Numerical simulation of the pore pressure regime in landslides with underdrainage

Simulation numérique du régime de pression des pores dans des glissements avec sous-drainage

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ABSTRACT
Large palaeo-landslides with considerable movements have sometimes caused the burial of permeable formations by the landslide mass. The pore pressure regime established in the landslide material where it overlies these permeable formations is strongly non-linear with depth. A close to hydrostatic pore pressure may be maintained down to a considerable depth, followed by a sharp drop upon approaching the base of the landslide material, to reach the pore pressure of the underlying permeable strata. This pore pressure profile is known as underdrainage profile. The paper presents the results of numerical analyses investigating the effect of inhomogeneity and anisotropy of the coefficient of permeability and infiltration from the ground surface. In order for such a non-linear pore pressure profile to exist in landslide materials there must be considerable infiltration from the ground surface and the coefficient of permeability of the landslide material must decrease with depth. This decrease is often due to the increase in vertical stress in the landslide material and also due to the orientation of clay particles along the slip surface, which may be located immediately above the upper boundary of the buried permeable formation.

RÉSUMÉ
Les paléo-glissements de grande taille avec des mouvements importants dès qu'ils apparaissent pour la première fois, peuvent mener quelquefois a l'enterrement des formations perméables par la masse glissante. Le régime de la pression de pores établi dans le matérial de l'éboulement, quand ceci recouvre ces formations perméables, est fortement non-linéaire avec la profondeur. Le profil de la pression de pores est considéré comme un profil de sous-drainage, vu que une pression de pores considérable peut être soutenue dans les matériaux du glissement jusqu' à une profondeur importante, avant que ca diminue dramatiquement à la base du matériau de glissement pour atteindre la valeur de la pression de pores dans la formation perméable enterrée. Cet article présente les résultats des analyses numériques qui investiguent l'effet de l' inhomogénéité et de l'anisotropie du coefficient de perméabilité et infiltration de la surface. Pour qu'un tel profil non-linéaire de pression de pores existe dans les matériaux de glissement, il faut qu'une infiltration considérable ait lieu à la surface et que le coefficient de perméabilité des matériaux de glissement diminue avec la profondeur. Cette diminution est souvent due à l'augmentation de la pression verticale dans les matériaux de glissement et aussi due à l'orientation des particules de l'argile au long de la surface du glissement qui peut être située immédiatement au dessus de la frontière supérieure de la formation perméable enterrée.

Keywords : Landslides, pore pressure, underdrainage, non-linearity, coefficient of permeability

1 INTRODUCTION

Large scale palaeolandslides with considerable movements often lead to the burial of permeable formations such as river gravel. The latter seems to be the formation most frequently buried by landslide materials, as rivers eroding the toes of valley slopes cause destabilization and movement of the landslide mass towards the toe. Bardanis et al. (2006) presented examples of two landslides in Greece, the toe of which has covered old river beds, while Dounias & Dede (2006) presented an example of a landslide the toe of which had covered permeable sandstones. The common characteristic in all three cases is that within the low permeability landslide materials an underdrainage pore pressure profile is established which is in equilibrium with the lower pore pressure in the underlying permeable formation and the infiltration condition at the ground surface. The paper presents the general shape of such pore pressure profiles, investigates numerically the factors causing their development (coefficient of permeability, infiltration boundary condition) and concludes with a summary of the parameters that need to be determined numerically before proceeding with simulations of the effect of drainage measures on the pore pressure regime of the landslide. The importance of this type of pore pressure profile lies in that it may be employed in a drainage scheme consisting of vertical large diameter wells drilled from the ground surface and extending down into the permeable formation. These wells allow a decrease of the pore pressure at the slip surface, which is often located just above the boundary between permeable formations and landslide materials.

2 PORE PRESSURE REGIME

The general form of an underdrainage pore pressure profile in low permeability landslide materials overlying a permeable formation in equilibrium with a much lower pore pressure is presented in Fig. 1. This is a theoretical profile drawn by considering the field measurements on three different cases (Bardanis et al, 2006; Dounias & Dede, 2006). The profile follows essentially the hydrostatic pore pressure distribution from a shallow depth from the ground surface down to a small distance from the boundary between low and high permeability materials and then the pressure drops considerably to the much lower value in the underlying permeable formation. When river gravel is buried, it often communicates with the existing river bed and its pressure reflects the water level in the present river.

Similar pore pressure profiles have been reported by Kennard & Reader (1975), Vaughan & Wallbancke (1975), and

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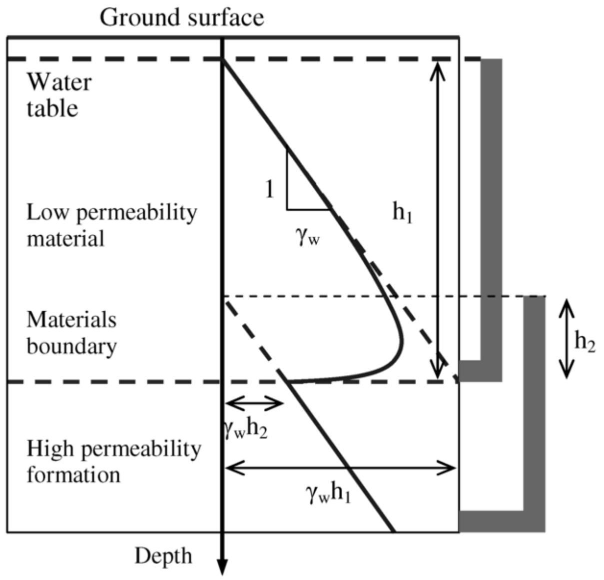

Fig. 1. Pore pressure distribution with depth in low permeability soil overlying higher permeability layer under lower pressure.

Vaughan (1994), who attribute their presence to the decrease in the coefficient of permeability k with depth as a result of stress increase with depth and the corresponding decrease of void ratio. Bromhead & Vaughan (1980), Vaughan et al. (1983) and Vaughan (1989) have investigated the effect of various types of distributions of the coefficient of permeability on the pore pressure profiles.

The underdrainage profiles reported in the aforementioned references however are characterised by a gradual decrease in the pore pressure that begins at quite a large distance from the interface between low permeability and high permeability material. Bardanis et al. 2006 have reported underdrainage pore pressure profiles exhibiting a decrease in the pore pressure at a much smaller distance from the interface between low and high permeability formations. These profiles were observed in landslide materials overlying permeable formations like old river beds, and the decrease in pressure was observed in the sub-layer lying only 2-3m above the interface, which contained the slip surface. In the vicinity of the slip surface the coefficient of permeability in the vertical direction k_v is expected to decrease even to a lower value than the one corresponding to the stress level at that depth as a result of the orientation of the clay particles parallel to the slip surface turning the slip surface into an impermeable “membrane” that inhibits the movement of pore water from the landslide material into the underlying permeable layer.

3 NUMERICAL ANALYSIS OF SEEPAGE

A simplified model was used instead of the actual landslide geometry, in order to illustrate the conclusions derived form the analysis. The problem was investigated numerically using the finite element method (FEM) as this is incorporated into SLIDE (Rocscience Ltd.). The geometry of the simplified example is presented in Fig. 2. The numerical model consisted of 415 quadrilateral eight-noded elements with degrees of freedom on pore pressure and seepage velocity. The landslide modelled has a length of 120m, a maximum depth of 17m, and a depth of the buried river bed of 5m. The landslide mass in Fig. 2 lies within BCDEFG, the permeable layer lies within DEFHIJK, and under them an intermediate layer was introduced down to LMNO, under which the rockbed was introduced as an impermeable layer.

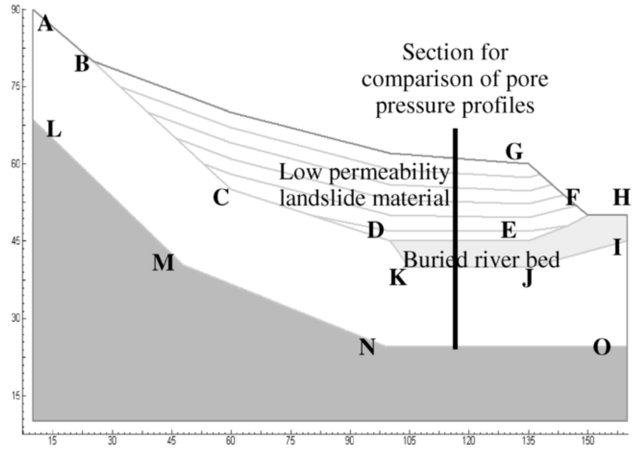

Fig. 2. Assumed simplified geometry.

4 HOMOGENEITY AND ANISOTROPY OF THE COEFFICIENT OF PERMEABILITY

The effect of the coefficient of permeability on the pore pressure profile was first investigated. Initially a unique value of the coefficient of permeability was investigated. Five different values of the coefficient of permeability were introduced into the model for the landslide materials (10^{-8}, 10^{-9}, 10^{-10}, 10^{-11} & 10^{-12} m/s, while the coefficient of permeability of the permeable layer was set at 10^{-4} m/s). None of these values allowed the prediction of the underdrainage profile and a linear hydrostatic distribution from the gound surface all the way to the bottom of the model was obtained.

After this stage, inhomogeneity was introduced in the coefficient of permeability of the landslide material. As inhomogeneity cannot be introduced directly into SLIDE, this was modelled by introducing separate layers into the landslide material in the model of Fig. 2, each having a different value of k. The layers were parallel to the ground surface in the part where the permeable layer is covered. The layers do not continue to be parallel to the ground surface at the toe of the landslide as the toe is formed by the erosion caused by the river and therefore a fair assumption is that the coefficient of permeability corresponds to a void ratio consistent with the stress regime before the erosion of the toe.

The coefficient of permeability profiles with depth that were introduced are presented in Fig. 3. Due to the introduction of inhomogeneity with diferent layers, these linear profiles were introduced as step profiles, with k values for each layer corresponding to the middle of each layer from the linear distribution. A linear distribution of the logarithm of the coefficient of permeability with vertical effective stress and therefore depth was assumed. The general form of such a relation is described by Eq. 1, where a is the coefficient of proportionality.

$$\log k = a \cdot \sigma'_v \qquad (1)$$

For all distributions for the coefficient of permeability, the same value of k was assumed for the depth at the middle of the landslide materials (10^{-8} m/s) and only the coefficient of proportionality a was changed. Five values of a were introduced: a) -0.050, b) -0.075, c) -0.100, d) -0.125, and e) -0.150 (Fig. 4). In a real problem the value of k may be determined from field and laboratory permeability measurements. Once again none of these values allowed the prediction of the underdrainage profile and a linear hydrostatic distribution from the ground surface all the way to the bottom of the model was obtained. Inhomogeneity of the coefficient of permeability by itself therefore does not allow the prediction of underdrainage profiles.

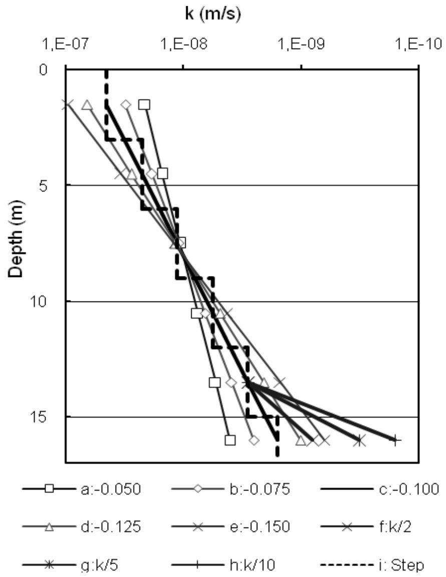

Fig. 3. Tested distributions of coefficient of permeability with depth for the landslide material.

In the last set of analyses investigating the effect of the coefficient of permeabilty, a decrease in the value of k was introduced for the lowest sub-layer of the landslide materials right above the permeable soil layer. The k-profile used in these analyses was profile c in Fig. 3 (where factor a corresponds to real data for totally weathered siltstone from north-western Greece, –Bardanis et al. 2006). The decrease in the value of k was introduced only in the vertical direction, while in the horizontal direction the value of k was kept constant, at the value corresponding to k-profile c for this depth. k_v was decreased 2 times (profile f), 5 times (profile g), and 10 times (profile h) over k_h. The latter was assumed to remain constant, equal to the value corresponding to the void ratio for the stress level at that depth, while the former was assumed to decrease as a result of the orientation of clay particles parallel to the slip surface. Once again the observed pore pressure profile could not be predicted, indicating that further decrease of k_v at the sub-layer containing the slip surface does not alone allow the prediction of underdrainage profiles.

5 EFFECT OF THE BOUNDARY CONDITIONS

The next set of analyses involved the investigation of the boundary condition at the ground surface of the landslide. Infiltration is affected by slope inclination, altitude, soil type and its degree of saturation near the surface, presence and type of plants covering the ground surface etc. Attempting to model in detail the infiltration condition along the ground surface is an almost impossible task. Therefore, a single value of infiltration was introduced into each of the analyses.

The results of these analyses are presented in Fig. 4. For a constant value of the coefficient of permeability in the landslide material, the presence of an infiltration condition at the ground surface has no effect at all (Fig. 4a). For inhomogeneously permeable landslide materials an underdrainage profile is actually predicted, as the larger the decrease of k with depth the closer the predicted profile comes to the theoretical one (Fig. 4b). Also, as may be seen in Fig. 4c, the larger the decrease of k_v in the lowest sublayer the better the theoretical profile is predicted. Finally, controlling for the value of infiltration allows essentially an exact prediction of the theoretical profile which deviates from it only because a step k-distribution was introduced rather than a continuous one.

6 THE PORE PRESSURE REGIME IN THE PRINOTOPA LANDSLIDE, EPIRUS, GREECE

The Prinotopa landslide is located on the path of Egnatia Highway, close to the city of Metsovo in the region of Epirus in north-western Greece. The toe of the landslide practically coincides with the northern bank of the Metsovitikos river, which in the area of the landslide has been diverted to the south by the movement of the landslide mass. The considerable movement of the landslide mass of this palaeolandslide has led to the burial of the old river bed of the Metsovitikos river. Still the buried river bed is hydraulically connected to the present river bed. The maximum depth of the slip surface is in the order of 50m, determined by a large number of inclinometer readings, and it is found in the area where the landslide material overlies the buried river bed. There, the slip surface is located approximately 1-2m above the buried river bed.

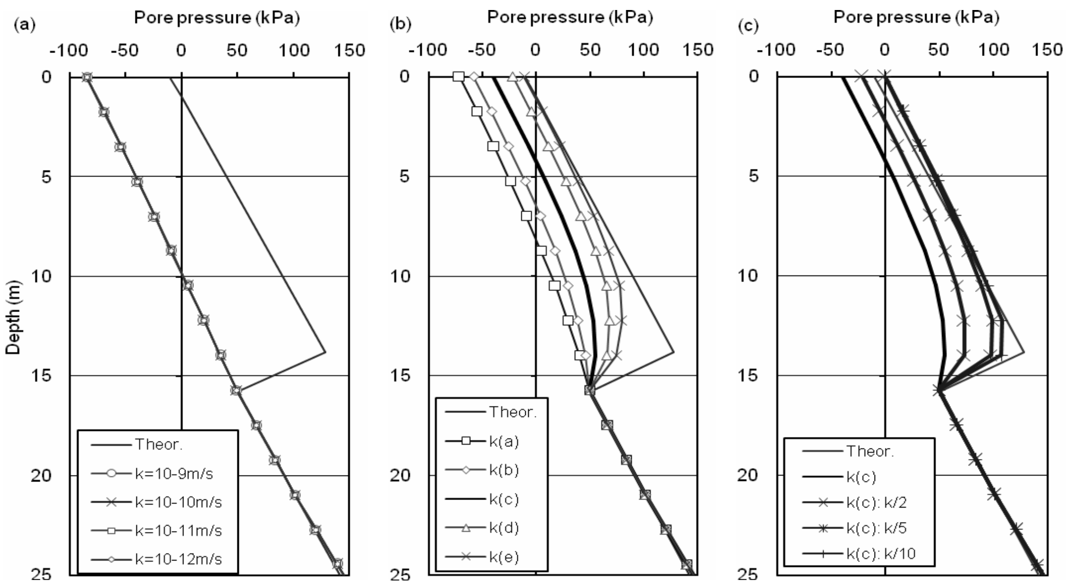

Fig. 4. Theoretical distribution of pore pressure with depth compared to predicted by FEM analyses after introduction of infiltration from the ground surface with: a) homogeneous with depth coefficient of permeability, b) coefficient of permeability decreasing with depth, and c) coefficient of permeability decreasing with depth with further decrease at the zone of the slip surface (distributions of coefficient of permeability with depth as shown in Fig. 3).

The landslide materials consist of siltstone, totally weathered into sandy silty clay with occasional limestone boulders which have been mixed with the landslide materials. The prevailing fines of the landslide material have on average: w_L=40%, I_p=21, γ_d=18.5 kN/m^3, and a void ratio ranging from 0.24 to 0.87. The values of the coefficient of permeability measured in-situ, using ceramic tip piezometers with the piezometer tips at various depths, vary from 6.3x10^{-10} m/s to 3.7x10^{-7} m/s. Measured k values are plotted with depth in Fig. 5, along with the continuous and stepped distribution that was used to model the landslide material. Dry unit weight increased with depth while void ratio and coefficient of permeability decreased with depth. The buried river bed consisted of coarse gravel with sand.

A part of the stabilisation measures of the landslide consisted of large vertical wells drilled from the ground surface down to 4-5m into the buried river bed. These wells would drain the landslide material down into the permeable material of the buried river bed, by reducing the high pressures in the vicinity of the slip surface. For the design of this drainage system, the initial condition of the underdrainage pore pressure profile needed to be modelled, essentially as a benchmarking exercise of the numerical model that would yield parameters neceassary to carry out the analysis of the drainage wells. The results of the analysis are presented in Fig. 6. Introducing the stepped distribution of the coefficient of permeability shown in Fig. 5 and an even infiltration of 1.3x10^{-9} m/s at the ground surface (which is consistent with rainfall, evaporation and transpiration data for the area) allowed a good prediction of the pore pressure profile. In agreement with the results of the numerical analysis in the theoretical model, anisotropy of the coefficient of permeability was introduced in the sub-layer of the landslide material containing the slip surface (k_v = 1/10 of k_h).

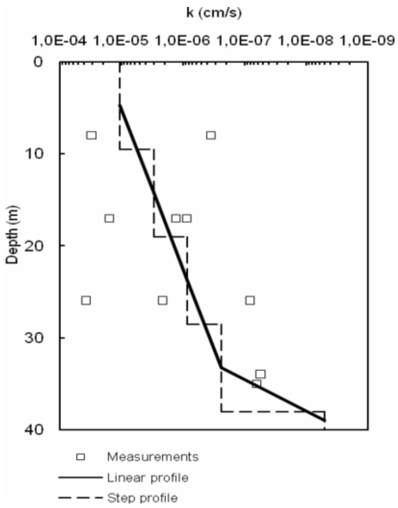

Fig. 5. Coefficient of permeability at various depths in Prinotopa landslide.

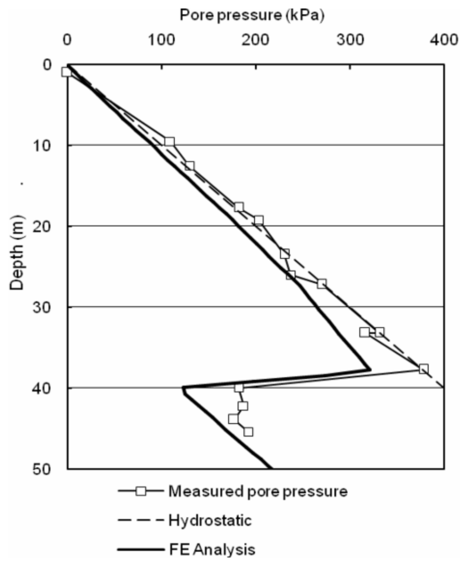

Fig. 6. Measured and predicted by FEM initial pore-pressure profile.

7 CONCLUSIONS

In order for an underdrainage pore pressure profile to be predicted in landslides underlain by permeable formations, the following should be considered:

i) Inhomogeneity of the landslide material must be introduced. This corresponds to a decrease of k with depth, which is consistent with increasing stress level with depth in landslide materials.
ii) A further decrease of k must be introduced for the zone containing the slip surface. This may be introduced by anisotropy of k, with a much lower value in the vertical direction than in the horizontal, which is consistent with the orientation of clay particles in the vicinity of the slip surface.
iii) When landslide materials are highly disturbed, anisotropy should not be introduced throughout their mass but only in the zone containing the slip surface. Introducing anisotropy in the whole landslide mass may not alter the results of the benchmarking exercise but it may result in misleading predictions when the drainage measures are introduced at the following stage of numerical investigation.
iv) Introducing inhomogeneity in the landslide mass and anisotropy in the vicinity of the slip surface does not allow the prediction of an underdrainage profile, as the fundamental requirement is the introduction of infiltration as a boundary condition at the ground surface. The actual value of infiltration, and the length along the ground surface in the model that it is applied, is more the result of a back analysis rather than exact calculation. If records of rainfall and evaporation are available, the mean value of their difference seems like a good starting point for the analyses investigating the value of infiltration to be carried out.

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