Reply to interactive comment on "Distinct Element geomechanical modelling of the formation of sinkhole cluster within large-scale karstic depressions" by Djamil Al-Halbouni et al.

Nestor Cardozo (Referee)

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Dear Nestor Cardozo, I would like to thank you very much on behalf of all co-authors for doing the review of the manuscript. We would like to address the comments and suggestions by this answer. Some parts/figures of the manuscript were rewritten/edited to improve the readability without changing the scientific content, these are highlighted in the re-submitted version. Please note that additional supplementary material (videos of multiple sinkhole collapse simulations) have been uploaded to the supplement.

With best regards on behalf of all co-authors,

Djamil Al-Halbouni

Answers to comments of reviewer no. 2

1) Assembly calibration: The tests were indeed run on subsamples of the assembly for each material. We added the requested information about sample size in the revised sec. 2.3. As noted on Line 26-27 of the revised manuscript, the calibration and benchmarking of the sinkhole modelling approach has been primarily part of the partner manuscript published in SE (Al-Halbouni et al. 2018). To avoid repetition, we just present a synthesis of that calibration work here.

2) Material behaviour: This is a correct observation to be considered. Salt can behave viscously even at low confining pressures (close to the surface) and perform creep at low deformation rates. However, several factors led us to restrain from going further into details on complex salt rock behaviour in this publication. The material at the Dead Sea consists of several evaporite deposits, e.g. aragonite, halite, gypsum and calcite. Including this would need a specific study on different evaporite rocks at varying differential stresses. In our case, we opted for halite as a representative, and at low temperatures and confining pressures with large deformation, cataclastic material behaviour with microcracking dominates (see e.g. Jackson & Hudec, 2017, Salt tectonics), which is well represented in the rock mechanical tests performed on the subsamples (see partner paper Al-Halbouni et al. 2018, figure 6). In our models we could capture the elasto-plastic behaviour of salt, and also the brittle-ductile transition. However, we do not consider time dependent (creep) behaviour in our quasi-static approach. This is a limitation of the DEM models with the chosen bond scheme, but, it is also clearly beyond the scope of this work and goes along with a more thorough investigation of several types of evaporite rocks with more complex material behaviour.

3) Particle size (and model size, i.e. resolution) indeed affects the estimation of rock mechanical parameters. Several authors have studied this for the parallel bond contact

scheme, e.g. Potyondy and Cundall 2004 and Martin Schöpfer (e.g. 2007,2009,2017). For the sinkhole models, we did not want to add upon these studies; instead we did an intensive study on particle and model size effects on the vertical surface displacement above a circular cavity, in comparison with analytical solutions. We came up with a trade-off solution between sufficient resolution & sufficient accuracy vs. computation time. We then used this "optimal" particle size distribution to determine rock mechanical parameters on subsamples with the same particle radii. This can be found in the partner paper published in SE in 2018, Appendix B. However, to answer the second part of the question, for the above reasons, we didn't take a survey on how the rock parameters change when, e.g. taking half the particle size, for this study. However, Holohan et al 2011 did test for mechanical effect of reducing the particle sizes by half and found little difference in the elastic parameters. This is in line with earlier result of Potyondy and Cundall (2004).

4) Strain evolution: Indeed the maximum shear strain and incremental shear strain as well as the maximum shear stress nicely complement the interpretation of the mechanical process leading to sinkhole/large depression formation. We included three new figures and texts after this suggestion. Now Fig. 8 shows the maximum strain for the same situations like Fig. 7 (Sec. 3.2.). The incremental strain evolution & maximum shear stress have been added to the appendix A4 and A5 to not overload the first part with figures. Nevertheless, they nicely show the different strain/stress distribution for several material combinations for the final models, and e.g. also nicely reveals crack/fracture patterns and remnant stable parts. We would like to thank you for this very useful suggestion.

5) Seismic: We restrained from adding another figure of forward calculation seismic model. We consider it somehow as repetitive, as we use seismic to derive model parameters (shear modulus, density), apply our material removal approach, and derive shear-wave velocity distribution. If we would then include a new forward model from the shear-wave velocity distribution it would form somehow a loop, which we did not find very appealing to the reader. Also, correctly, it would be better part of a manuscript specifically dealing with seismic in the field area, which is under preparation.

Erroneous points in the manuscript: Thanks to the reviewing effort, the typos, references, unclear formulations and mistakes have been corrected.

Additional changes:

Supplementary material of collapse videos of multiple sinkholes for different material assemblies has been uploaded.