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Highway slope stabilisation by a drainage tunnel - A parametric study
Stabilisation de la pente d'une autoroute par tunnel de drainage - Une etude parametrique

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ABSTRACT: Seepage finite element analyses have been carried out to assess the effectiveness of a drainage tunnel along 4km of the Egnatia highway in Greece. The highway passes through unstable ground (old and recent landslides), where ground water controls stability. A drainage tunnel was proposed as a stabilisation measure, providing large scale drainage. Parametric studies have been conducted in terms of permeability. The influence of vertical drains constructed above the tunnel was investigated. It is concluded that the tunnel is an effective means of drainage, but the time to achieve an acceptable reduction of the pore pressures varies from days to years depending on permeability.

RÉSUMÉ: Des analyses utilisant la methode des elements finis ont été conduites pour évaluer l'éfficacité d'un tunnel de drainage sur quatre kilometers au bord de l'autoroute Egnatia en Gréce. L'autoroute traverse un terrain instable (glissements de terrain anciens et recents), ou l'eau souterraine controle la stabilité. Un tunnel de drainage a été proposé comme solution pour stabiliser le terrain permettant ainsi un drainage a grande échelle. Des études paramétriques ont été menees en fonction de la permeabilité. L'influence de drains verticaux construits audessus du tunnel a été etudieé. On peut conclure que le tunnel est une solution efficace de drainage parce que le temps requis pour une réduction suffisante des pressions interstitielles des pores peut valoir des jours comme des anneés selon la permeabilité du sol.

1 INTRODUCTION

The Egnatia highway in Greece, which is presently under construction, is a 680km long road

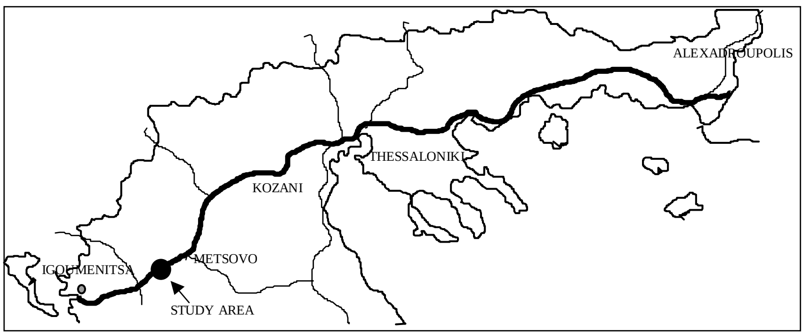

Figure 1. The route of Egnatia Highway in Northern Greece.

crossing the northern part of the country from east to west (Fig. 1). In the west the highway crosses the Pindos mountain range (Epirus region), which is considered to be one of the most geotechnically challenging parts of the route due to the presence of the flysch, which is the dominant geological formation in the area and can cause major instabilities.

As part of the finalisation of the highway routing near the town of Metsovo, studies were performed in order to examine the feasibility and cost of alternative routes. The work presented in this paper deals with a 4km long part of the highway, which was initially selected on the basis of topographical rather than geotechnical criteria. The area in fact consists of many old and recent landslides, screes and places with marginal stability. The available geotechnical data at the time of the studies were very scarce. Design was to be performed under some considerable uncertainty. Water appeared to be a critical factor controlling stability. Hence, it was decided to investigate the feasibility of stabilisation by drawing down the phreatic surface using a tunnel running parallel, in plan, to the highway. Drainage tunnels have been used extensively, worldwide, to stabilise landslides. The advantages of drainage methods were reported by Hoek & Sharp (1970) while Valore et.al. (1987) examined the optimum location of a drainage tunnel.

This paper presents a parametric study using finite element analysis to assess the effectiveness of the drainage tunnel as well as the time needed for the lowering of the phreatic surface. Various assumptions were made regarding the coefficient of permeability. The long term pore water pressure distribution predicted from the analysis was then used to assess the improvement in slope stability using Limit Equilibrium.

2 GEOLOGY - SITE CONDITIONS

The Pindos mountain range is a surface expression of part of the Pindos zone which is largely composed of highly contorted flysch, thin bedded limestone and cherts. The Pindos range was formed by deep sea carbonate and silicate sedimentation from the Triassic to the upper Cretaceous, followed by the deposition of the Eocene flysch. Flysch is composed mainly of sandstone and mudstone/siltstone layers. The sediments have been subjected to high stressing, due to the tectonic activity of the area, and have been faulted and folded.

The slopes, along the chainage under examination, have been subjected to large scale movements. These movements have been recorded in recent years (creeps, flows, landslides) while the older ones have been imprinted in characteristic landscape forms in the area. Dounias & Marinos (1993) have classified the complex modes of flysch failure, which exhibits in some cases soil-like behaviour, in other rock-like behaviour and occasionally some complex combinations.

Particular to the site is a relatively thick cover of colluvium which blankets the slopes while the outcrops of in-situ flysch are limited (Fig. 2). Colluvium is the product of weathered flysch, at some sections up to 40m deep, which has been transported from its site of origin by gravity and has degenerated into a cohesive soil with rock fragments. At the toe of the slopes flows the Metsovitikos river, which is the main drainage artery of the area. The river contributes to slope erosion and thus instability.

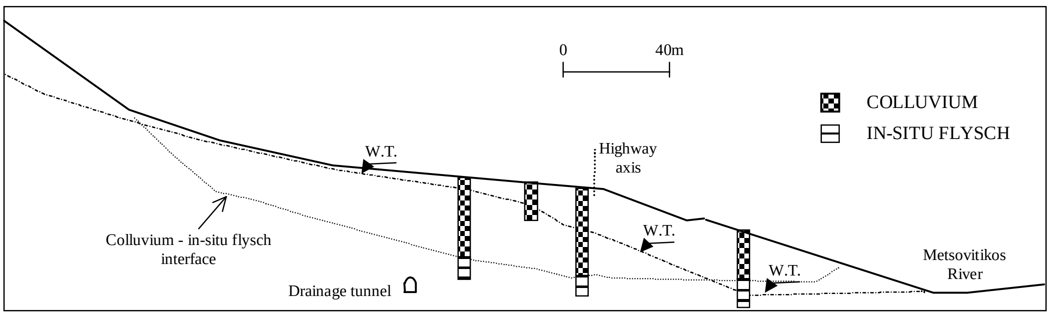

Figure 2. Typical cross section and geological profile of the study area.

3 PROPOSED DRAINAGE MEASURES

The drainage tunnel, 4300m long, was to be constructed upslope and running parallel to the highway. It was planned to bore through competent in-situ flysch, below the colluvium, in order to allow easy construction and to avoid re-activation of any landslides. It was to be located at an elevation just above the river bed (Fig. 2). Drainage of the unstable mass was to be achieved by gravity. To accelerate draw down of the phreatic surface, and to penetrate any perched water tables, a line of vertical drainage wells (30cm in diameter) were to be sunk at reqular intervals (15 - 25m), from the ground surface down to the crown of the tunnel.

4 SEEPAGE FINITE ELEMENT ANALYSES

The Imperial College Finite Element Program (ICFEP) has been used to carry out all the analyses presented. A coupled consolidation formulation was used to trace the process of phreatic surface draw down with time to the final steady state. Figure 3 illustrates a finite element mesh corresponding to the geometry of Figure 2.

Two material types have been modelled in the finite element mesh, in-situ flysch and the overlying colluvium. The mesh itself consisted of eight noded plane strain isoparametric, quadrilateral elements. Both displacement and pore pressure degrees of freedom existed at the corner nodes, and displacement degrees of freedom at the mid-side nodes. The mesh was extended 350m upslope from the drainage tunnel and downslope to the centre of the river. The upslope distance was assumed to be outside the zone of influence of the tunnel. The finite element mesh is finer around the tunnel and along the phreatic surface.

The drainage tunnel has a horse shoe cross section of width 3.6m and height 4.6m. Analyses were performed assuming plane strain conditions. The vertical drainage wells were modelled by a column of thin solid elements (30cm wide) above the tunnel crown. In reality flow to the vertical wells would not be in the plane analysed here. An increased permeability was ascribed to these elements to assess the effect of preferential drainage.

Both prescribed displacement and pore water pressure boundary conditions were specified for the two vertical boundaries of the mesh as well as for the base (Fig. 3). The vertical boundaries of the mesh were horizontally restrained whereas the base was both horizontally and vertically restrained. Down the vertical boundaries of the mesh hydrostatic pore water pressures were specified and hence each of them was assumed to be an equipotential line. The lower boundary of the mesh was assumed to be impermeable and hence a flow line.

4.1 *Soil parameters for the analyses*

There was limited soil data available from laboratory tests carried out on samples recovered from very few boreholes at the site. There was insufficient information to employ a non-linear elasto-plastic model for the analyses. So a linear elastic constitutive model used specifying Young’s Modulus E'=4000MPa and Poisson’s ratio v'=0.20 for the in-situ flysch and E'=15MPa and v'=0.25 for the colluvium.

A parametric study has been carried out to examine the effect of permeability on the time for lowering the phreatic surface (locus of points with zero pore water pressure). Three coefficients of permeability were examined, $k=10^{-6}$, 10^{-7}, 10^{-8}m/sec, while the soil was assumed to be isotropic and homogeneous with respect to permeability. The permeability of the vertical drains was assumed 100 times higher than that of the surrounding soil.

4.2 *Procedure of the analyses*

Each analysis was divided into three stages and each stage into a series of time increments. At the 1^{st} stage, before tunnel excavation, the phreatic surface, initially at the ground surface was

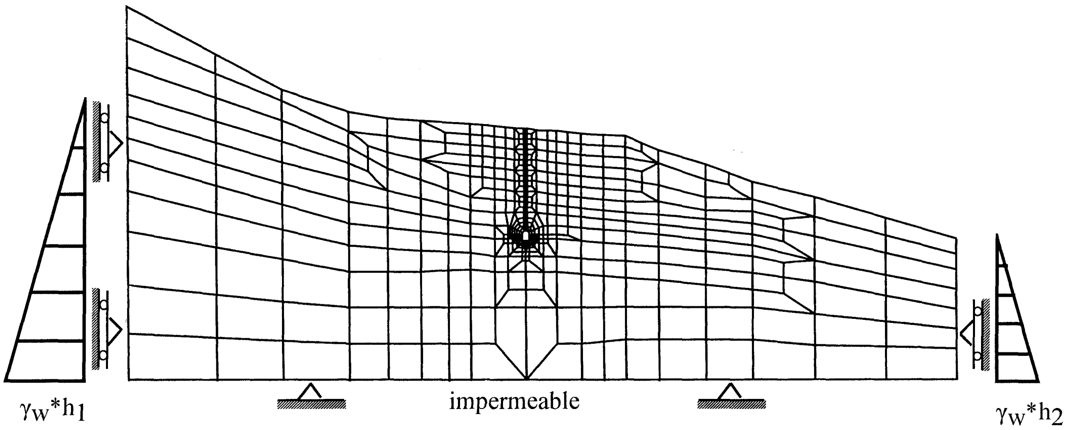

Figure 3. Finite element mesh with boundary conditions.

allowed to reach equilibrium with respect to the specified pore water pressure boundary conditions. As the phreatic surface dropped the water table remained unchanged, implying continuous infiltration, so suctions developed above the phreatic surface. The upslope boundary condition was adjusted so that at the end of the 1st stage the contour of zero pore water pressure matched the observed water levels in the boreholes. ICFEP models unconfined flow by reducing the permeability of soil sustaining tensile pore pressures (Fig. 4). If the accumulated pore water pressure is more compressive than p_1 the soil's specified permeability is adopted, whereas if it is more tensile than p_2 it is reduced by a factor R equal to 100. If the pore pressure is between p_1 and p_2 the permeability is found by using a linear interpolation between the two extreme k_{max} - k_{min}.

The 2nd stage modelled the excavation of the tunnel by removal of the solid elements within the tunnel boundary. During the excavation, drainage toward the tunnel was not allowed.

At the 3rd stage drainage to the tunnel was modelled. The tunnel was treated as drain using a special boundary condition which prevents water being drawn across the boundary at nodes where suction exists in the adjacent soil, but permits free flow at nodes where the soil water pressures are compressive by prescribing zero pore pressure at the relevant nodes.

5 RESULTS OF THE ANALYSES

Two different analyses have been carried out for each coefficient of permeability, without and with vertical drains. Figure 5 summarises the results obtained for both analyses, showing the phreatic surface position for various elapsed times. An order of magnitude reduction in permeability gives an order of magnitude increase in the time to reach steady state. In the long term the phreatic surface has dropped beneath the colluvium - in-situ flysch interface which is considered as a pre-existing shear surface. The phreatic surface in its final profile is fully drawn down to the tunnel. The final pore water pressure drop ranges from about 320Kpa immediately

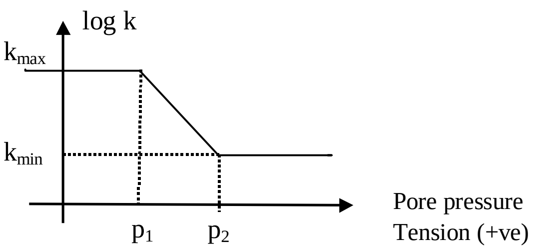

Figure 4. Values of permeability with respect to suction

above the tunnel to about 160 Kpa one hundred meters upslope and downslope of the tunnel.

The presence of vertical drains accelerated the draw down of the phreatic surface only within a zone 50 - 60m around the tunnel. Although their construction does not influence the time needed for reaching long term conditions in the whole slope, they do have a rapid local effect.

During the draw down of the phreatic surface the slope undergoes displacements due to the process of consolidation. The maximum settlement of the ground surface due to the draw down to the tunnel was approximately 40cm above the tunnel, and 20cm at the location of the highway. The settlements took place mainly within the colluvium due its low stiffness in comparison to the

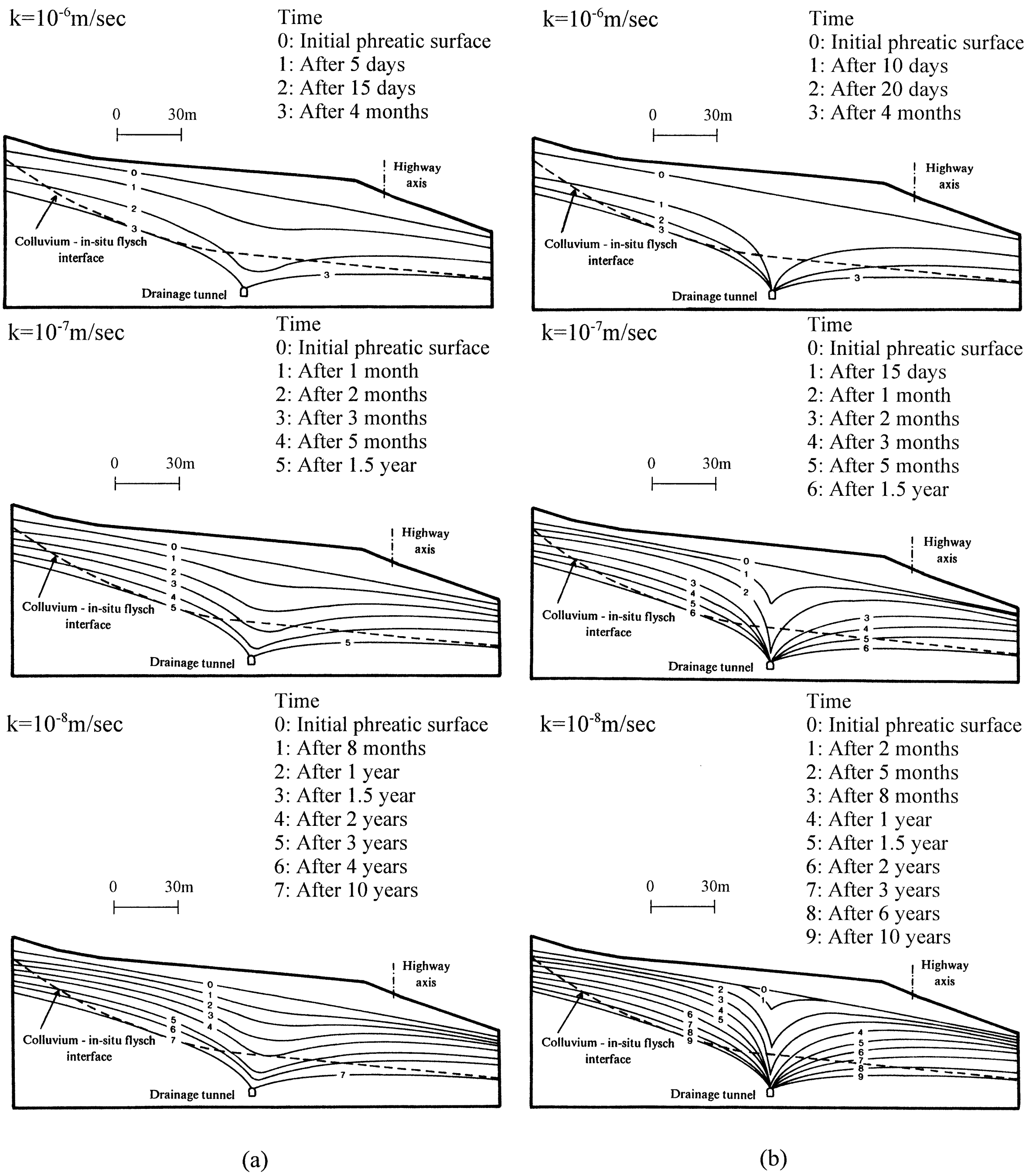

Figure 5. Rate of draw down of the phreatic surface. Analyses (a) without and (b) with vertical drains

stiffness of the flysch. These are not considered to be accurate predictions as the soil was not permitted to desaturate and the linear stiffness that was assumed may be unrealistic.

6 SLOPE STABILITY ANALYSIS

The effect of the drainage tunnel on improving the stability of the slope has been expressed in terms of changes in the factor of safety before and after drainage. The slope section has been analysed using Limit Equilibrium under drained conditions. The slope stability analysis concentrated on the danger of re-activation of a deep landslide along the interface between the colluvium and the in-situ flysch. Janbu's simplified method was used due to the non-circular geometry of the shear surface. The slope was considered just stable, i.e. F=1.0, before drainage which gave average Mohr-Coulomb criterion strength parameters along the interface: $c'_r=0$ and $\varphi'_r=12.45^o$. Using these parameters (i.e. making no allowance for strength gain during consolidation) the factor of safety after drainage was calculated to be F=1.265, an increase of 26.5%.

7 CONCLUSIONS

The analyses proved the effectiveness of the drainage tunnel as a stabilisation measure. The time to achieve an acceptable degree of drainage is however very sensitive to permeability. The need for a realistic assessment of the coefficient of permeability is thus highlighted as the need for adequate draw down may severely delay the construction programme. Any significant differential settlements predicted by a realistic fully coupled analysis must be designed to have taken place prior to pavement construction.

These analyses indicated that the inclusion of vertical wells gave benefit in draw down locally, but that the overall time to steady state was not reduced. It may be that vertical drains in combination with radial drainage holes from the tunnel and other drainage solutions from the surface may reduce the time needed to reach long term conditions within an acceptable engineering time scale.

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