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.

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Received and published: 5 March 2019

Dear René Tussaint, I would like to thank you very much on behalf of all co-authors for 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. 1

1) Dynamics of the particles: The DEM code uses an explicit time-stepping algorithm to calculate forces and translation/rotation of the non-deformable, interacting particles solving the respective Newton-Euler-Equations. The inertia is calculated via the mass (volume & density) and velocity, and an incremental force law has been used. Indeed, the code is slightly overdamped, using the standard value of 0.7 for damping. The purpose of the high damping is to ensure a quasi-static model behaviour. Viscous dissipation was not used (though this is possible within the PFC contact laws). Particle size affects the absolute values of the material strength and the variability of elastic parameters derived from simulated rock mechanics tests (cf. Potyondy and Cundall 2004), and it can have some influence on the macroscopic model behaviour. Relative to the scale of the system modelled, the values of particle radii chosen here minimise such discrepancies (cf. Appendix to Holohan et al., 2015). Further details of the dynamics can be found in an extensive study on benchmarking, particle and model size influence, and parameter calibration of this code, published in 2018 in the same journal by the same authors (and referred to in the main text of the present manuscript).

2) The precision of subrosion procedure: Indeed, the description in the submitted manuscript has led to the misunderstanding that particles are all removed at once. Rather, they are removed progressively (incremental, refer to p 6 l 10) and the speed of removal ($f=1^i-1.1^i)*A_0$) has been stated in the appendix A1. This speed of removal is sufficiently slow and the increments sufficiently spaced in time that model can re-equilibrate to maintain quasi-static conditions. This part of the text is now updated (p 6), and a more precise formulation has *been used. The same procedure as for individual cavity formation has been used as investigated in the partner manuscript (Al-Halbouni et al. 2018, Solid Earth). Regarding the dissolution kinetics, this is definitely a subject to include and a relation of particle removal speed to concentration etc. is important. However, in our purely mechanical, quasi-static simulations we rely on a simplified, time-independent approximation of the process by progressively but incrementally removing the particles within small domains of the model (the cavity domains). Nevertheless, future simulations should include groundwater flow aspects and ideally dissolution kinetics of rock salt.*

3) Concentration fields: As stated above, the simulations are purely mechanical, just mimicking the hydraulic process with a particle removal scheme. Please refer to page 6. So no concentration can be given as we do not simulate water and the chemistry of water. However, with coupled FEM-DEM modelling this would be an interesting approach for more realistic simulations in future.

4) Velocity in unconsolidated media: Seismic velocities of unconsolidated media are non-zero, that's true. But here we have to define an arbitrary threshold of porosity, above which the area is considered as empty, i.e. no particles or only a few, non-bonded ones at the bottom of a cavity. A shear wave velocity in air is zero, therefore we keep the colorscale in Fig.8. The threshold has been defined by looking at material calibration via uniaxial stress tests, for porosities above 0.5 those tests are not meaningful anymore, the particles totally disconnected and we consider the area as "empty".

Erroneous points in the manuscript: These typos, reference errors and mistakes have been corrected.

Additional changes:

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