

THE USE OF SINKHOLE MODELS IN ADVANCED GEOTECHNICAL ENGINEERING TEACHING

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ABSTRACT: This paper demonstrates an approach to integrate geotechnical research into an advanced geotechnical engineering course. It involves the use of a simple 3D small-scale sinkhole model, a 2D numerical model of an idealized sinkhole, and an advanced 3D numerical model. A three-week teaching activity that integrates this material into the course is developed, ranging from the introductory material through to experiment conduction and reporting. By incorporating some advanced topics such as this into the course, it is expected that the students will have an increased awareness and understanding of natural geotechnical phenomena. It is also hoped that the model will help foster further interest in the geotechnical discipline, for either research or practice.

Keywords: Sinkhole, Physical Model, Stability, Education, Teaching

1. INTRODUCTION

In traditional geotechnical engineering teaching, the basic concepts of geomechanics are normally introduced alongside various standard soil tests such as soil particle size and distribution and void ratio for example. The transition between these basic geomechanics concepts into more advanced applications can be a large learning curve and challenging for students [1].

As discussed in [2], teaching these advanced concepts using physical models offers a more engaging experience for the students, away from the traditional methods of ‘chalk, book, and talk’, which may not be effective for the subject matter. Physical modeling has always been an important part of geotechnical research and engineering [1 and 2] and should be incorporated more into the geotechnical classroom, alongside numerical analysis.

Geotechnical engineering involves the analysis of natural hazards such as earthquakes, landslides, and in particular sinkholes. Sinkholes are a global phenomenon, which can have serious consequences. There are many different causes, but fundamentally, they are caused by changes to soil and rock beneath the ground. There are naturally formed sinkholes where underlying rock is dissolved creating a non-stable cavity. There is also man made cases, which can occur at tunnel, pipeline and mining collapse.

However, they all fail for the same reason; the soil overburden pressure overcomes the withholding pressures. At this breaking point, the overburden falls into the underground cavity, leaving, in many cases, a conical shape and circular ground opening, as shown in Fig. 1. Physical models have been used in sinkhole research to examine a soil sample from a sinkhole stricken area [3], as well as for sinkhole

educational purposes [see 4, 5 and 6].

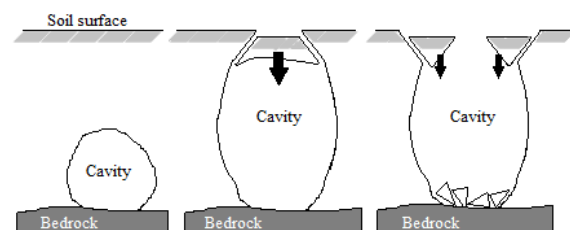


Fig. 1 Sinkhole formation

In this paper, both physical and numerical models are developed for a three-week teaching activity to study sinkhole phenomena. The aim is to demonstrate how a tool such as these models can be integrated into an advanced geotechnical engineering course and enhance student engagement with the subject matter in an effective and satisfying way.

2. THE PHYSICAL MODEL

The development of initial physical model for this study can be found in [7]. Figures 2 & 3 show a front and 3D view of the acrylic box with height gauge markings at 20 mm centers. They were centrally positioned on the front face, as this is where the maximum displacement will occur. The height gauge also aids in the understanding of the collapse as it gives an indication of the current displacement during collapse.

The box is water tight. Water is to be drained into the centre of the front face of the overburden to dissolve the sugar which represents a water soluble rock such as limestone. This solution will then drain

through the holes, representing soil being washed through underground soil cracks.

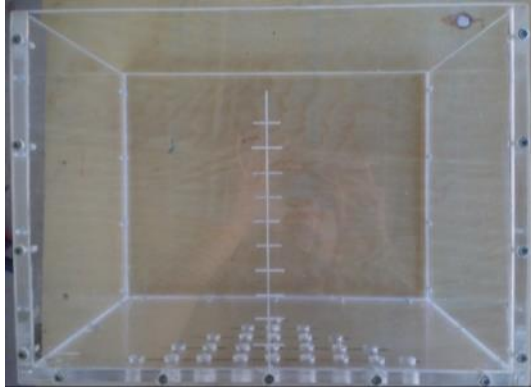


Fig. 2 Physical model tank front view

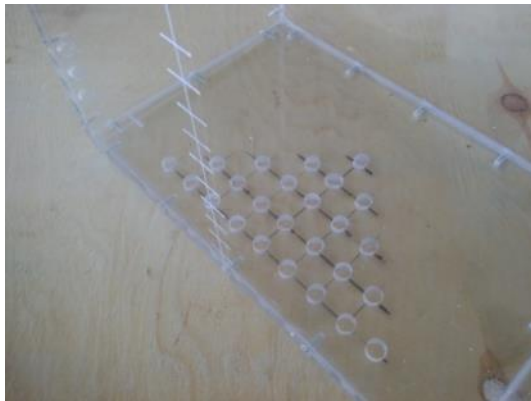


Fig. 3 Physical model tank, drainage holes and height markings



Fig. 4 Rock drainage layer

Figure 4 shows the drainage rock layer provided in the physical model. This is to ensure that the water and sugar solution can drain freely. The stones allow for some overflow water volume to be detained.



Fig. 5 Overburden placement

Figure 5 shows the placement of the soil medium before the experiment commenced. Also note the water nozzle on the left hand side in the figure. This is the nozzle which delivers the water to the soluble material (white sugar). This cavity is placed towards the front center of the box. By making use of symmetry, it allows the soil deformation and failure mechanisms to be observed.

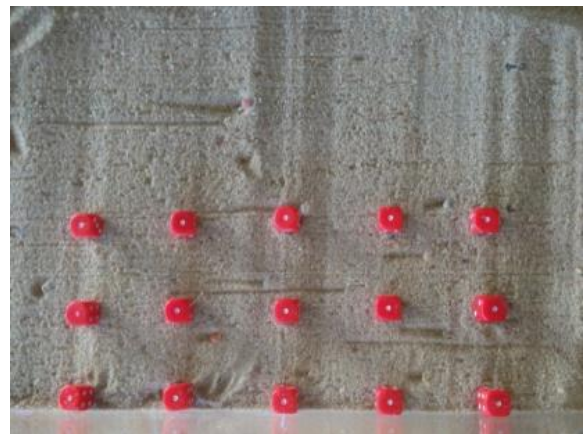


Fig. 6 Dice placement top view

Dice were placed on the surface of the soil, as shown in Fig. 6. They were used as displacement indicators for visualization purpose. As the soil material moves both vertically and horizontally towards the center of the sinkhole, creating the maximum displacement at the center of the sinkhole as well as the conical shape.

Figures 7 & 8 show the front view of the sinkhole with its initial cavity created due to the sugar dissolution. It also shows the collapse of the overburden into the cavity which creates a sinkhole. Note the circular appearance and conical shape of the sinkhole in the figures.



Fig. 7 Initial cavity opening

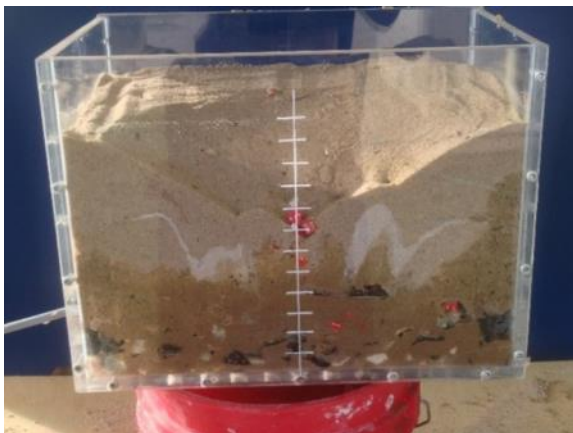


Fig. 8 Final cavity collapse



Fig. 9 Sinkhole surface opening

Figure 9 illustrates the final circular conical shape of the sinkhole. This sinkhole represents half symmetry of a whole sinkhole. The sinkhole was captured entirely within the boundary of the tank. In later numerical simulations, these boundaries need to be optimised to save computation time. They also need to be large enough that they do not have effect on the results. This is to ensure that the boundaries

give enough space for the sinkhole to form within the numerical solution.

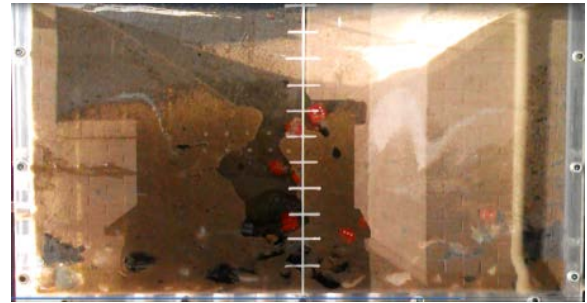


Fig. 10 Final sinkhole cavity

Figure 10 shows the final cavity created by the sinkhole model. Note the convex and then concave curves of the funnel leading to the sinkhole. The cavity appears vertical like a chimney. The opening is round and the conical funnel leading to the surface leaves a circular extent. These are characteristics which compare favorably to sinkholes formed naturally [8, 9 and 10]. The physical modelling successfully demonstrates the mechanics of sinkhole failure by the utilization of a scaled model.

3. TWO DIMENSIONAL NUMERICAL MODEL

Despite the fact that sinkhole is a complex three-dimensional problem, it can be simplified to 2D plane strain conditions, that is defined in Fig. 11. The sinkhole has a soil overburden height h and trapdoor width w . The soil body is modelled as a uniform Mohr-Coulomb material, which has cohesion (c), friction angle (ϕ), and unit weight (γ).

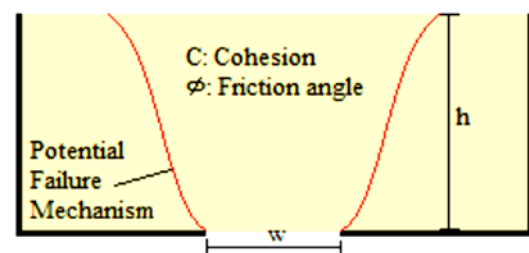


Fig. 11 Idealised sinkhole in 2D space.

A typical mesh for the finite difference modelling using *FLAC* is shown in Fig. 12. A *FLACish (FISH)* script was developed to automate the modeling process; increasing the easiness for the students at their first stages of learning. Alternatively, the graphical interface in *FLAC* may be used by students to manually construct the numerical model.

It is possible to analyse the stability problem in terms of factor of safety (FoS) for many different

underground cavities. Using the so-called shear strength reduction method, the analysis appears to be meaningful for determining the likelihood of overburden collapse and formation of a sinkhole. This 2D approach is understood to be conservative, yielding a lower *FoS* than those produced from an actual 3D analysis [2].

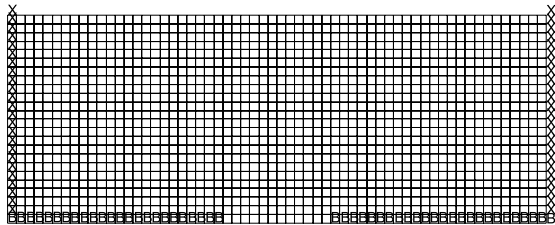


Fig. 12 A typical *FLAC* mesh with boundary conditions

Failure of the model is triggered by the removal of the boundaries conditions for the width of the trapdoor, shown in Figs. 11 & 12, and then by reducing the shear strength of the material using the strength reduction technique ~ a built-in *FoS* solver in *FLAC*.

An analysis is performed with the initial shear strength parameters: cohesion and friction angle, followed by a gradual increase or decrease of the parameters. Soil strength parameters would be increased if the model is not in equilibrium at the start of analysis. This leads to stress redistribution in the soil system until the limiting equilibrium is established in the soil body, equating to a factor of safety of 1. The actual factor of safety of the model can be calculated by dividing the actual strength parameters of the soil body by strength parameters of the soil at the solution point.

The stability problem is expressed in terms of factor of safety (*FoS*), which is a function of the depth ratio h/w , the soil strength ratio $c/\gamma w$, and the angle of internal friction ϕ . Parametric studies are expected to be performed by the students using both the above geometrical and material parameters. This will provide a good learning tool for students to study the effects of strength parameters and trapdoor size on *FoS*. The mesh density effect can also be efficiently studied by making use of the developed script.

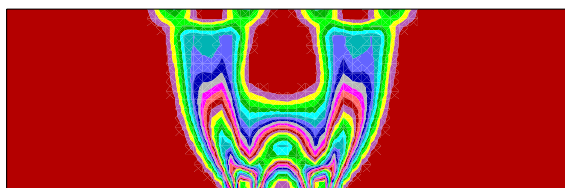


Fig. 13 A typical shear strain rate plot for undrained clay ($h/w=2.5$, $c_u/\gamma D=3.0$)

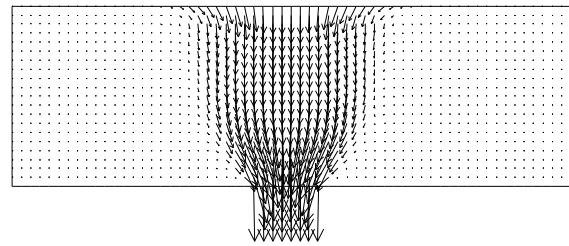


Fig. 14 A typical velocity vector plot for undrained clay ($h/w=2.5$, $c_u/\gamma D=3.0$)

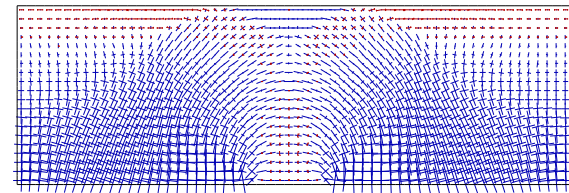


Fig. 15 A typical principal stress plot for undrained clay ($h/w=2.5$, $c_u/\gamma D=3.0$)

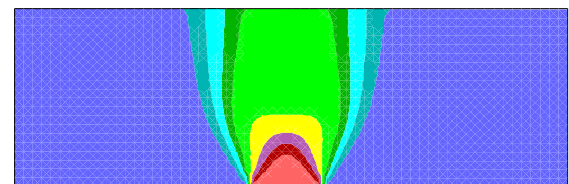


Fig. 16 A typical y -displacement contour plot for undrained clay ($h/w=2.5$, $c_u/\gamma D=3.0$)

Figures 13-16 present typical plots for shear strain rate, velocity field, principal stress tensors and y -displacement contours. These plots are useful for student learning in observing and comparing model responses. They can also be used to provide an increased understanding of soil behavior and the induced failure mechanisms.

Introducing students to numerical modeling of a trapdoor in 2D space and by relating this to the sinkhole phenomena allows students to see the practical application of numerical analysis. It also elaborates on the many different ways that a numerical analysis can be implemented to show different characteristics of a soil body.

4. THREE DIMENSIONAL NUMERICAL MODEL

A three dimensional sinkhole model was created using *FLAC3D*. Students can use this model as a basis to study sinkhole collapse in its three-dimensional nature, and further extend it to perform a comparative study between the 2D and 3D modeling, as well as other parametric studies.

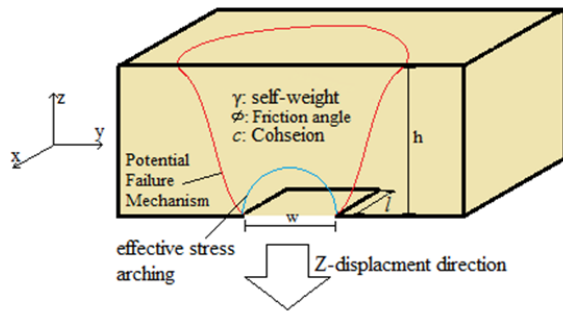


Fig. 17 Idealised trapdoor cavity sinkhole in 3D space

Figure 17 shows the idealised trapdoor cavity in 3D space. h is the height of the overburden material above the cavity and w represents the width of the cavity roof. Due to the symmetrical condition, l is the half-length of the trapdoor cavity in the x -axis. The sinkhole model uses a homogenous Mohr-Coulomb soil with characteristics of mass-density, elastic modulus, Poisson's ratio, cohesion and friction angle.

Artificial boundary conditions are required to allow the finite difference model to function. This goes against the endless continuum of soil strata in which sinkholes form in real life. They are necessary to set the quantity of overburden to be tested, which has a large control on computation time. However, these boundaries can be set to minimise their effect on the results, as elaborated by the physical modeling. Figure 18 shows a typical 3D mesh used in the analysis.

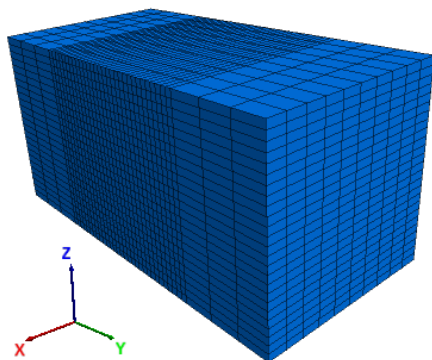


Fig. 18 Typical 3D mesh ($h/w=2$, $w/l=2$)

Failure of the 3D model is triggered by removing the boundary conditions of those surface nodes bounded by the width and the length of the trapdoor. It is then solved by reducing the shear strength of the material using the strength reduction technique ~ a built-in *FoS* solver in *FLAC3D*. The 3D stability problem is expressed in terms of factor of safety (*FoS*) that is a function of the depth ratio h/w , the

width ratio l/w , the soil strength ratio $c/\gamma w$, and the angle of internal friction ϕ .

Figures 19 & 20 present typical plots of displacement contours. These plots are useful for student learning in observing and comparing 3D model responses. They provide an increased understanding to students concerning the behavior and the mechanism of sinkhole creation. They can also be used to compare to the results from 2D numerical model. Further to this, a series of 3D parametric studies using the dimensionless geometrical and material parameters can be performed by the students.

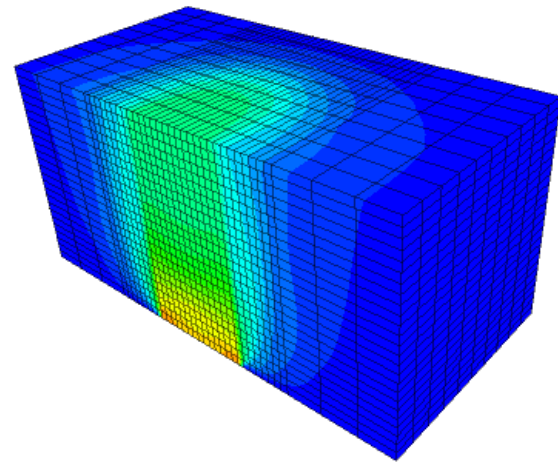


Fig. 19 A typical displacement contour plot ($h/w=2$, $w/l=2$, $c_u/\gamma D = 1.05$)

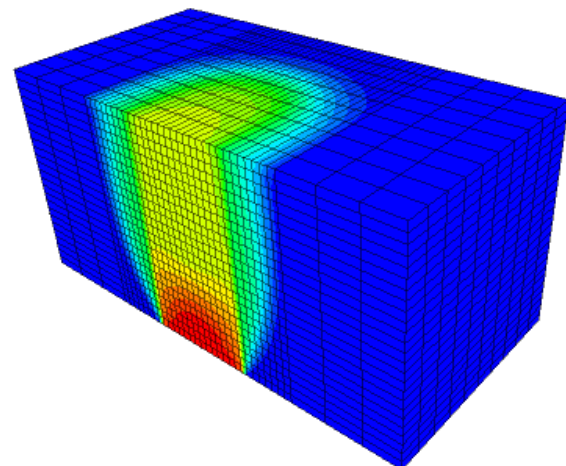


Fig. 20 A typical velocity contour plot ($h/w=2$, $w/l=2$, $c_u/\gamma D = 1.05$)

Note that the numerical results in these figures represent half of a square trapdoor ($l/w = 0.5$). It is interesting to see the circular surface extents of the sinkhole despite a square opening. This circular surface extent does point to an important research

direction in studying the 3D responses of surface extents with changing l/w ratios, such as those for rectangular trapdoor or any other shapes.

While physical soil conditions and overburden to trapdoor cavity interactions have high complexity, the current model successfully uses simplification and assumptions to aid with predicting theoretical soil responses within the trapdoor cavity opening and overburden soil in 3D.

5. CLASSROOM INTEGRATION – THREE WEEK ACTIVITY

A three-week activity based on the developed physical and numerical model has been proposed to complement the traditional method of teaching. The three-week group-based activity will involve a brief lecture and resources from the internet to improve their understanding of sinkhole problems. It will also involve the construction and demonstration of a sinkhole model, and the demonstration of the 2D and 3D numerical models. A formative assessment has also been designed to monitor the students learning as well as to ensure the students are learning from the activity. Each week represents a single three hour session.

Week One Activity

Week one will start with a brief lecture into the three week activity so the students understand what to expect. Included in the lecture will be information about geotechnical natural disasters, landslides and sinkholes for instance, and what engineers can do to prevent such disaster. Leading from this will be information about sinkhole formation and direct research links to videos and research papers relating to the sinkhole topic. This would ensure that students are prepared for the entire activity.

The second half of the first weeks activity will include a computer laboratory session where students are to research a case study of a particular sinkhole of their interest, noting how it collapsed and the size and shape if the sinkhole.

Week Two Activity

The second week's activity will be an introduction into 2D and 3D numerical simulation of trapdoors and its relation to sinkholes. Students will perform a series of parametric studies given using 2D and 3D cases. Results and conclusion drawn from the preliminary study of sinkhole failure mechanisms will lead to creating physical sinkhole model in the following week.

Week Three Activity

In week three, the students will be given the sinkhole model tank. They will be shown the pebbles, sand and sugar which will be used to make the model. The students are then, with some instruction, required to construct the model to demonstrate sinkhole failure.

After the creation of the sinkhole via the placement of pebbles sugar and sand, group demonstrations are followed by using the water pipe to trigger the sinkhole collapse. The students will be asked to sketch the top front and cross-sectional side view of the actual failure slip plane of the sinkholes. They will then be asked to compare the physical and numerical sinkholes to those that naturally occur and to draw conclusions between numerical and physical models, as well as observing similarities to naturally occurring geotechnical phenomena.

The Formative Assessment

The final submission will include one case study from the existing sinkholes occurred in the past few decades as well as the numerical model results and physical model results from the failure sketches in Week 3. The formative submission will also include a brief conclusion based on their observation.

6. CONCLUSION

A three-week teaching activity has been developed to introduce students with some advanced aspects of sinkhole formation and collapse. This activity involves physical modelling and advanced computational modelling in 2D and 3D spaces. This development would suit a postgraduate course; it could also suit a professional development course for practicing engineers.

One important positive outcome of this type of activity is the increased engagement of both staff and students. Teaching advanced geotechnical engineering courses with physical and numerical modeling adds a brand new perspective for students, when compared to the traditional method of textbook teaching. It is hoped that by developing these exercises would provide students better vision in relation to the breadth and potential of the geotechnical practice and research, and help to increase awareness and interest in the field of geotechnical engineering.

7. ACKNOWLEDGEMENTS

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REFERENCES

- [1] Shiau, J., Pather, S., & Ayers, R. (2006). Developing physical models for geotechnical teaching and research. *Physical Modelling in Geotechnics – 6th ICPMG*, London.
- [2] Shiau, J., Sams, M., & Lamb, B. (2016). Introducing Advanced Topics in Geotechnical Engineering Teaching – Tunnel Modelling. *International Journal of GEOMATE*, 10(1), 1607-1614.
- [3] Lei, M., Gao, Y., Jiang, X., & Hu, Y. (2005). Experimental Study of Physical Models for Sinkhole Collapses in Wuhan, China. *Sinkholes and the Engineering and Environmental Impacts of Karst*, pp. 91-102.
- [4] Geology Rocks! Sinkhole in a Cup (2010). NM Outdoor Classroom Program, Bitter Water, Bottomless Lakes.
- [5] A Hole in the Ground (2006). Oregon Museum of Science and Industry, Expedition Northwest.
- [6] Hudyma, N. (2004). Model study of the formation of Sinkholes, Geotechnical Engineering Earth Science Outreach, University of North Florida.
- [7] Lamb, B., & Shiau, J., (2014). Physical and Numerical Investigation into Sinkhole Collapse. *Fourth International Conference on Geotechnique, Construction Materials and Environment*, Brisbane, Australia.
- [8] Meng, Y., Lei, M. T., & Lin, Y. S. (2012). Models and mechanisms of drilling-induced sinkhole in China. *Environmental Earth Sciences*, 67(1), 1961-1969.
- [9] Yechieli, Y., Wachs, D., Abelson, M., Crouvi, O., Shtivelman, V., Raz, E., & Baer, G. (2003). Formation of sinkholes along the shore of the Dead Sea - summary of the first stage of investigation. *current research - Geological Survey of Israel*, 13, 1-6.
- [10] Heidari, M., Khanlari, G. R., Taleb-Beydokhti, A. R., & Momeni, A. A. (2011). The formation of cover collapse sinkholes in North of Hamedan, Iran. *Geomorphology*, 132, 76-86.
- [11] Augarde, C. E., Lyamin, A. V., Sloan, S. W. (2003). Prediction of Undrained Sinkhole Collapse. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(3), 197-205.
- [12] Itasca Consulting Group Inc (2003). FLAC2D User's Manual. Minneapolis, USA.
- [13] Itasca Consulting Group Inc (2003). FLAC3D User's Manual. Minneapolis, USA.

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