Detailed Response Referee 2

Thank you to the authors for their interesting study. However, I have some concerns regarding the assumptions and methodology. Without clarification, it is difficult for me to discuss the results. I have outlined my concerns as follows:

1- Please clearly state the application of the current study. How does it help to characterize the specific site?

5- What is the initial state of stress in the system? When there is a fault and wedge-shaped structures, the system has already experienced stress changes. See the following paper: "The evolution of pore pressure, stress, and physical properties during sediment accretion at subduction zones".

6- Line 72: How does "Optum CE" work? Which equations are considered? How does it discretize the equations? Is there any mesh refinement scheme used? Please provide a summarized explanation.

7- Line 75: I noticed that the applied load is unknown, so I assume that a fixed displacement rate was implemented. Please mention this. Also, how did you verify the stability and mesh independence of the results? I noticed that a similar mesh was used for all cases.

8- For 2D, 10,000 elements were used, while for 3D, 40,000 elements were considered. Are the element sizes the same in both cases? If not, on what basis are the results compared? Furthermore, the mesh dependency analysis for the 3D cases is unclear, and the stability analysis is not included. Without this information, the accuracy of the results and the impact of boundary conditions are questionable (at least for me).

In order to answer the above questions, we give a more detailed explanation of the method used in this paper. The referee is referred to section 2: "Models setup and Limit Analysis implementation" (lines 60-134).

The section was completely reviewed and details were implemented.

Briefly:

In this paper we adopt the geotechnical software Optum G2/G3. We apply limit analysis and we perform calculations on the onset of rupture. The fact that we are at the onset of rupture means that we do not need to perform a full elastoplastic analysis and thus the initial stress state becomes irrelevant in this type of calculations.

LA is a double bounded approach. The stress field obtained from LA lower bound is not only robust (Souloumiac et al., 2010) by the fact that the calculated stress state is always on the safe side of failure but it is also mathematically compliant with the fundamental principles of equilibrium and yield conditions.

The results of the Optum CE software have been tested for both 2D and 3D models in the preliminary testing phases and the values were in accordance with the analytic results (Adwan 2023) Nonetheless, the robustness of this software has been verified throughout the years with many articles using the finite element limit analysis (FELA) method incorporated. For example, Oberhollenzer et al., 2018 explained the advantage of such a method though a comparison between Optum G2, Plaxis 2D where they studied the performances of strength reduction finite element analysis (SRFEA) with finite element limit analysis (FELA), focusing on non-associated plasticity.

Adwan et al., 2024 recently introduced an automated fault detection method mainly using FELA, and showed its applicability to usual elastoplastic analysis.

As for the meshing and the type of elements used, we conducted a thorough convergence test for all kind of possible configurations going from 5000 elements and up to 100,000 elements in a 3D model that was slightly more complex than the one considered in this paper. The parameters used assure a solid convergence and high accuracy. In Figure 1 below, we present an example of convergence tests performed throughout the preliminary testing phase:

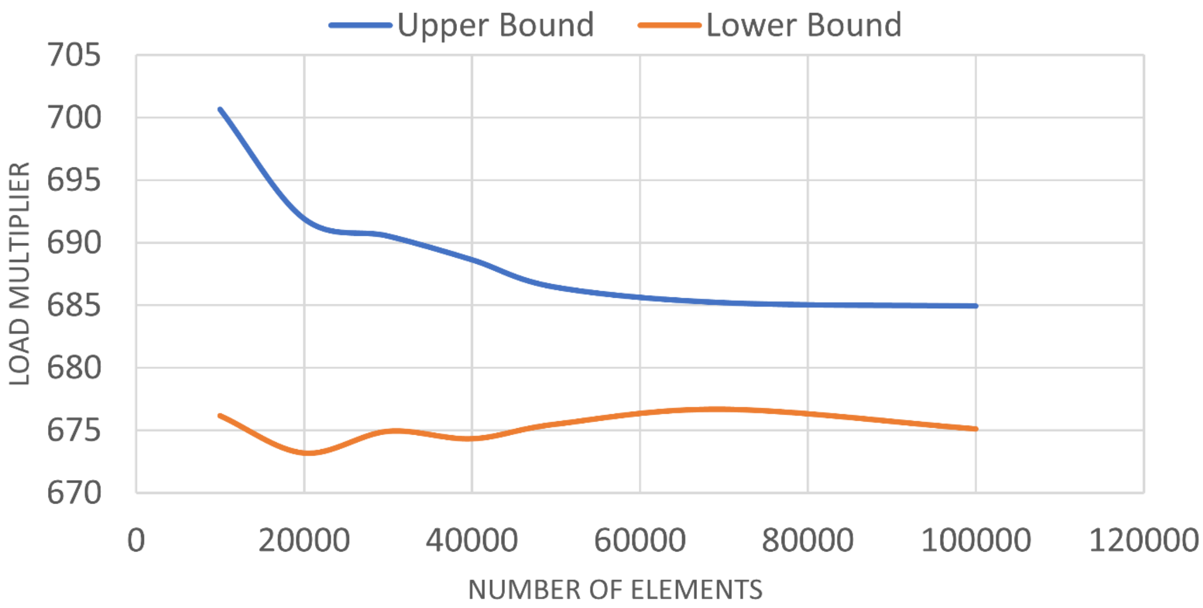

Figure 1: The variation of the obtained load multiplier in function of the number of elements for both lower and upper bound analyses is shown. This load multiplier is one of the criteria used in the preliminary testing phase to determine the number of meshing elements needed to obtain acceptable results between lower and upper bound analysis. It shows that the 40000 elements adopted yield an error lower that 2.5% (Adwan 2023).

Based on our convergence tests, we were able to identify two main weak points in the direct application of LA using Optum:

- The lower bound analysis shows some instability for certain high complex cases.
- The need to run the analysis twice, for lower and upper bound results, is time consuming.

These issues are common in numerical applications of Limit Analysis (LA), which is why there was a need for a mixed bound theory (Casciaro and Cascini 1982, Zouain et al., 1993, Borges et al., 1996, Krabbenhoft et al., 2007). This approach is a compromise based on both an acceptable velocity field and a stable stress field. In the present paper we adopted that approach for 3D simulations, but we kept the lower bound approach for 2D cases.

In addition, adequate comparison with higher order elements was also performed in previous studies and thus is available in this example of referenced articles: Lyamin and Sloan a-b, 2002; Krabbenhoft et al., 2005; Krabbenhoft et al., 2007. These references explain why accurate solutions can be obtained with a moderate computational effort using low-order elements, under given conditions (for example, for the upper bound analysis, kinematically admissible discontinuities must be included between adjacent elements).

Finally, as for the question about the applicability of this method and how it helps characterize a specific site, its advantage lies in its ability to detect rupture without the need for elastic parameters. With fewer parameters and efficient optimization procedures, we can consider uncertainties in the mechanical and geometric parameters by performing sufficiently numerous simulations to define categories describing the different rupture patterns. These categories can be used as reference in order to compare existing data and validate a given assumption (for example, the results will be close to a given obtained category, with a defined range of parameter values).

PS: Since in this study the geometry was not varied from a simulation to another, the uniform meshing was adopted and is valid for all the 2D cases and 3D cases.

2- In all cases, the dip angles are constant. What would happen if these parameters were to change?

In the preliminary testing stages of this study, we compared different inherited fault dip angles and varying fault parameters (friction angles and cohesion). The changes in the stress fields were generally very sparse, the sole difference was in the direction of the principal stresses surrounding the fault.

Yes, the change in the principal directions is important and we acknowledge that in this paper we decided to limit geometric changes and thus adopted fixed dip angles.

3- Line 48: What do you mean by "homogeneous categories"? What is homogeneous within these categories?

In this study, we adopted LA method (refer to answer 1), allowing us to study the onset of rupture ("Our objective is to evaluate how changes associated with the two varying parameters impact the stress field at the onset of rupture"). Since we are performing a huge number of simulations, we decided to group them based on the rupture pattern obtained. This is why we use image processing and data analysis in order to detect the failure location, including fault propagation, to group the simulations in clusters defined by these two criteria. The "homogeneous categories" refer to the obtained clusters with the same rupture pattern (number of obtained faults, their location and extension in 3D).

No corrections were implemented

4- Line 53: How did you define the deviatoric stress?

We follow the definition of deviatoric stress:

$$q = \sqrt{\frac{1}{2}(\sigma_1 - \sigma_3)^2 + \frac{1}{2}(\sigma_1 - \sigma_2)^2 + \frac{1}{2}(\sigma_2 - \sigma_3)^2}$$

Where σ_i are the three principal stresses. This definition was added line 225 of the revised manuscript.

9- Line 64: Did you evaluate the capability of the "uniform bulk Coulomb material" in modeling real cases or sandbox models within the proposed framework of this manuscript? Please include the validation results.

We know that Mohr-Coulomb gives a realistic representation of failure in geomaterials. The referee points to capability of the "uniform bulk Coulomb material" in modeling real cases or sandbox models. All these questions are linked and well known in the structural geology community (as shown by Krantz 1991, Schellart 200, Lohrmann et al. 2013, Maillot 2013, ...). The peak deviatoric stress are treated simply by defining two sets of Coulomb parameters: one at peak, called the peak -- or static -- values, and one achieved after a stable behavior is reached following the peak, called "stable" -- or "dynamic" --.

The difference between these values is often associated to the initial density of the material, but it also dependent on the confining pressure during the test. If the material is not very compacted and in a low confining pressure, it will not develop much dilatancy, and the peak and stable strengths will be close. Of course, since we do not treat the ensuing deformation (onset of rupture), we do not need a second set of Coulomb values.

About the uniformity... recall that we have distinct basement and fault Coulomb parameters. Only the material is uniform. Of course, a layered material could have been considered, at the cost of a more complex analysis. We think this can be postponed for a case study.

10- Line 148: In all cases, back-thrust is observed. However, in the literature, there are instances where back-thrusting does not occur. If the entire range of parameters is explored, some cases would likely show no back-thrust. Clarification is needed here. See the following paper: "Control of décollement strength and dip on fault vergence in fold-thrust belts and accretionary prisms."

This study focuses on the onset of rupture. Material in the hanging wall slides over the existing or created ramp/fault marking a discontinuity in the velocity field which is represented by the back thrust. As stated by Cubas et al., 2008 this back-thrust should be seen as a migrating hinge since materials from the back stop are crossing it to reach the hanging wall. This analysis follows the assumption that every material block undergoes rigid body motion. Thus, a material points from the back-stop region would be translated toward the back thrust, be sheared when crossing it, and then be translated again parallel to the ramp. Therefore, what we call back-thrust in this paper are really merely the hinges of the imposed ramp which is really a fore-thrust. So, we do agree with that remark: we clarified our definition of back-thrusts as being only the conjugate fault of a fore-thrust, at the onset. We also added that we do not explore here the general question of back-thrusting which has been investigated earlier with the LA method (Cubas et al., 2016), and with more classical numerical method (vonHagke et al., 2024).

11- Pore pressure and overpressure development are not considered. What would happen if these parameters were included? What is the sensitivity of the conclusions to this parameter?

It is true that the pore pressure and the overpressure developments are important aspects when studying such geo-mechanical models. Pore pressure is known for reducing effective stresses which can weaken the rock and make it more prone to failure or even reducing shear strength, making it easier for ruptures to initiate along pre-existing weaknesses or faults. As for the overpressure (higher pressure than the hydrostatic pressure at a given depth), it can have a role in reactivating existing faults by reducing the normal stress on the fault plane, thereby lowering the frictional resistance and potentially triggering slip or rupture along the fault.

We acknowledge these limitations, but in this study, we wanted to show the tendency of rupture in the context of a fault termination. The lateral propagation of the existing fault will not change. Yes, with the consideration of these parameters some cases might shift from a cluster to another since the existing fault might be activated more easily but the overall conclusion on the frontal, back or even extending propagation of the inherited fault stands.

As for the stress fields, we don't believe that the pore pressure will have a huge influence on the stress direction, yet it will alter the stress magnitudes. Nonetheless, each failure pattern will conserve the same stress distribution and orientation.

Finally, the comparison between 2D and 3D cases remains valid, despite such simplifications.

We thank the referee for these questions and we hope that our answers offered the needed information for the referee to discuss the results of this study.

PS: Following Both referees comments and questions, adjustments have been made to the manuscript in order to better explain the methodology and present LA in a more detailed way. We provide a manuscript with marked changes.

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