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A large-scale drainage field array to establish the effect of vertical drainage wells on underdrainage pore pressure profiles as part of a landslide stabilization scheme

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Abstract

The paper presents results from a large-scale field array of vertical drainage wells penetrating the landslide material of a large palaeolandslide in Greece overlying a buried river bed. Piezometers with Casagrande type tips were installed before drilling the wells. Monitoring of pore pressures in these piezometers allowed the measurement of the pore pressure regime in the landslide material before drilling the wells and the actual effect of the wells on this regime after they were drilled. The initial pore pressure profile established corresponded to underdrainage. The monitoring results after drilling the wells indicated considerable decrease of pore pressure in the landslide materials downstream of the wells and some decrease upstream of the wells.

Keywords: Underdrainage, Palaeolandslides, Drainage wells, Pore pressure, Non-linear profiles

1. Introduction

Palaeolandslides originating from toe erosion by a river often exhibit movement leading to coarse-grained beds being covered by landslide material. These coarse-grained beds are hydraulically connected to the river that caused the erosion. If precipitation is high and the landslide material fine-grained with a decreasing permeability with depth, the part of the landslide close to the toe can maintain a non-linear pressure profile (Bardanis et al, 2009). Near the ground surface this profile follows practically the hydrostatic distribution of pore water pressure until, at a depth close to the interface between the landslide material and the buried bed, pressure drops rapidly to equilibrate with the lower pressure in the buried river bed. This pore pressure profile is described by the term underdrainage profile. Fig. 1 describes the progressive coverage of river beds by a slow-moving landslide from the stage before the landslide occurs (Fig. 1a) all the way to the full extent of the phenomenon shown in a cross-section, a section vertical to the movement of the landslide at the part that the landslide material covers the river bed and in plan view (Fig. 1c).

If these landslide materials are penetrated by vertical wells extending into the buried river beds, the higher water pressures at the lower part of the landslide material decrease to come in equilibrium with the lower pressure in the buried river bed. Given that the sliding surface of the landslide is found at this part of the landslide, this decrease results in an increase of the factor of safety of the landslide.

The paper presents the design and monitoring of one field array constructed to establish the effect of vertical wells on underdrainage pressure profiles and the actual use of a vertical drainage wells system used as part of stabilisation measures of a large palaeolandslide in North-western Greece. The landslide was approximately of 10mil cubic meters volume, having a maximum sliding depth of 35m. The landslide originated from erosion of its toe by river flow. The array consisted of 10 25m long wells and piezometers with Casagrande type tips monitoring pressure at various depths upstream, downstream and along the line of the drainage wells. The array established the characteristic non-linear shape of the underdrainage pore pressure profile. The results from the array after drilling the wells indicated considerable decrease of pore pressure in the landslide materials downstream of the wells and some decrease upstream of the wells.

2. Field array in Peristeri landslide

2.1 Introduction

Egnatia Highway is the major highway connecting north-western with north-eastern Greece through very adverse geological conditions, especially in its western part over mountain Pindos. In Section 3.1 (Peristeri to Anthochori) in the western part of Egnatia Highway a major landslide was identified on the path of the proposed alignment. The landslide is located in flysch with present or old slide surfaces being identified at depths as large

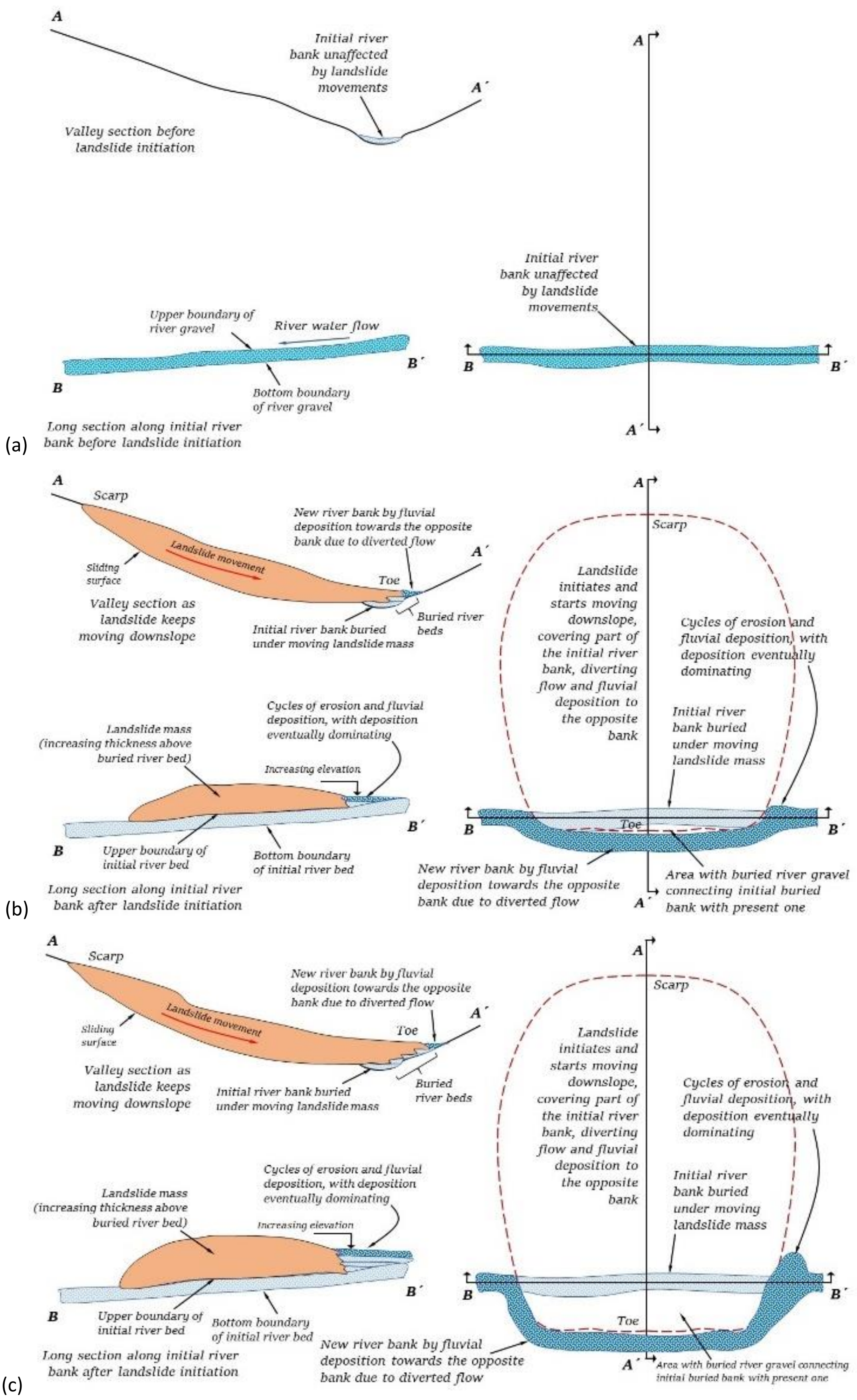

Figure 1: progressive coverage of river beds by a slow-moving landslide from the stage before the landslide (Fig. 1a) to the full extent of the phenomenon (Fig. 1c) shown in a cross-section (A-A′), a section vertical to the movement of the landslide at the part that the landslide material covers the river bed (B-B′) and in plan view.

as 35 m. It is a palaeo-landslide extending to approximately 800 m parallel to the highway alignment and more than 2 km in the other direction –coinciding with the direction of past and present movements. Inclinometers placed and monitored for more than two years at the stage of the design indicated movements only in relatively shallow depths and concentrated only in one limited area. Throughout the area of the palaeo-landslide the water table was found practically at the surface. Attempts to change the alignment in order for the highway not to pass through the landslide proved more expensive due to geotechnical problems in surrounding areas and the necessity of other major works (e.g. bridges etc). The alignment was finalised so as to pass through the landslide at its toe via a large embankment acting as stabilizing berm. Fig. 2 shows a plan of the landslide area.

The presence of the buried river-bed was identified during geotechnical investigation undertaken for the design of the highway. The bed consisted of coarse river gravel with sand, with thickness ranging between 5 and 13 m found at depths as large as 35 m and extended between 100 and 150 m from the landslide toe in a meandering fashion similar to that of the river in its present and suspected past course. Such extended coverage of the buried river-bed reveals a long travel distance of the toe of the ancient landslide. The buried river-bed is approximately 4m lower than the present river bed at its deepest point.

The landslide mass material consisted of clayey silt to silty clay with liquid limit ranging from 30% to 45% and plasticity index ranging from 13 to 25. The dry unit weight ranged from 16.8 kN/m^3 to 20.8 kN/m^3. Permeability measured in-situ ranged from 1.4x10^{-9} m/s to 9.0x10^{-6} m/s. Dry unit weight was found to increase with depth while void ratio and permeability to decrease with depth. The material of the old river-bed consisted of coarse gravel with sand with less than 7% fines in all samples recovered. Permeability measured in-situ ranged from 1.4x10^{-5} m/s to 1.7x10^{-4} m/s.

In order to investigate the ability to use the buried river-bed so as to drain the landslide, an extensive field-testing programme was undertaken. As part of this, an extensive array of large diameter vertical drainage wells and Casagrande-type piezometers for monitoring water pressures was constructed. Its position in the landslide area is shown in Fig. 2. A section of the landslide at the position of the field testing array is shown in Fig. 3.

The field testing array was monitored for more than two years. The identification of the initial pore pressure profile in the landslide mass overlying the old river-bed and the prediction of the effect of vertical drainage wells, from the results of the field-testing array, allowed the design of the stabilization measures. These included the aforementioned large embankment at the toe of the landslide and a total of two rows of vertical drainage wells through the landslide mass overlying the buried river-bed.

2.2 The field-testing array

The field-testing array consisted of ten approximately 25 m long large diameter vertical drainage wells extending from the surface to the underlying river-bed and 27 Casagrande-type piezometers with their tips at various

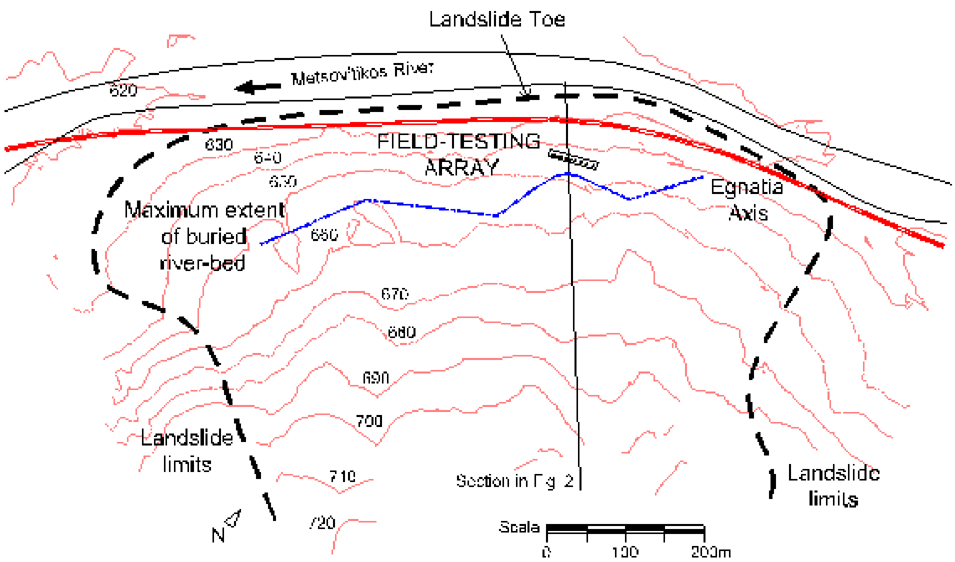

Figure 2: Plan of the Peristeri Landslide with the location of the field-testing array.

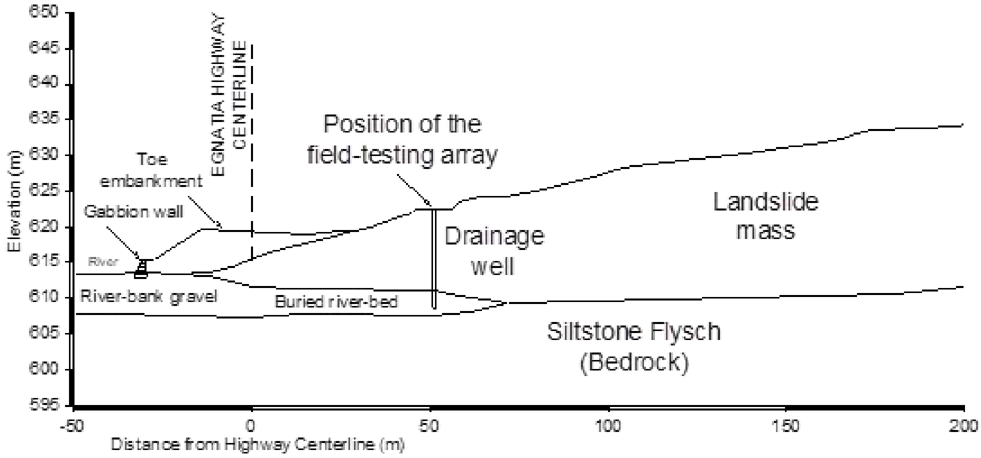

Figure 3: Section of the Peristeri Landslide at the location of the field-testing array.

depths and positions relative to the drainage wells. The layout of the array is shown in Fig. 4 along with a typical section and a photograph of the field-testing array. The drainage wells were placed on a straight line at different spacings. Wells F1 to F4 were placed at a spacing of 4 m, F4 to F7 at a spacing of 6 m and F7 to F10 at a spacing of 8 m. At the middle of each part of the array with equal well-spacing, three triplets of Casagrande-type piezometers were placed. One triplet was placed 4 m upstream of the array, one 4 m downstream of the array and one on the axis of the array. Each triplet of piezometers consisted of three piezometer tips placed at different depths in separate boreholes drilled at distances of 1 m. The shallow piezometers of each triplet were placed at a depth of 8 m, the medium-depth ones at 16 m and the deepest ones at a depth between 20 and 22 m (between 1 and 2 m above the old river-bed). The piezometers were installed prior to the construction of the vertical drainage wells and water levels were monitored in order to establish the water pressure profile in the landslide mass. Once pore pressure equilibration in the piezometer tips was achieved and all falling- and rising-head permeability tests in the piezometer tips finished, the drainage wells were drilled and the evolution of the water pressure profile due to their presence was monitored for more than two years. The next section discusses the initial pore-pressure profile identified, the effect of the well-spacing, the position relative to the array, and the variation of well influence with depth.

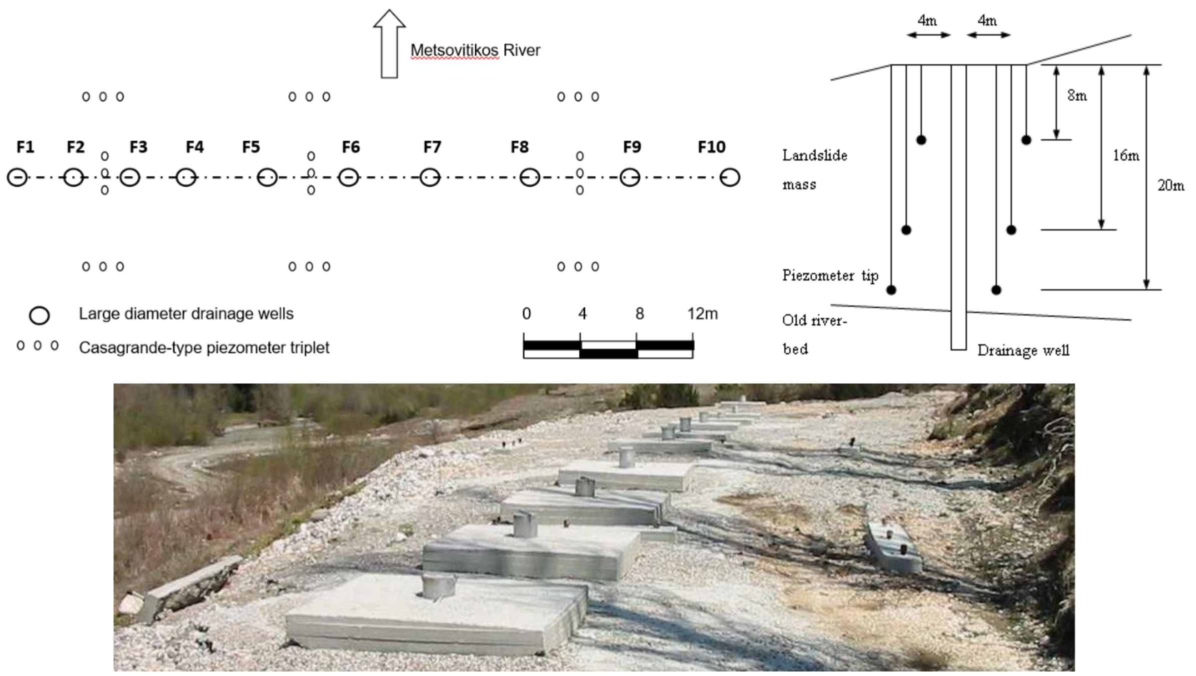

Figure 4: Plan view of the array (top left), typical section (top right) and the actual field testing array (bottom).

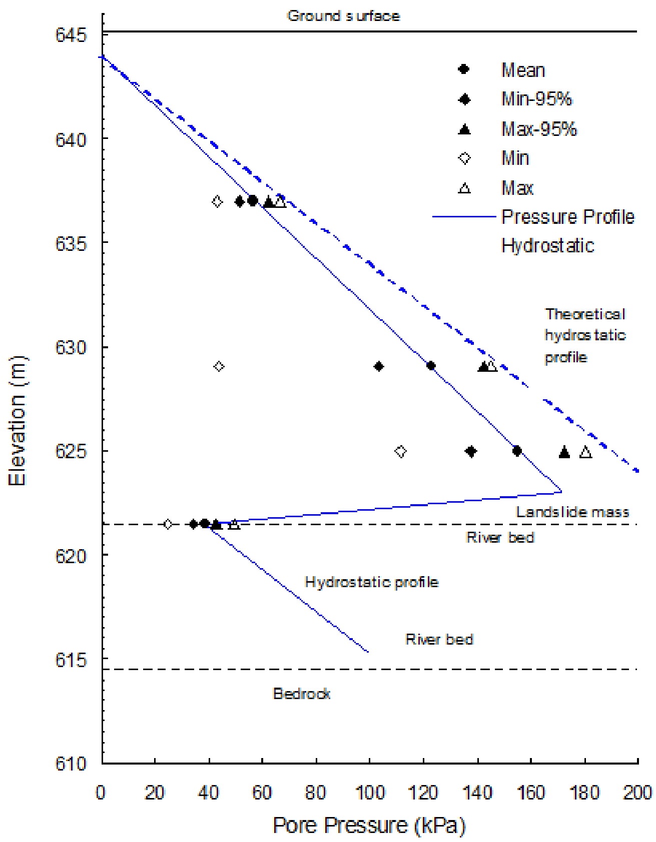

Figure 5: Initial pore-pressure profile in the landslide mass overlying the old river-bed.

2.3 Initial pore-pressure profile

The piezometers were installed prior to the construction of the vertical drainage wells. Average values of pressure at each depth, absolute minimum and maximum values of pressure and minimum and maximum values at a confidence level of 95% are plotted with depth in Fig. 5. An average pressure of approximately 40 kPa is measured in the drainage wells as the buried river-bed in the area of the field-testing array lies approximately 4 m below the river level at its present course. The initial water pressure profile indicated the presence of water table at only 1 m from ground surface, increase of water pressure by approximately 80% of the hydrostatic distribution down to 2-4 m above the river-bed, followed by a rapid decrease to the much lower pressure in the river-bed, as indicated by the water levels in the wells. The identified pore pressure profile is a typical underdrainage pressure profile. Similar pressure profiles have been identified and reported by numerous researchers (e.g. Kennard & Reader, 1975, Vaughan & Walbancke, 1975, Bromhead & Vaughan, 1980, Vaughan et al, 1983, Vaughan, 1989, Vaughan, 1994). Their presence is attributed to the difference in permeability between overlying (less permeable) and underlying (more permeable) materials, decreasing permeability with depth and infiltration from the surface (a numerical investigation of these factors may be found in Bardanis et al, 2009).

2.4 The effect of the drainage well spacing

Fig. 6 shows pore pressure recorded in downstream-of-the-array piezometers at a depth of 20 m for each well spacing versus time. After 2 years of operation, the pressure had decreased by approximately 50 % in the piezometer at the wells with 6m spacing and only 25 % in the piezometer at the wells with 8m spacing. The downstream triplet of piezometers monitoring the 4m spacing wells was lost, due to the failure of the embankment they were drilled from, after 8 months of operation. Comparing the decrease by that time, for 4m spacing the reduction had reached 25%, for 6m spacing 20% and for 8m spacing no reduction had been recorded. Similar differences were noticed for all piezometers at the same depth and position relative to the array for different well spacing, indicating that pore pressure reduction is larger for closer spacings as expected. For the permeability of the landslide material in the area spacings above 6-7 m proved practically incapable of achieving any significant pore pressure reduction even after two years of operation of the wells.

2.5 The effect of the position relative to the array

Fig. 7 shows pore pressure recorded in piezometers at a depth of 16 m for 6m well spacing placed downstream, upstream and on the axis of the array versus time. After 2 years of operation pressure had decreased by approximately 35% in the piezometer downstream of the array, 35% in the piezometer on the axis of the array and only 25% in the piezometer upstream of the array. Similar differences were noticed for all piezometers at the same depth and well-spacing for different positions of the piezometers relative to the array, indicating that pore pressure reduction as a result of the presence of the drainage wells is increasing as we move from upstream to downstream.

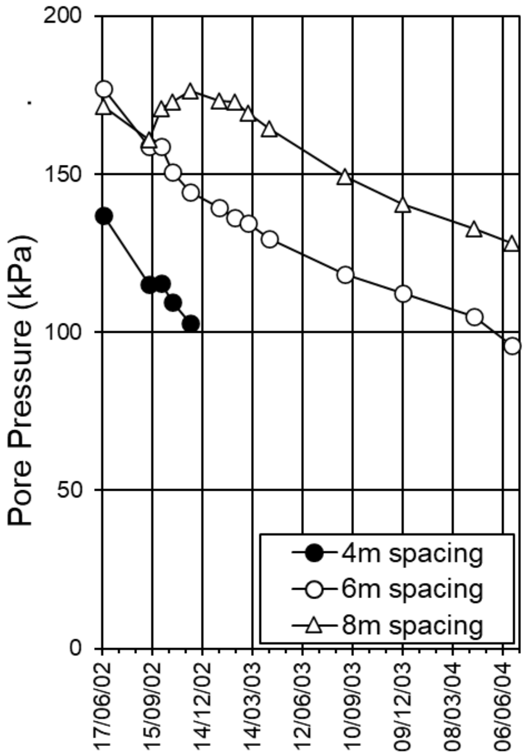

Figure 6: Pore-pressure evolution of downstream of the array piezometers at 20m depth for all well spacings.

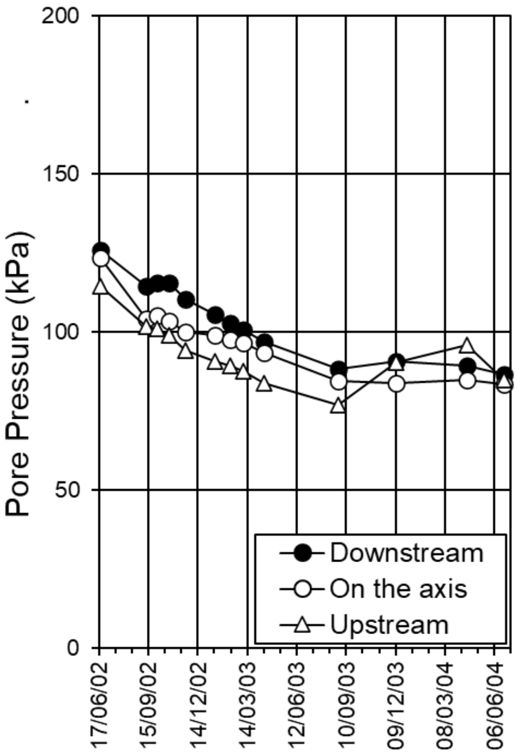

Figure 7: Pore-pressure evolution of 16m depth piezometers for 6m well spacings.

2.6 The effect of depth

Fig. 8 shows pore pressure recorded in piezometers at all depths and all well spacings placed downstream of the array versus depth. Different curves correspond to different times. It may be seen that pressure profile curves seem to 'rotate' with time in such a way that pressure reduction is larger at depth and very small (if any) at shallow depths. This is apparently due to infiltration causing continuous recharge near the surface. At depth, given the low permeability of the landslide material, infiltration from the surface cannot cause recharge and the drainage wells achieve drainage (reduction of pore pressure). As already discussed in Par. 2.4, this reduction with depth is increasing with decreasing well spacing. This may also be seen in Fig. 8 as in Fig. 8a (4m spacing) the apparent 'rotation' of the pressure profile curves is larger than that for the corresponding times in Fig. 8b (6m spacing) and even larger for the corresponding times in Fig. 8c (8m spacing). Especially for the 8m well spacing this phenomenon is limited to very large depths only as the spacing is too large for any decrease in pressure to be achieved even at depths as large as 16m.

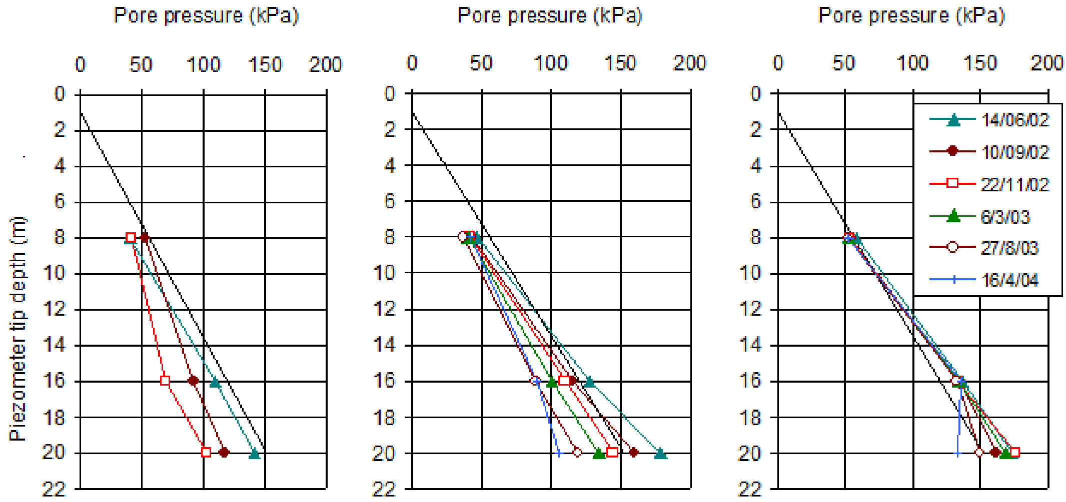

Figure 8: Pore-pressure in downstream-of-the-array piezometers for (left) 4m well spacing, (middle) 6m well spacing and (right) 8m well spacing with depth. Curves for various times. Solid extended line corresponds to part of the initial pressure profile in the landslide mass (before the rapid decrease).

3. Conclusions

Large diameter vertical drainage wells extending from the surface to the underlying permeable soils may effectively lead to the reduction of pore water pressure in the overlying low-permeability soil merely by gravitational drainage. The reduction in pore water pressure due to the presence of such drainage systems increases with decreasing well-spacing and increasing depth as at small depths, recharge due to infiltration is more pronounced. Similarly, in sloping ground like that in Peristeri Landslide the reduction of pore water pressure is more pronounced downstream of the drainage wells probably due to the interception of the near-surface flow.

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