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Transient inverse analyses of overcoring data for improved stress estimation

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ABSTRACT: Overcoring is a common technique for measuring stresses in mining projects. Knowledge of the in-situ stress state is essential to ensure the stability of underground infrastructures as well as to assess the induced microseismic risk associated with deep mining operations. There are different types of overcoring probes. Some are bonded in the pilot hole with an epoxy resin and allow for 3D stress measurement (e.g. CSIRO-HI), and others are based solely on a mechanical coupling of the probe, but are limited to biaxial stress measurement (e.g. USBM). The need to glue the probe to obtain a 3D measurement limits the applicability of this technique to short boreholes because it is technically difficult to glue probes in deep boreholes. In any case, traditionally the data analysis is done only based on the final deformation obtained after overcoring. In this paper we propose to use the transient deformation response during overcoring to: (1) allow to evaluate the 3D stress field from a single biaxial overcoring measurement, and (2) add a quality control component by reproducing the entire overcoring response. The general principle of our approach is to simulate the transient response of overcoring by numerical elastic simulation. The principle of superposition is used to derive the responses for any set of parameters from a limited number of basic models and thus allows to limit the total number of model runs. Such approach allows for a systematic inversion procedure to be applied for determining the optimal parameter sets that best capture the transient response of the overcoring. This allows the estimation of a 3D stress tensor from biaxial measurements. It also allows to have a quality control on the measurements evaluating the quality of the fit between the model and the data. In this paper, we evaluate the robustness of the proposed approach by performing a systematic sensitivity analysis on the stress estimation from the inversion of transient overcoring data. We demonstrate the advantages of the approach but also its limitations. The preliminary results obtained in this study suggest that the transient overcoring response contains sufficient information for constraining efficiently the 3D stress tensor. The inversion must be performed using multiple starting point, and the mode of the obtained calibrated parameters is in close adequacy with expected values, while some outliers can be present in the calibrated set. Further work is required for confirming these encouraging results by testing of broader range of stress configurations and applying the method to actual field measurements.

1 INTRODUCTION

Stress characterization is essential for any deep engineering project. Whether it is for the dimensionning of excavations in a mining or nuclear waste storage context or whether it is in the context of understanding the mechanisms of fault activation and reservoir development in injection projects (e.g. deep geothermal energy), stresses play an controlling role. If over the years many measurement techniques have been developed (Ljunggren et al., 2003; Zang and Stephansson, 2010), it is still difficult to fully characterize all components of the stress tensor and their variability in the rock mass. Indeed, there is no standard measurement technique that can robustly derive all the components of the tensor and even less to obtain a sufficient sampling to characterize the variability of stresses.

The technique concerned by this paper, overcoring (Leeman, 1964), does not escape these limitations. There are various overcoring probes (e.g. USBM, CSIRO-HI, Borre, ANZI,...). Some allow the estimation of all components of the stress tensor but require to be glued in the borehole before overcoring. Gluing and curing overcoring probes have been shown to be often problematic (Lahaie et al., 2010). Others are purely mechanical (no need for gluing and curing time), but are limited to radial deformations and do not allow a priory according to standard analysis methods to obtain all the components of the stresses. All these overcoring methods share a common limitation: they are measurements taken on a borehole scale involving only small volumes of rock of centimetric dimensions.

One approach to overcome this limitation would be to acquire many measurements along profiles in order to assess the variability of stresses at different scales, and then use appropriate statistical approaches to average the resulting tensors and thus upscale the measurements (Hudson and Cooling, 1988; Gao and Harrison, 2018). Overcoring methods that require gluing and thus take a considerable amount of time (typically several hours of curing before allowing overcoring) are clearly not suitable for acquiring much data along profiles. Only purely mechanical probes that would allow efficient sequencing of measurements would allow profiles to be derived. But as mentioned above, standard methods of data analysis of mechanical probes (radial deformation measurement only) do not offer the possibility to characterize the complete stress tensor.

This limitation is due to the fact that with standard analysis methods, only the final deformations are considered. On the other hand, modern measurement equipment allows the acquisition of deformation data in a continuous way during overcoring and thus opens the door to new methods of data analysis. This is what we propose in this paper, i.e. the analysis of transient deformation data during overcoring to derive the complete stress tensor based on radial measurements only. This approach is first evaluated theoretically, especially its sensitivity in different stress regimes and geometric relationship between the borehole orientation and the principal directions of the stress tensor. From this sensitivity analysis, a stress inversion method considering the deformation transient is proposed.

2 METHODOLOGY

2.1. USBM overcoring geometry and characteristics

We apply our approach to the specific case of overcoring with a USBM deformation gauge (ASTM, 2016), but a similar approach could be applied to other borehole deformation gauges. The USBM probe is designed for measuring the diameter changes over three directions 60° apart in a 38 mm pilot hole. The pilot hole is typically 60 cm long and the probe measurement plan is positioned at the middle of the interval. The pilot hole is drilled concentrically at the end of a accesss hole which is 101 mm in diameter for our case study. The 60 cm test section is then overcored and produces a 86 mm diameter overcore in our case study (see Fig. 1).

For this paper, we define a borehole referential with x and y in the plane perpendicular to the pilot hole and z axial to the borehole.

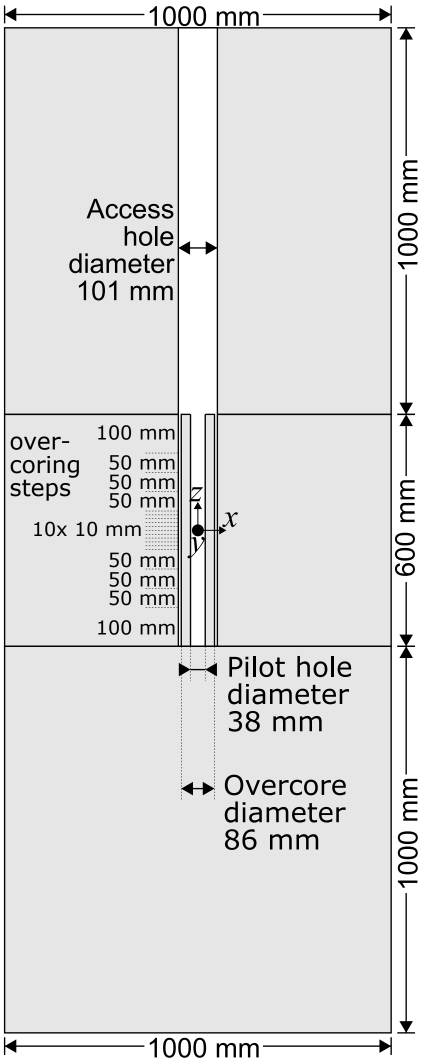

Fig. 1: Section view of the model geometry.

2.2. Standard estimation of stress from USBM data

USBM data consist of the diametrical changes of the pilot hole is three directions 60°apart, U_1, U_2 and U_3. These data are used for estimating the principal stresses magnitude and orientation in the plane perpendicular to the pilot hole (plane x–y). We will call these principal stresses in the plane x–y, σ_1^{xy}, σ_2^{xy} and θ_{xy}, the maximum and minimum princpal stress in the plan x–y and the angle between σ_1^{xy} and the x-axis, respectively. These stress parameters are typically analyzed using only the final deformation and the following equations (ASTM, 2016):

$$\sigma_1^{xy} = \frac{E}{6d}\Bigg\{(U_1+U_2+U_3)+\dots \\ \frac{1}{\sqrt{2}}\left[(U_1-U_2)^2+(U_2-U_3)^2+(U_3-U_1)^2\right]^{1/2}\Bigg\} \quad (1)$$

$$\sigma_2^{xy} = \frac{E}{6d}\Big\{(U_1+U_2+U_3) - \dots$$

$$\frac{1}{\sqrt{2}}\left[(U_1-U_2)^2+(U_2-U_3)^2+(U_3-U_1)^2\right]^{1/2}\Big\} \quad (2)$$

$$\theta_{xy} = \frac{1}{2}\arctan\frac{\sqrt{3}(U_2-U_3)}{2U_1-U_2-U_3} \quad (3)$$

This approaches is an approximation because it considers the solution for an infinite hole in and infinite media, while the overcoring length is actually of finite size (60 cm).

2.3. *Forward simulation of overcoring data*

In order to not limit our analyse to the final deformation data only, but to capture the complete transient response during overcoring, we simulated the overcoring process using the RS3 3D finite element simulator from rocscience (www.rocscience.com/software/rs3). We built the geometry of Fig. 1 and mesh it using 10-noded tetrahedral elements. We used a graded mesh size, with fine elements in the borehole and overcoring volume and coarser elements towards model boundaries. This resulted in a model with 1,140,999 nodes, 825,816 elements and 3,406,527 degrees of freedom. A view of the model mesh is shown in Fig. 2. We staged the model so that to capture the advance of the overcoring transient response using overcoring steps as indicated in Fig. 1 and Fig. 2b. In our specific case, we used 18 stages to represent the continuous overcoring process, with coarse stages (10 cm and 5 cm advances) at the beginning and end of the overcoring process and fine stages (1 cm advances) when advancing over the middle section of the overcore, where diametrical changes are measured.

In order to be able to reproduce any stress state from a limited number of model runs, we used the superposition principle. For this, we run only 6 models to estimate the response for a unit stress components and add the results of the models. We also consider the effect of Young's moduli and performed the superposition using the following formula:

$$\mathbf{U}_{tot} = \frac{E_o}{E}\sum_{i=1}^{6}\mathbf{U}_i\sigma_i \quad (4)$$

where $\mathbf{U}$ is the displacement field where the indices $n = 1$ to 6 refers to the six unit response model, σ is the corresponding target stress components and $\frac{E_o}{E}$ is the ratio between the Young modulus used in the unit response models and the target Young's modulus.

2.4. *Inverse problem and objective function*

In order to compare two models or a model with some observation, we define the following objective function:

$$O = \sum_{n=1}^{s}(\mathbf{U}_o - \mathbf{U}_m)^2 \quad (5)$$

The observed ($\mathbf{U}_o$) and modeled ($\mathbf{U}_m$) deformation field are compared for all ($n = 1$ to s) overcoring steps (in our specific case, we used up to s=18 overcoring steps).

The inverse problem consist in minimizing the objective function O. Various standard approaches exist to incrementally find the minimum of the objective function by successive model calls. Here we use the Nelder-Mead simplex method implemented in the `fminsearch` Matlab™ built-in function.

3 RESULTS

3.1. *Forward modeling of overcoring*

In order to illustrate the typical output from our forward model, we consider the base case with parameters listed in Table 1. We simulated this specific case and extract the pilot hole diameter changes during overcoring in three directions 60°apart to mimic the expected response from a USBM gauge measurement. In our specific case, we set the direction for the U_1 diameter change 20°off the x-direction (see Fig. 3).

The transient pilot hole diameter changes for the three diameters (U_1, U_2 and U_3) is shown in Fig. 3. The obtained response is typical of a overcoring test response. When the final deformation of this simulation are used in Eqs (1) and (2), the obtained principal stress magnitudes in the plane

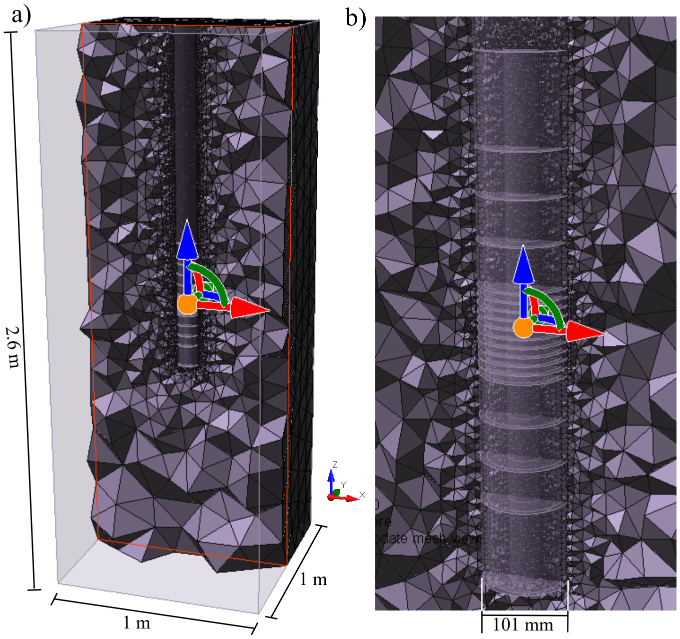

Fig. 2: View of the meshed model. a) section through the mesh. The grading of the mesh with a fine mesh in the borehole vicinity, coarsening toward model boundaries is well visible. b) Close-up view on the overcoring section of the model. The 38 mm pilot hole can be seen in transparency and well as the overcoring stages.

Table 1: Properties of the base case model.

σ_{xx}	15	MPa
σ_{yy}	10	MPa
σ_{zz}	12	MPa
σ_{xy}	0	MPa
σ_{xz}	0	MPa
σ_{yz}	0	MPa
E	20	GPa
ν	0.25	

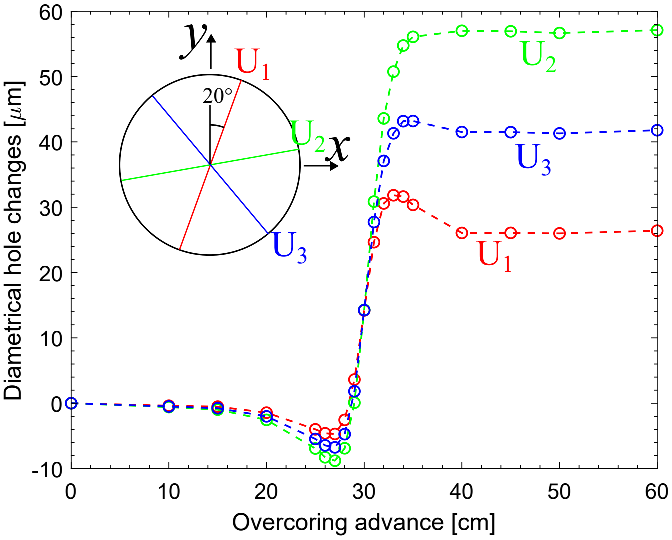

Fig. 3: Simulated USBM signal for the stress and elastic conditions of Table 1.

x–y are σ_1^{xy}= 13.3 MPa and σ_2^{xy}= 8.7 MPa. This is about 15% less than the input values (Table 1). The orientation of the principal stress direction are accurately reproduced. The discrepancy in the magnitude can be explained by the fact that the assumption behind Eqs (1) and (2) is a infinite length pilot hole, while the modeled geometry is the actual typical overcoring geometry with a 60 cm long overcore. Another explanation could be some effect of the boundary conditions on our overcoring model (fix boundary conditions). This will be further investigated in future analyses.

3.2. *Sensitivity of the transient overcoring response to off plane stress components*

In order to investigate the sensitivity of the overcoring response to different stress tensor, we generated a set of stress tensors sharing the same stress components in the $x - y$ plane (σ_{xx}=15 MPa, σ_{yy}=10 MPa and σ_{xy}=0 MPa, see Table 1) but a variety of principal stress directions. The maximum stress direction (σ_1) of these stress tensors are displayed in the stereographic projection of Fig. 4. We do not cover the entire range of principal stress directions because this would require extreme stress values for some components. We bounded σ_{zz} in the range 0.5 to 90 MPa and σ_{xz} and σ_{yz} in the range -50 to 50 MPa.

For each of these stress tensor, we computed the overcoring transient response using Eq. (4). We then compared these responses with the base case model (see Table 1) by computing the objective function (Eq. 5) for each cases. In order to focus on the most discriminant section of the overcoring, we computed the objective function only for the 1 cm fine overcoring stages (steps 5 to 15). The σ_1 direction in Fig. 4 are colored with the logarithmic value of the Objective function. We used the logarithm for facilitating visualization, because the obtained objective function value spans multiple order of magnitude. The value are generally small because we computed these objective values from the diametrical changes in meter while the observed diametrical changes are actually in the range a few tens of μm.

In order to further illustrate the process, we show in Fig. 4b the full transient overcoring response for two examples (Example 1 and Example 2 in Fig. 4a) together with the base case transient overcoring response. We see the close similarity of the Example 1 with the base case as these two examples share very similar stress tensor and results in a low value of the objective function. Example 2 however present the case of a stress tensor that differ significantly from the base case : here the maximum principal stress σ_1 is sub-vertical while it is sub-horizontal for the base case. In this case it can be readily seen that the overcoring transient response differs visibility from the base case and this corresponding to a relatively high value of the objective function.

3.3. *Inverse modeling of an overcoring response*

In order to test the robustness of the inverse problem, i.e. does the transient overcoring response contains sufficient information to determine the complete stress tensor, and not solely the stress component in the $x - y$ plane, we setup a test inverse analyses. In this case, we use the forward model of our base case (see Table 1 and Fig. 3) as our observations ($\mathbf{U}_o$ in Eq. 5). We then performed 40 calibration on the entire stress tensor (all 6 components, σ_{xx}, σ_{yy}, σ_{zz}, σ_{xy}, σ_{xz}, σ_{yz}), starting from randomly drawn value and adjusting the stress components in order to minimize the objective function of Eq. 5. The starting points for the normal components (σ_{xx}, σ_{yy}, σ_{zz}) were taken in the interval [0.5 90] MPa. The starting point for the shear components (σ_{xy}, σ_{xz}, σ_{yz}) were taken in the [-50 50] MPa interval.

The calibrated stress component values for the 40 calibrated values are shown in Fig. 5. The direction of the maximum principal stress σ_1 for each calibrated model is shown in the stereographic projection of Fig. 5. Over

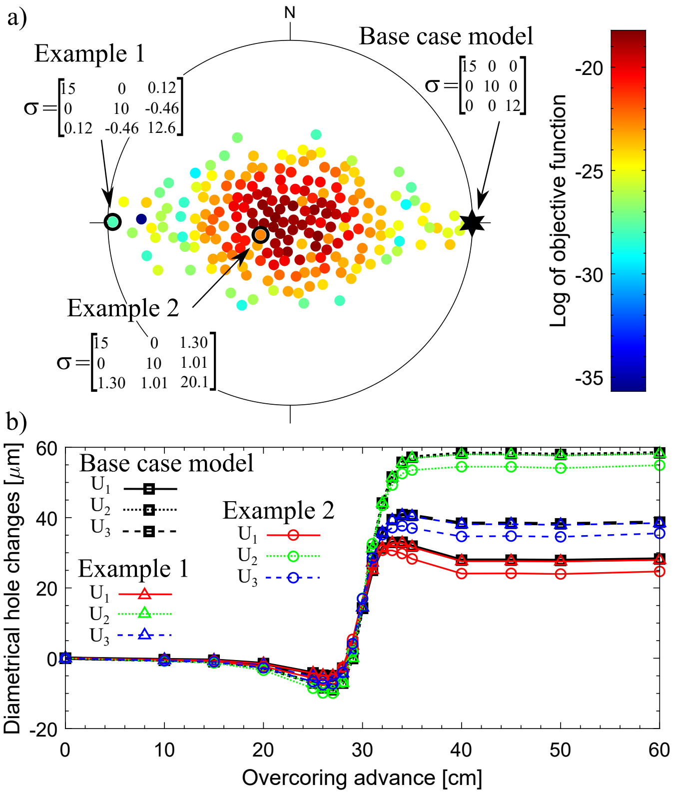

Fig. 4: Sensitivity analyses of the overcoring transient response to the stress tensor. A set of stress tensor sharing the same stress components in the $x-y$ plane (σ_{xx}=15 MPa, σ_{yy}=10 MPa and σ_{xy}=0 MPa, see Table 1) are generated. Other component varies and thus the principal stress direction for each tensor varies. a) orientation of σ_1 for each generated stress tensor in a lower hemisphere, equal area stereographic projection. The maximum principal stress (σ_1) direction of the generated stress tensors are not covering the the entire stereonet because this would require in some cases extreme stress components. Limits have been imposed on each stress components (see main text for detail). The σ_1 direction are colored by the value of the objective function computed from the comparison of the transient overcoring response of each stress tensor with the Base case scenario (see Table 1). b) two examples of transient overcoring response computed and compared with the transient overcoring response of the base case. The two examples are chosen for being similar (Example 1) and dissimilar (Example 2) to the base case. Both examples are labeled on the stereographic projection in the upper part of the Figure.

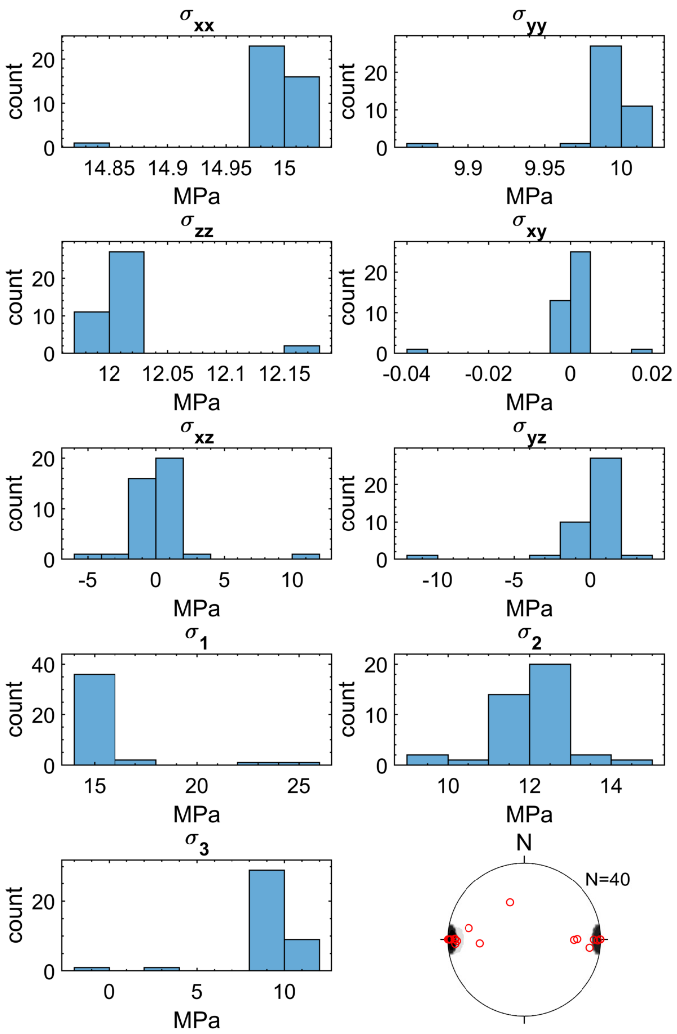

Fig. 5: Results of the calibration of the inverse models. 40 calibrations are performed with random starting point for the optimization method. The stereographic projection shows σ_1 orientation in lower hemisphere, equal area projection.

the 40 models, about 90% of the model converged to a solution very close to the expected values from the base case (see Table 1). Five models show maximum principal stress direction differing from the expected horizontal E-W (x-axis) direction. In terms of magnitudes, The $x-y$ plane components all converge very closely to the expected value. This is not surprising, because it is known that the problem is well constrained in the plane. The axial stress component σ_{zz} is also nicely converging to the expected value of 12 MPa for most models. The out of plane shear stress components (σ_{xz} and σ_{yz}) display more variability, although the mode of the histograms are corresponding with the expected values (= 0 MPa). The principal stress magnitude are generally in adequacy with the expected values, although some dispersion is observed.

4 DISCUSSIONS AND PERSPECTIVES

The forward overcoring model based on finite element developed here seems to be efficient and accurate in reproducing the general transient displacement response expected during overcoring with a USBM probe. The principle of superposition allows for computing the response for many possible stress states by superposing the solutions of 6 unit-stress finite element models that are run initially and thus provide a computationally effective way of producing results. The approached proposed allow for the consideration of variable Young's modulus. The Poisson's ratio as not been yet considered and the sensitivity of the problem to this parameter should be further investigated. The discrepancy between our model and the analytical solution derived from an infinite hole hypothesis must also be further investigated in order to insure that this is not related to model boundary effects. Another aspect that would be useful to consider in the future are models with transverse isotropy. A superposition approach for such a case would be needed for performing sufficiently efficient analyses for applying inverse problems sovling and parameter estimation.

A sensitivity analyses has been performed by focusing on identifying the difference in the transient overcoring response for a set of stress tensor sharing the same components in the plane perpendicular to the borehole ($x - y$ plane). According to standard overcoring data analyses approach (Eqs 1 and 2), these case should be indistinct based on final deformation only. We compare the transient response using an objective function based on a least square approach. We show that the transient overcoring responses are sufficiently distinct to produce large differences in the objective function value. This is a favorable condition to set an inverse procedure for determining the full stress tensor.

We setup and tested such inverse procedure for calibrating the full stress tensor (not just the off x–y plane stress components). We used random seed for the starting value in the optimizations procedure. Most of the starting points (about 90%) lead to calibrated parameter in excellent agreement with the expected values. This exercise validate theoretically the inversion approach and demonstrate that enough information is contained in the transient overcoring data for fully constraining the full stress tensor.

Further work are required to apply the approach on actual overcoring data set and assess the suitability of the approach in real situation. In such situation, it is expected that measurement noise induced for example by drilling fluid pressure variation and additional transient effect as for example induced by thermo-elastic processes, may affect the possibility to use the transient overcoring data for full tensor stress inversion. This will be assessed and tested in the future.

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