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Advances in Numerical and Experimental Analysis of Transportation Geomaterials and Geosystems for Sustainable Infrastructure

Edited by
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ADVANCES IN NUMERICAL AND EXPERIMENTAL ANALYSIS OF TRANSPORTATION GEOMATERIALS AND GEOSYSTEMS FOR SUSTAINABLE INFRASTRUCTURE

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Preface

This Geotechnical Special Publication (GSP) contains 23 papers addressing a variety of current issues in Soils and Rock Instrumentation, Behavior, and Modeling; Earth Retaining Walls and Slope Stability; and Seismically Induced Hazards and Mitigation. These papers were presented at the GeoChina International Conference held on July 25-27, 2016 in Shandong, China. The technical programs for the GeoChina International Conference struck a balance between the fundamental theories and field applications. Sustainable civil infrastructures using innovative technologies and materials are endorsed by a number of leading international professional organizations. This GSP includes investigations and solutions from numerous countries. It expands ranges of tools that are available to engineers and scientists.

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Contents

Exploring the Geomechanics of Sinkholes: A Numerical Study of Sinkhole Subsidence and Collapse

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Abstract: The processes of sinkhole development are strongly dominated by the geomechanical characteristics of rock and soil behavior that are complicated by the interaction with chemical reactive processes as well as hydraulic transport processes. Sinkholes formed in soils are generally of a sudden, catastrophic nature, and understanding of cover-collapse sinkholes presents probably the biggest challenge to research communities due to the difficulties in formulating an effective quantitative approach to assess a number of diverse mechanisms behind many intricate processes involved, which are further complicated by a variety of scenarios that can trigger these sinkholes. This paper presents some of the preliminary results of an ongoing research that is aimed to explore a geomechanical modelling approach to understand the process of sinkhole developments. The explicit finite difference program, FLAC is used to model the behavior of geomaterials around a cavity in a potential water drawdown scenario. A parametric study is conducted to examine the effects of different mechanical and hydraulic properties. The results show some key characteristics of sinkhole subsidence and collapse, and demonstrate the feasibility of a numerical modelling approach which must be complimented by theoretical and analytical developments to be able to explore many intricacies and complexities of the mechanisms involved in the mechanisms of cavity growth and propagation.

INTRODUCTION

Sinkholes are a spectacular yet devastating geo-hazard which poses a significant threat to environment, infrastructure and human lives. The conceptual nature of the involved key mechanisms is well-known, as it is usually related to formation or development of a cavity as a result of the interaction between the underlying karstic rock layer and the groundwater. The processes of sinkhole development are strongly dominated by the geomechanical characteristics of rock and soil behavior that are also complicated by the interaction with chemical reactive processes as well as hydrological processes.

However, there has not been extensive geomechanical and geotechnical research devoted to the study of sinkholes; current practice heavily relies on the traditional geological approach or guidelines of empirical nature.

Sinkholes can develop in karstic bedrocks where the dissolution of soluble rocks plays a dominant role, or in overlying soil layers where complex hydro-mechanical processes are involved. The progress of rock failure is much dependent on dissolution in karstic rocks and in general this process usually require extended periods of time likely in geological scale for limestone, while gypsum or anhydrite dissolves at a moderate rate but dissolution of rock salt (Halite) occurs quite rapidly (e.g., Waltham et al. 2005). Sinkholes formed in soils are a more widespread geohazard and can be of a sudden, catastrophic nature. They are generally caused by the erosion, transport and failure of the soils that overlie cavernous rock. They can manifest either as a gradual process of surface depression in so-called cover-subsidence sinkholes, or a sudden soil collapse in cover-collapse sinkholes that are typically caused by the growth and upward propagation of the cavity and eventual failure of soil arch over the growing cavity in the soil layer. The development of these two types of sinkholes is often a very complicated process in which water flow plays a critical role.

The complexity of sinkhole development strongly suggests a necessity of multi-physics considerations to address the interaction of geomaterials with other geochemical and hydrological processes. Geotechnical investigations of sinkholes have been traditionally centered on the analysis of stability around a cavity/opening (e.g., Drumm et al. 1990; Abdulla and Goodings 1996; Goodings and Abdulla 2002; Augarde et al. 2003), usually with an aim to identify the limit or maximum load (e.g., overburden pressure) as a function of geometric configuration of soil layer and cavity size and strength properties. Geotechnical research of sinkholes can certainly be enhanced by theoretical, analytical and numerical efforts to explore the geomechanics of sinkholes in an innovative way that enables understanding of the progressive nature of the sinkhole process.

This paper presents some of the preliminary results of an ongoing research aimed to explore a geomechanical modelling approach to understand the multi-physics processes of sinkhole development. It specifically focuses on the sinkhole formed in soils typically triggered or affected by complex hydrogeological events. General modelling approaches are discussed briefly, followed by an introduction of basic background of numerical modelling utilizing a computational software. The underlying mechanisms of subsidence and collapse in soils are also discussed and the presented simulations are focused on the scenarios of water drawdown.

BACKGROUND AND BASICS OF NUMERICAL MODELLING

An in-depth understanding of the underlying mechanisms for sinkhole failure in soils remain elusive, in particular, the continuing growth and propagation in a cohesive soil is a very intricate process, no consensual theory or explanation has yet offered a clear quantitative description. This process is almost invariably associated with water flow usually (but not always) as a consequence of drawdown. Paradoxically both water drawdown and excessive rainfall can trigger this type of failure, indicating different mechanisms may be involved in different scenarios. Pore pressure change (Tharp 1999, 2002, 2003), vacuum/suction effects (Xu and Zhao 1988; He et al. 2003), piping (Hyatt et al. 1999) have been investigated as causes for soil failure. Most likely distinct scenarios may involve specific mechanisms or a combination of multiple mechanisms.

The present simulations examine some fundamental aspects of numerical modelling utilizing computational software FLAC (Itasca 2011). It is a two-dimensional explicit finite difference program which simulates the behavior of soils, rocks and other materials which undergo plastic flow once the yield limits are reached. Use of readily available computational programs facilitates convenient investigations of hydrological scenarios and allows considerations of more realistic geometric configurations (e.g., Parise and Lollio 2011; Shalev and Lyakhovsky 2012) free of simplifications needed for analytical models (e.g. Tharp 2002), however, it is restricted by the software's capability in handling complicated material behavior and scenarios of multi-physics nature. Consequently the present numerical simulations do not consider the growth of the void/cavity which may require specific hydro-mechanical interactions to be considered and numerically implemented. The geometry and material behavior are kept simple in the present simulations. The main goal is to focus on the potential scenarios of water table variations and drawdown that may induce sinkhole formation and in the following sections we present the main characteristics of deformation and stress around a cavity under these circumstances.

A typical conceptual cavity model in FLAC2D is shown in Fig. 1a, in which the materials are represented by the elements or the zones; and the grids and meshes are adjusted to make the desired circular cavity. In this model, the bottom layer represents the limestone whilst the upper layer represents the clay overlaying the limestone rock. Figure 1(b) and 1(c) shows typical (vertical) displacement and stress distribution in a purely mechanical analysis in FLAC. A parametric study undertaken to investigate the characteristics of deformation and stress around a cavity as influenced by different factors including overburden pressure, thickness and size of the cavity without hydrological considerations was reported in Rawal et al. 2015. This study is now extended to examine the scenarios of water table variations and drawdown.

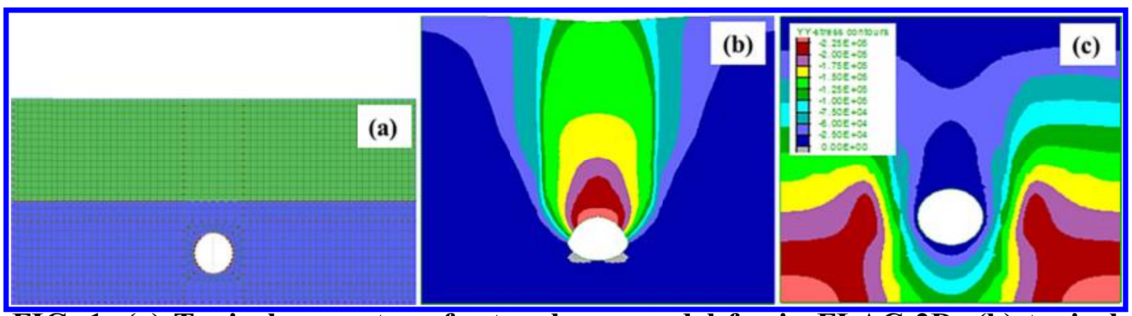

FIG. 1: (a) Typical geometry of a two-layer model for in FLAC 2D; (b) typical vertical deformation contours forming inverted conical shape of potential failure surface; (c) typical map of vertical stress contours.

Soil and Rock Properties

Mohr-Coulomb plasticity model is used to define the properties of the materials. The model parameters include density (ρ), friction angle (ϕ), cohesion (c) and tensile strength (T), as well as modulus of elasticity (E) and poisons ratio (υ) as shown in Table 1. The porosity and permeability are also the essential input parameters for hydrological study which are described later in this paper.

Table 1. Parameters used for simulations.

Input Parameters	Clayey Soil	Limestone Rock
ρ	2000 kg/m^3	2700 kg/m^3
ϕ	27°	30°
c	15 kPa	1 MPa
T	10 kPa	100 kPa
E	30 MPa	5 GPa
υ	0.3	0.3

It should be noted that in the presented hydro-mechanical simulations, only one layer (of 10m thick) is considered, for the two following reasons; first of all we are mainly concerned with possibilities of sinkholes in soil layers, secondly, as the different material parameters are varied for the comparison purpose, it is more instructive to focus on the presentation of the results of a one-layer model; obviously multi-layer models can be similarly explored.

NUMERICAL SIMULATIONS

Influence of Water Drawdown and Ground Water Table

A drawdown scenario is initiated by imposing a difference in water pressure at the top and bottom, inducing a downward water flow that eventually lowers the water table (Fig. 2a). As the water table is lowered down, the deformation around the cavity starts to grow (Fig. 2b). The presented results in Fig. 1 are based on a very "strong" soil layer (by prescribing high values for strength parameters), thus the deformation is eventually stabilized as shown in Fig. 2b, especially when the drawdown is stopped, this is in contrast to weak soils where the deformation can progress continually and eventually collapse occurs when given sufficient time, as discussed in the subsequent discussion.

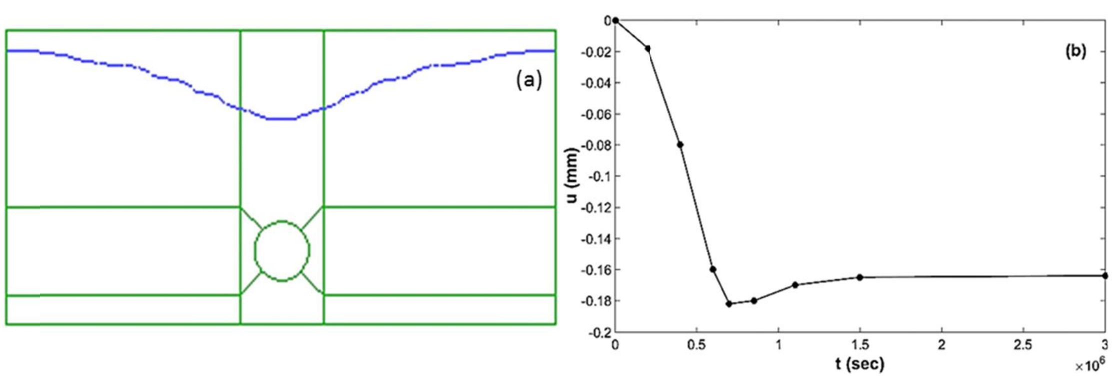

FIG. 2: (a) Simulated piezometric water drawdown, the concave upward curve shows the present water table (after 3×10^6 seconds) and the original water table is at the ground surface; (b) evolution of vertical deformation (u) at the top of cavity.