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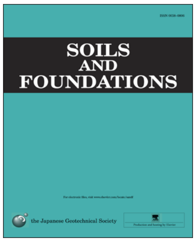

Soil–water–air fully coupling finite element analysis of slope failure in unsaturated ground

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Abstract

In this paper, a program of the finite element method (FEM), named as SOFT, using a finite element–finite difference scheme (FE–FD) for soil–water–air three-phase coupling problems, has been developed based on a rational and simple constitutive model for unsaturated soil proposed by Zhang and Ikariya (2011). In the program, similar to the works by Uzuoka et al. (2009) and Oka et al. (2010b), the FE–FD formulation in saturated condition of soil–water coupling problem, proposed by Oka et al. (1994), has been extended to unsaturated condition in soil–water–air fully coupling scheme, taking the saturation as a state variable. In order to verify the availability of the proposed numerical method, triaxial tests on unsaturated silty clay under fully undrained and unvented conditions, conducted by Oka et al. (2010a), are firstly simulated by the proposed method. The development of pore air pressure and pore water pressure measured in the specimen can be reproduced well by the proposed method. Furthermore, model tests on slope failure in unsaturated Shirasu, carried out by Kitamura et al. (2007), are also simulated by the same numerical method. From the simulation it is known that the slope failure behavior of the model ground observed in the tests can be described, on the whole, with satisfactory accuracy

Keywords: Slope failure; Constitutive model for unsaturated soil; FEM; Soil–water–air coupling; Model test

1. Introduction

Slope failure is always one of the most interesting research topics for geotechnical studies and engineers, not only because it may lead to tremendous disaster to human beings and civil facilities, but also because of the difficulties in predicting when and where the slope failure may occur in most cases. Generally speaking, slope failure is thought to be related to the shearing deformation due to excavations, the cyclic drying–wetting process, and the decrease in effective stress due to the elevation of the underground water table or heavy rainfall.

In a slope, the groundwater table is usually below the ground surface and the pore water pressure (PWP) in the soil above the groundwater table is negative, or in other words, suction exists. This suction will enhance the stability of a slope in an unsaturated ground. With the infiltration of water from

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rainfall or the elevation of the groundwater table, the water seepage may cause a gradual loss in suction in the unsaturated soil of the slope. The loss of suction consequently causes a decrease in effective stress, which may then give rise to a decrease of shear strength of the soil and sometimes may even cause a slope failure, namely, a typical surface failure of a slope.

In order to investigate the mechanism of slope failure, some model experiments on slope failure due to rainfall had been done in the laboratory such as the works by Yagi et al. (1983), Kitamura et al. (2007), Tohari et al. (2007), Jeng. and Lin. (2011) and Maeda et al. (2012). In the work by Kitamura et al. (2007), model tests were conducted on the slope failure in an unsaturated Shirasu ground with different infiltration patterns. In the tests, the PWP at some selected points of the slope was carefully measured by tensiometers and PWP sensors.

Meanwhile, many numerical analyses on the slope failure were also conducted in the past decades. Zhang et al. (2003) carried out a soil–water coupled finite element analysis on the progressive failure of a cut slope in a model ground based on an elastoplastic model with strain hardening and strain softening. In the work by Cai and Ugai (2004), the finite element method was used with a shear strength reduction technique to evaluate the stability of slopes due to rainfall. Ye et al. (2005) conducted numerical analyses on the progressive failure of slope due to heavy rain with a 2D and a 3D FEM. FEM simulation using a 2D unsaturated–saturated seepage analysis and a slope stability analysis was performed to clarify the slope failure mechanisms due to heavy rain in the work by Sako et al. (2006).

The above-mentioned simulations were conducted with the soil–water coupling formulation, the air pressure was assumed as constant, and its value is taken as zero for unsaturated soil. In general circumstances, however, the air pressure does not remain constant, but varies, as pointed out in the work by Yamamura (1971) and Gens et al. (2009). In the work by Oka et al. (2010b), the multiphase deformation analysis of a river embankment was carried out using a soil–water–air fully coupling finite element method, in which a complex elasto-viscoplastic constitutive model for unsaturated soil proposed by Oka et al. (2008) was used. Mori et al. (2011) conducted a 2D dynamic finite element analysis to predict the seepage and the seismic behavior of a slope with unsaturated ground. Iwai et al. (2013) also conducted a numerical simulation of the decomposition behavior and the ground deformation of methane hydrate bearing sediments induced by the depressurization method. In the work, a multiphase mixture theory, in which not only the soil–water–air coupling problem, but also energy conservation were considered, was employed in the finite deformation analysis of a deformation problem caused by the depressurization of the methane hydrate beneath the sea bed.

Much research has been done on the mechanical behavior of unsaturated soils experimentally, empirically, and theoretically. Many constitutive models for unsaturated soils had been developed, e.g., Barcelona Basic Model (BBM) (Alonso et al., 1990), Kohgo et al. (1993a, b), Cui and Delage (1996) and Sun et al. (2000). In these models, the stress and the suction were taken as the independent state variables and the stress–suction–strain relations of unsaturated soil were considered explicitly while the degree of saturation was not considered directly. On the other hand, constitutive models considering the influence of the degree of saturation were also proposed, e.g., the works by Karube et al. (1997), Gallipoli et al. (2003), Sheng et al. (2004), Sun et al. (2007) and Sheng et al. (2008).

Zhang and Ikariya (2011) proposed a simple elastoplastic constitutive model for unsaturated soil using the Bishop-type skeleton stress and the degree of saturation as the state variables. The constitutive model is able to describe not only the behavior of the unsaturated soil but also the saturated soil because the skeleton stress can smoothly shift to effective stress if the saturation changes from an unsaturated state to a saturated state. In the model, a simple moisture characteristics curve (MCC) considering wetting–drying moisture hysteresis of an unsaturated soil is also proposed. Furthermore the overconsolidation of soil is also properly described based on the concept of subloading (Hashiguchi and Ueno, 1977). The main feature of the model is that the model can describe both the saturated and unsaturated soils using one set of parameters. A brief introduction of the constitutive model and the MCC is given in Appendices A and B. The disadvantage of the model, as pointed out in the work by Sheng (2011), is that when using Bishop-type effective stress as the state valuable and assuming that e–log p'curves at different S_r are parallel to each other, an overlooked restriction exists at zero mean effective stress, which may contradict to the aforementioned assumption under typical stress state, e.g., $p'=1$. Further revision on this model is needed in the near future.

In this paper, based on the model (Zhang and Ikariya, 2011), a soil–water–air fully coupling FE–FD method is developed to investigate the mechanism of the surface failure of slopes. Because the model (Zhang and Ikariya, 2011) is adopted into FEM, a new special calculating scheme is needed and the field equations related to the FE–FD scheme in a soil–water–air fully coupling problem is firstly deduced in detail. The validity of the newly proposed numerical method is then confirmed by the element tests on unsaturated silty clay under undrained and unvented conditions, carried out by Oka et al. (2010a). Finally, the model tests on a slope failure in an unsaturated Shirasu ground, carried out by Kitamura et al. (2007), are also simulated by the proposed numerical method. The applicability of the proposed numerical method is verified in detail.

2. FE–FD scheme in soil–water–air fully coupling problem

The governing equations of the soil–water–air three-phase coupling theory can be classified into three groups: the equilibrium equation, the continuity equation for water, and the continuity equation for air. Details on the derivation of soil–water two-phase equations can be found in the works by Oka et al. (1994), Kanazawa et al. (2008), and Kato et al. (2009), while details on the soil–water–air three-phase equations can be found in the works by Li et al. (2004), Borja (2005), Uzuoka et al. (2007, 2008, and 2009), Uzuoka (2010), and Oka et al. (2010b). These equations are directly listed as follows.