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Finite element simulation of an excavation-triggered landslide using large deformation theory

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ABSTRACT

Numerical simulation of an excavation induced landslide in a strain softening material is presented and the results are compared with field measurements. The simulation is based on the methodology proposed to estimate the post-failure deformation of slopes in strain softening materials. The method includes: a) the Updated Lagrangian formulation which is essential in capturing the changing geometry and configuration of the slope during failure, b) a strain softening constitutive model which enables simulation of the progressive failure mechanisms, c) a stable solution scheme to prevent problems associated with numerical convergence in strain softening materials, and d) the *h*-adaptive mesh refinement technique to prevent excessive distortion of the finite element mesh due to large deformation and to increase the accuracy of the numerical solution.

For the slope considered here, it is shown that failure initiated due to the excavation at the toe of the slope and propagated upward due to the strain softening behavior of the geomaterials which eventually led to the progressive failure of this slope. The failure surface is mainly within a thin layer of soil with substantial strain softening behavior but propagates to the surrounding soil as the excavation proceeds. The predicted crest settlement, toe movement, and deformed shape of the slope are lower than the observed behavior of the slope. However, the numerical analysis clearly predicts the triggering factor and the failure mechanism of the landslide and the impact of the large deformation of the soil mass on the houses at the toe of the slope.

1. Introduction

Landslides are natural phenomena induced either by natural factors such as erosion of geomaterial, rain and changes in groundwater level, loss of vegetation and earthquakes or by human activities such as extra loading and construction works at the top of slopes, vibrations, blasting and earthworks and excavation at the toe. Landslides cause significant damage to infrastructure and can lead to loss of life. In order to reduce the substantial social, environmental and economic impacts of landslides, multi-disciplinary experts from geotechnical engineering, geoscience, remote sensing and hydrology are required to design predictive measures to reduce the vulnerability to landslides. Development of early warning systems as well as advanced numerical modeling techniques is crucial in predicting the possible initiation of a slide and the extent of its movement. The magnitude of deformations after failure can be used to evaluate the extent of the failure and to design the remedial work required to limit the associated damage to infrastructure. It is therefore important to be able to predict the post-failure deformation of slopes and to identify slopes with small post-failure deformation from those with progressive failure which may lead to large landslides. This can be achieved by numerical simulation of slope failure, provided that a suitable numerical algorithm and an appropriate constitutive relationship are available.

The standard finite element method based on infinitesimal strain formulation has been found to be very effective in slope stability analysis especially in finding the location of failure surfaces and in obtaining accurate factor of safety, FoS, of slopes in complex soil strata. However, the standard finite element method can give the deformation of slopes only up to the onset of failure. A large deformation finite element analysis based on finite strain formulation can give the deformation of slopes after failure, provided that the geomaterials can be assumed to deform in a continuum. This assumption is valid if the extent of deformation is relatively small. Geomaterials in landslides lose their integrity due to large deformation and cannot be modeled by constitutive relationships that are based on continuum mechanics. However, a relatively large deformation predicted for a slope by a large deformation analysis will be a good indicator of the possible occurrence of a landslide.

In this paper, the results of a large deformation analysis of the failure of a slope are presented and discussed. The geometry and material properties of the slope are presented followed by a brief description of the large deformation finite element formulation. Then detailed step-by-step procedures are used to simulate the failure of the slope and its

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post failure behavior is presented. Finally the finite element results are compared with field records and the observed behavior of the slope.

2. The Senise slope failure

The Senise landslide occurred at Timpone on 26 July 1986 in southern Italy. The landslide was triggered by an excavation at the toe of the slope and although the vertical cuts were protected by 9–10 m concrete retaining walls, the slope movements could not be avoided. The landslide affected a large area and led to loss of eight lives and destruction of seven houses. The dimensions of the landslide were about 150 m in width and 230 m in length. The depth of the soil mass moved in the landslide varied between 10 to 15 m except at the toe which was about 5 m. The borehole investigation of the Senise area showed that the subsoil is mainly composed of yellow sand with clayey silt levels and blue gray clay as shown in Fig. 1. The comparison of the modified morphology of the area after the landslide with the initial slope configuration, showed that the landslide occurred by a slipping translational mechanism which occurred along a weak planar surface approximately parallel to the slope with little rotation or backward tilting (Guerricchio and Melidoro, 1988). The geological and geomorphological mapping of the landslide area, as well as the subsurface investigations indicated that the base of the slide slip surface was on the thin clayey silt layer interbedded with a slightly cemented sand formation inclined 18 degrees to the horizontal (Del Prete and Hutchinson, 1988). The stability analyses conducted by Del Prete and Hutchinson (1988) and Viggiani and Di Maio (1991) also suggested that the landslide occurred along the clayey levels parallel to the slope with shear strength parameters near residual values. The landslide occurred during a very dry period (Guerricchio and Melidoro, 1988) where the location of the water table was estimated to be 23 m below the toe of the slope (Del Prete and Hutchinson, 1988). Therefore, water could not have contributed to the failure of the slope. A plan view of the landslide is shown in Fig. 2. The geometry of the Senise hill in section A–A and the location of the excavation at the toe of the slope is shown in Figs. 3 and 4. The landslide caused movement of a large mass of soil by about 30 m downhill along section A–A (Figs. 2 and 3).

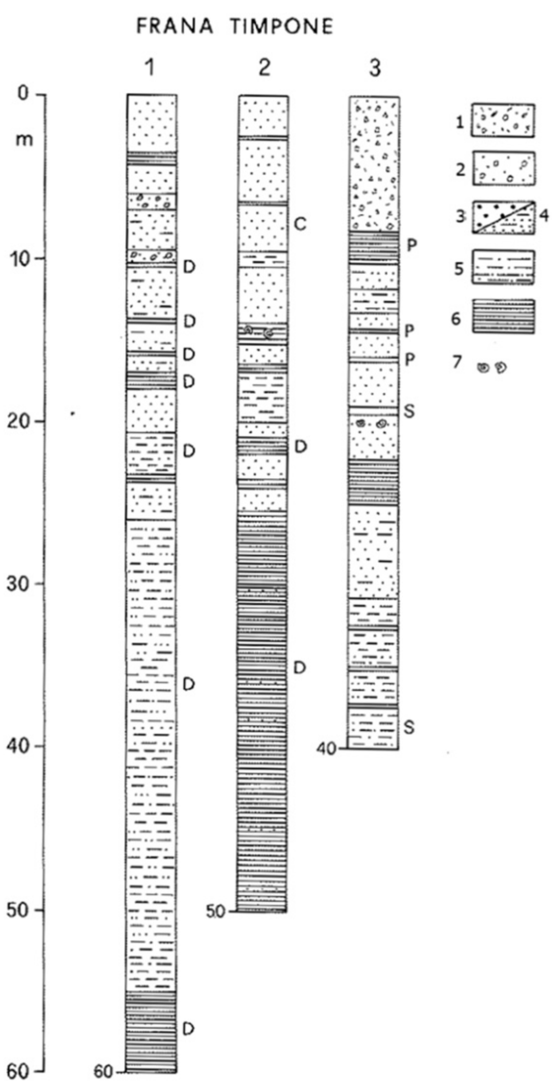

Fig. 1. Bore hole results of the Senise area, adapted from Guerricchio and Melidoro (1988), soil symbols: 1—sand with remolded gravel, 2—fine sand with gravel, 3—medium coarse sand, 4—weakly compact cemented fine sand, 5—yellow sand with thin layers of silty clay, 6—blue gray clay, 7—fossils.

Numerical analyses were performed to investigate the contributing factors leading to the Senise landslide (Conte et al., 2013; Tang, 2008; Troncone, 2005; Troncone et al., 2014). Elasto-plastic finite element analyses of the landslide did not reach convergence when the excavation was modeled to its maximum depth. According to Troncone (2005), the elasto visco-plastic analysis captured the position of the failure surface very well and a converged solution was found for the model. However, the predicted crest displacement was limited to a maximum of 0.53 m at the onset of failure which is very small compared to that observed in the field. Obviously this small deformation would not raise any concern about a possible landslide. Tang (2008) applied the elasto-plastic Cosserat continuum model and resolved the convergence issues of the classical continuum models when simulating the excavation to its maximum excavation depth. The analysis captured the position of the failure surface accurately. However, no attempt was made to predict post-failure deformations. The three-dimensional numerical analysis of this landslide performed by Troncone et al. (2014) showed the direction of the slip surface accurately but could only predict the crest settlements up to the onset of failure as expected from any standard finite element analysis based on infinitesimal strain formulation. The focus of all previous studies has been on simulation of the slope up to failure rather than evaluating the post-failure deformations. The magnitude of the post-failure deformations is important as it shows the extent of failure and differentiates between small slope failures and landslides.

3. Soil profile and constitutive model

The geotechnical profile of the Senise hill in section A–A is shown in Fig. 3. The subsoil consists of yellow sand interbedded with clayey silt layers, which overtops blue gray clay (Troncone, 2005). The clayey silt shows a pronounced strain softening characteristic. The factor of safety of the slope was calculated for the peak and the residual strength parameters as $FoS_{peak} = 1.73$ and $FoS_{res} = 0.60$ (Troncone, 2005), considering a slip surface similar to the one actually observed in the field with its base on the thin clayey silt layer. This implies that the progressive failure occurred with a mobilized strength varying between the peak and the residual values, depending on the magnitude of strains developed in the layer due to the excavation of the toe. The three-dimensional back-analysis of the landslide also confirmed that a progressive failure occurred at Senise hill (Conte et al., 2013; Troncone et al., 2014). A back analysis of the slide based on the Janbu method also gives an average mobilized friction angle in between the peak and the residual values (Viggiani and Di Maio, 1991).

In this paper, the strain softening behavior of the Senise slope material is taken into account using the framework of the Mohr–Coulomb failure criteria. In this model the shear strength parameters, such as cohesion and internal friction angle, are defined as functions of the shear