ , i.e.  $1 \leq S'_H/S'_h \leq$ 4.3. It can be observed that:
- <sup>695</sup>  $\sigma'_r < \sigma'_z < \sigma'_{\theta}$  in  $\theta = \pi/2$  for all the values of  $S'_H/S'_h$ . The presence <sup>696</sup> of visual observations of failure directions could thus allow a further <sup>697</sup> refinement of  $S'_H$  bounds.
- <sup>698</sup> in  $\theta = 0$ , since no tensile fractures are registered at the considered <sup>699</sup> depth, the relation between stress components cannot be used to further <sup>700</sup> limit the anisotropy  $S'_H/S'_h$ .
- <sup>701</sup> Step 3: limits on the stress state from rock failure criterion
- <sup>702</sup> Breakout failures have been registered in the section taken into account, <sup>703</sup> while tensile fractures are absent. The Mohr-Coulomb failure criterion with <sup>704</sup> tension cut-off is assumed to hold ( $\phi' = 39^{\circ}$ , C = 132 MPa,  $S_T = 0$  MPa). <sup>705</sup> The lines delimiting the presence or absence of fractures are inserted in <sup>706</sup> the stress polygon (Figure 13(b)); the stress state has to lie below the <sup>707</sup> line representing tensile fractures, and above the line delimiting breakout <sup>708</sup> failures.
- Considering the absence of tensile fractures, it can be stated that  $S'_H$  has to be smaller than 72.43 MPa; for shear failures in  $\theta = \pi/2$   $S'_H > 50.60$  MPa. Therefore  $2.6 < S'_H/S'_h < 3.7$ .
- Step 4: accounting for breakout i
- <sup>712</sup> Step 4: accounting for breakout size



Fig. 13 (a) Admissible stress polygon. (b) Lines dividing stresses associated to different type of failures. The blue thin solid line represents tensile fractures, red dashed line the shear failures in  $\theta = \pi/2$ . The green dotted line indicates the value of  $S'_H$  at  $\theta_b = 73^\circ$ , according to Eq. 20.



Fig. 14 Visualization of the relation between normalized principal components as a function of  $S'_H/S'_h$ , limited between admissible values derived by tectonic limits;  $\nu = 0.26$ ,  $p_{net} = 0$ .

<sup>713</sup> Being the breakout angle approximately known ( $\theta_b \approx 73^\circ$ , corresponding <sup>714</sup> to an amplitude  $\alpha_b \approx 34^\circ$ ), a single value of the maximum horizontal *far-*<sup>715</sup> *field* stress state can be determined. According to eq. 20,  $S'_H \simeq 54.56$  MPa <sup>716</sup> (corresponding to  $S'_H/S'_h = 2.8$ ) and thus  $S_H = 74.7$  MPa. This value falls <sup>717</sup> between the limits obtained in Step 3.

The tectonic regime is strike-slip, as it is clearly shown in Figure 13(b). The maximum horizontal stress ( $S_H = 74.7$  MPa) differs of only 4.6 MPa from the value estimated from hydraulic fracturing data, equal to 79.3 MPa, reported in Zoback & Healy (1992).

Table 5 summarises the bounds for  $S'_H$  for each step of the proposed approach for the Cajon Pass Borehole at 2048 m.

| Step | $S'_H{}^{min}$ [MPa] | $S'_H{}^{max}$ [MPa] | Information needed             |
|------|----------------------|----------------------|--------------------------------|
| 1    | 19.81                | 85.75                | Broad estimate of $\phi'$      |
| 2    | Data not available   | Data not available   | Visual information of failures |
| 3    | 50.60                | 72.43                | $C, \phi', S_T$                |
| 4    | 54.56                | 54.56                | $C, \phi',$ breakout width     |

Table 8 Bounds for  $S'_H$  for each step using the proposed procedure for Cajon Pass Borehole at 2048  ${\rm m}$ 

| 724 | Material parameters are listed in Table 9, while the principal stress com         |
|-----|---|
| 725 | ponents $S'_v$ and $S'_h$ and the breakout width have been introduced in Table 7. |
| 726 |   |

| E              | ν    | $\mu$ | $S_T$ | $G_c$  | $L_0/\Delta_c$ |
|----------------|------|-------|-------|--------|----------------|
| [kPa]          | [-]  | [-]   | [kPa] | [kN/m] | [-]            |
| $90\cdot 10^6$ | 0.26 | 0.8   | 39700 | 0.005  | 1              |

**Table 9** Material parameters introduced in the numerical simulations for Cajon Pass Borehole at 2048 m depth.

Different simulations have been carried out by varying  $S'_H$  between 20 MPa (corresponding to  $S'_H/S'_h = 1$ ) and 109 MPa (corresponding to  $S'_H/S'_h = 5.5$ ), measuring for each simulation the predicted breakout width. The obtained results are plotted in Figure 15, where a comparison with the  $S'_H$  trend, obtained via eq. 20, is shown.

732 Also in this case the numerical and analytical predictions are essentially co-

incident up to an anisotropy equal to 4 and to a width  $\alpha_b \approx 90^\circ$ , being the maximum relative error lower than 3.5%.

#### 735 5 Conclusion

Determination of in situ stress state is a preliminary activity necessary for any 736 application in the field of civil and reservoir engineering, as well as for geolog-737 ical and geophysical applications. Among the different techniques proposed in 738 the literature to estimate in situ stress state in rock masses, borehole meth-739 ods are certainly the most diffused. For these methods to be reliable, a sound 740 geomechnical model is needed, in order to address all the relevant characteris-741 tics of rock mechanical response that influence the behaviour of the material 742 at the borehole scale. Unfortunately, refined models always requires a signifi-743 cant number of parameters, which can hardly be known without a dedicated, 744 time consuming and expensive laboratory activity. In order to overcome such 745 limitations, this paper presented an analytical procedure to estimate in situ 746 stress state trying to combine a rigorous approach to the applicability of the 747



**Fig. 15** Cajon Pass; evaluation of  $S'_H$  through the Mohr-Coulomb failure criterion imposition in  $\theta = \theta_b$  and results of simulations with brittle damage model.

procedure in engineering practice. In particular, the procedure is intented to 748 be applied following some clear steps, each one requiring some input parame-749 ters and proving some bounds to the maximum horizontal stress, i.e. the most 750 difficult stress component to determine. Step 1 stems from the application of 751 the well-known Anderson faulting theory together with the Mohr-Coulomb 752 failure criterion to provide some initial bounds to the stress state, exploing in-753 formation known at the reservoir scale, as already proposed in the literature. 754 A refinement on in situ stress bounds is provided by Step 2, that just relies 755 on visual information on failures at the borehole scale. In Authors' knowledge, 756 this approach has never been proposed in the literature, and provides a sig-757 nificant reduction in stress bounds without the need of knowing rock failure 758 parameters. Further refinement is provided by Step 3, which combine the in-759 formation of the possible presence of failures at the borehole scale with the 760 information on the failure criterion of the rock. Finally, if also breakout failure 761 amplitude is available, a unique value of the maximum horizontal stress can 762 be estimated via Step 4. Remarkably, just three parameters to describe rock 763 strength have been introduced: the friction angle, the uniaxial strength and 764 the tensile resistance. As a further advantage of the procedure, no program-765 ming or use of dedicated software is need: once the input data are known, just 766 explicit algebric equations are proposed. 767

The procedure has been then validated by means of both numerical anal-768 yses and some field data coming from the literature. Numerical analyses have 769 been performed to check if the simplifications introduced in Step 4, involv-770 ing both the mechanical behaviour of the rock and the geometry of the failed 771 borehole, are relevant. To this aim, numerical Finite Element analyses at the 772 borehole scale have been performed, assuming a brittle damage behaviour of 773 the rock. The constitutive model adopted in the simulations is able to well 774 reproduce the behavior of different rocks under different stress levels, and 775 in particular the expected post-peak brittle response. The model, based on 776

micro-mechanical considerations and on strong thermodynamical bases, pro-

vides predictions that can be considered consistent with softening/hardening

elasto-plasticity, yet in a framework more consistent with the failure processes

<sup>780</sup> in rocks. The outcomes of the numerical simulations have been compared with

<sup>781</sup> the Equations proposed in Step 4 in terms of borehole breakout dependence

<sup>782</sup> on stress anisotropy: the agreement between the two approaches is very good,

 $_{783}$  at least for breakount amplitude lower than 90°, confirming that the assump-

<sup>784</sup> tion on which Step 4 relies are acceptable for the problem at hand. Finally,

reasonable agreement has been obtained also between the predictions of the

<sup>786</sup> procedure with some data already present in the literature, where in situ stress

restimate was performed by means of the combination of different techniques.

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