Increase of slope stability with time by drilled drains

L'Augmentation de stabilité des talus dans le temps par les drains forés

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ABSTRACT

Drilled drains are installed in cases when the unfavorable groundwater regime is one of the main causes of slope instability. The time required for achieving the satisfactory factor of safety has to be calculated for effective application of drilled drains. The analysis of performance and effectiveness of drilled drains requires the application of 3D seepage models. The application of 3D models is, however, not practical due to their complexity in defining spatial relations in the slope and they are rarely used. As opposed to 3D models, 2D models can incorporate geometrical and material heterogeneities in vertical planes and they are relatively simple to use and apply. The research on this topic has examined the possibility of the application of 2D models in cases of slopes with installed drilled drains. The applicability of this solution for the calculation of the increase of slope stability with time was also examined. The research results enabled us to define a procedure for analyzing the influence of drilled drains on the increase of slope stability with time with the use of 2D models with the appropriate selection of equivalent drain permeability.

RÉSUMÉ

Les drains forés sont installés dans les cas où le régime des eaux souterraines est un des causes principales de l'instabilité du talus. Le temps nécessaire pour obtenir le coefficient de sécurité nécessaire doit être calculé pour garantir l'efficace des drains forés. L'emploi des modèles d'infiltration 3D serait nécessaire dans l'analyse de comportement et efficacité des drains forés. Néanmoins, l'emploi des modèles 3D n'est pas pratique car la définition des relations spatiales dans le talus à l'aide de ces modèles est très complexe et, pour cette raison, ces modèles sont utilisés rarement. Par contre, les modèles 2D sont à même d'incorporer les hétérogénéités géométriques et matérielles dans les plans verticaux, et leur emploi et application est assez simple. La possibilité d'application des modèles 2D pour les talus avec les drains forés déjà en place a été examinée. L'applicabilité de cette solution pour le calcul d'augmentation de la stabilité de talus dans le temps a été analysée. Les résultats de cette étude nous ont permis de définir la procédure pour analyser l'influence des drains forés sur l'augmentation de stabilité de talus dans le temps en utilisant les modèles 2D, et en choisissant la perméabilité équivalente des drains.

Keywords : slope stability, horizontal drains, consolidation

1 TWO DIMENSIONAL ANALYSIS OF HORIZONTAL DRAINS IN SLOPES

1.1 *Slope stabilization with drilled drains*

Water is one of the main causes of slope instability. The slope stability can be greatly improved by reducing the effect of the seepage forces by installing horizontal drilled drains. Such drains affect the direction of seepage, reduce the groundwater levels and cause soil consolidation and the reduction in the water content. All these effects result in the increased shear strength of the soil.

Horizontal drilled drains are used for stabilization of slopes with deep slip surfaces. They are constructed of small diameter perforated pipes installed at a desired spacing in order to change the seepage directions and to create drainage path for removing water form the slope. The use of horizontal drains dates back to 1939 when the California Division of Highways (CDH) successfully stabilized 53 landslides using this technology (Stanton 1948). Today, the horizontal drains are widely used as a method for improving the stability of unstable slopes.

Since the time of first application and the description of their effects on stability, several review articles have been published documenting the effectiveness of properly installed drains in a variety of geological and hydrological settings (Smith and Stafford 1957; Rico at al. 1967; La Rochelle at al.1977). All the authors emphasize the importance of developing rational design methods for selecting proper position and size of the drains. Majority of the papers highlight the dominant effect of the change in the seepage direction, i.e. redistribution of pore pressures, as opposed to the amount of water drained from the slope, in order to achieve the stabilization effects.

When using horizontal drains for slope stabilization it is necessary to define the location of the drains with respect to the slip surface, i.e. their elevations, length and spacing, as well as the time required for the stabilizing effects to take hold. Length and spacing are often determined by the design engineer from experience, not necessarily leading to the optimal and most economical solution. The need for rational design criteria led to the publication of a number of papers containing various design charts (Choi 1974, Kenney et al. 1977; Prelwirz 1978; Nonveiller 1981, Stanić 1984; Resnik and Znidarčić 1991). Some of the design charts were obtained from the analyses of model tests (Choi, 1974, Kenney et al., 1977; Resnik and Znidarčić, 1991). Most of these papers considered only geometric characteristics of location, length and spacing, while the work by Nonveiller (1981) included the time component as well.

1.2 *Solution methods*

For the three dimensional geometry (Figure 1) Nonveiller (1981) obtained the excess pore water pressure distribution

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upon drain installation as the difference between steady state pressures in the slope with drains (3D analysis) and the slope without drains (2D analysis) at homologous points. The three dimensional diffusion (consolidation) equation was then solved to evaluate the length of time needed to reach the new steady state pore pressure distribution within the slope with installed horizontal drains.

The analyses results were presented in a series of dimensionless design charts which relate the increase in the factor of safety to drain length, spacing and the coefficient of consolidation of the slope material. While the presented design charts provide some guidance on the required time to reach the desired stabilization effects in homogeneous slopes with a constant coefficient of consolidation, they do not provide an engineer with enough flexibility to adopt the solution to a realistic stratigraphy of an actual slope. More recent numerical tools provide an opportunity to revisit the problem and offer an alternative approach for solving the time dependent problem with more flexibility for designers.

Commercially available software SEEP/W provides solutions to transient seepage problems in unsaturated soils using the finite element technique. In addition to the geometric and stratigraphic data the two dimensional model requires at input the soil water retention characteristics (SWRC) as well as the hydraulic conductivity function (HCF). For a specified initial head distribution the program provides the time dependent head changes in response to the boundary condition changes until the new steady state condition is reached. The time dependency of the process stems from the storage capacity of the unsaturated soil as described by the SWRC. Mathematically, the transient problem due to the storage in unsaturated soils is identical to the consolidation problem due to the soil compressibility. Thus, the SEEP/W program can be used to analyze the consolidation process due to installation of drains in a slope with compressible material. For a specified coefficient of consolidation the SWRC should include, in the positive pore water pressure range, a slope that corresponds to the oedometric modulus for the soil which in combination with the hydraulic conductivity generates the given coefficient of consolidation. Thus, the consolidation analysis of a slope stabilized with horizontal drains is performed in two steps. First, the steady state seepage solution is obtained for the slope without the drains. Second, taking this steady state as the initial condition the boundary conditions at the drain location are changed and the transient analysis is performed until the new steady state is reached. The factor of safety can then be calculated at any time during the transient process.

The two dimensional SEEP/W program allows only a blanket drain to be considered in the analysis. However, as is described in the next section, an "equivalent" hydraulic conductivity for the drain material could be defined so that the obtained pore water pressure distribution corresponds to the "average" pore pressure at the drain location and in between the drains.

1.3 *The equivalent conductivity hypothesis*

The basic idea is that the slope with the installed drains at a distance S could be modeled as a slope with a blanket drain as long as the hydraulic conductivity of the drain material kd is adjusted so that the distributions of heads in the 2D case is similar to the average heads distribution in the slope with tubular drains, the 3D case (Figure 1).

The equivalent hydraulic conductivity kd is determined by adjusting its value and comparing the head distributions to those obtained by Nonveiller (1981) from the three dimensional analysis for the same slope.

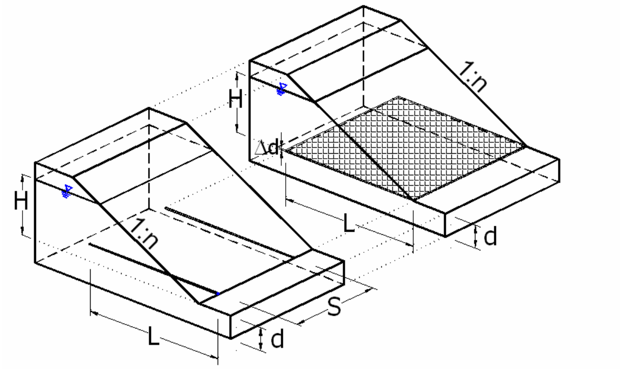

Figure 1 The slope model with drains installed at a distance S and with the blanket drain.

In order to determine the equivalent hydraulic conductivity for the blanket drain, a number of seepage analyses using the numerical model SEEP/W were performed. In the analyses the hydraulic conductivity for the soil ks was constant while the blanket drains hydraulic conductivity kd was changed over the desired range of values. The analyses were performed for the slope and boundary conditions shown in Figure 2.

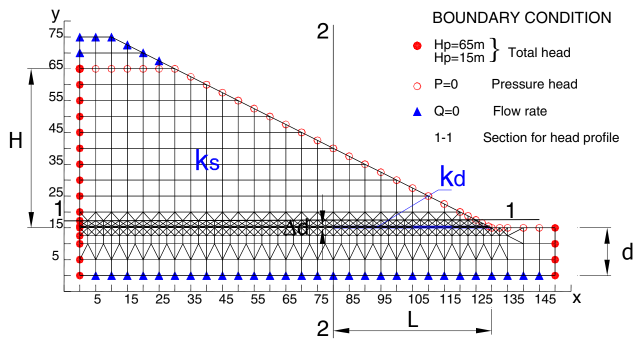

Figure 2 Slope model for SEEP/W analyses.

From the analyses, a relation between the hydraulic conductivity of the drain kd with the thickness Δd, and the soil hydraulic conductivity kt, total head H, drain length L at a distance S is obtained in the form (1):

$$\left(\frac{kd}{kt}\cdot\frac{\Delta d}{H}\right)=1.2\left(\frac{L}{S}\right)+6.09\cdot 10^{-15} \quad (1)$$

An approximate expression for the equivalent hydraulic conductivity of the blanket drain kd can be written as (2):

$$kd \cong 1.2\cdot kt\cdot\frac{H}{\Delta d}\cdot\left(\frac{L}{S}\right) \quad (2)$$

This relation is then used to establish the equivalent hydraulic conductivity used in the two dimensional SEEP/W analyses for a particular case of drain length, spacing and soil hydraulic conductivity.

1.4 *Comparison between two and three dimensional analyses*

Using the calibrated equivalent hydraulic conductivity values for the blanket drain, several cases of the three dimensional analyses reported by Nonveiller (1981) were simulated using the two dimensional model SEEP/W. Figures 3 to 5 compare the two analyses. The dashed lines are from the 3D solution while the shaded areas are from the SEEP/W 2D analysis. While the differences are visible the two results are in a general agreement, verifying the adopted methodology.

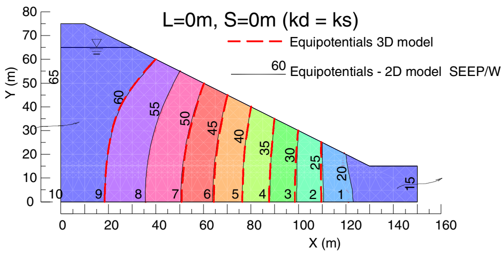

Figure 3 Equipotentials for slope n = 1:2,L=0m, S=0,kd=ks.

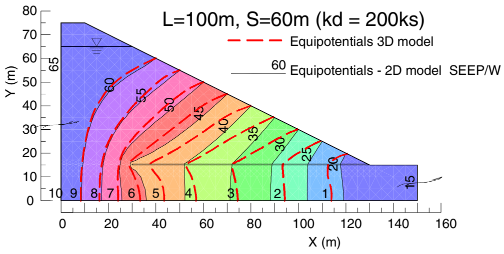

Figure 4 Equipotentials for slope n=1:2,L=100m,S=60m,kd=200ks.

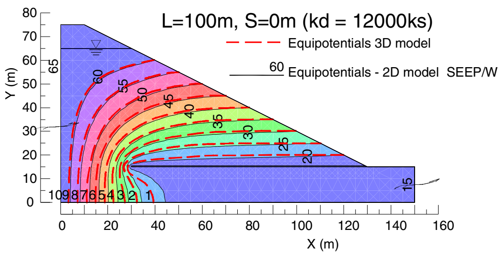

Figure 5 Equipotentials for slope n=1:2,L=100m,S=0m,kd=12000kt

Figure 6 compares the 2D (lines) and 3D (dots) seepage results for the vertical plane at the end of the drain (section 2-2 in Figure 2), while Figure 7 compares the results for the plane just above the drain (section 1-1 in Figure 2). Again the general agreement between the two solutions is noted.

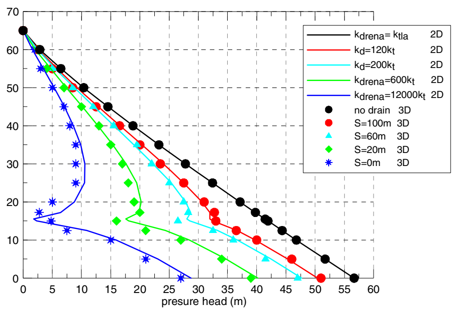

Figure 6 Pressure head from 2D (lines) and 3D (dots) model in vertical plane at the end of the drain, L=100m.

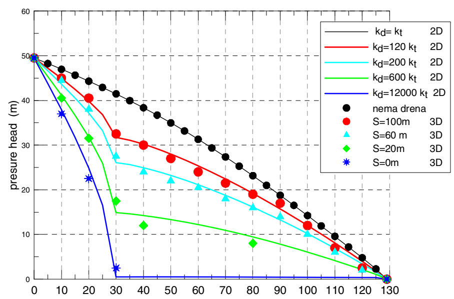

Figure 7 Pressure head from 2D (lines) and 3D (dots) model in the horizontal plane just above the drain, L=100m.

1.5 *Comparison of the factor of safety from 2D and 3D seepage analyses*

To further verify the equivalency of the 2D and 3D analyses the slope stability factors of safety were calculated for two slope geometries and seven potential failure surfaces in each. For slope with the inclination of 1:2 the shear strength parameters were c=26 kN/m^2, and ϕ =29^0, while for the slope with an inclination 1:3 the shear strength parameters were c=22 kN/m^2, and ϕ =22^0 (Figure 8).

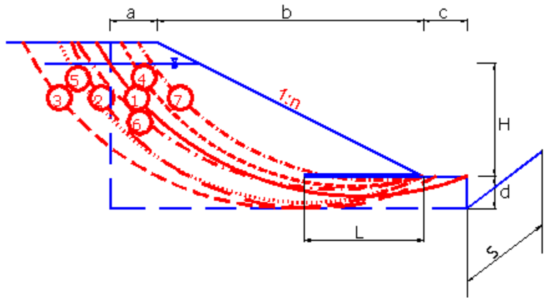

Figure 8 Geometry of the analyzed slope with slip surfaces.

Figure 9 presents the results from the slope stability analyses. On the abscissa are the factors of safety values obtained with the 3D seepage analysis results and on the ordinate are the factors of safety values obtained with the 2D seepage analysis results.

While there are some differences in the two values in general there is a good agreement between the two approaches, certainly within the usual values in the engineering practice.

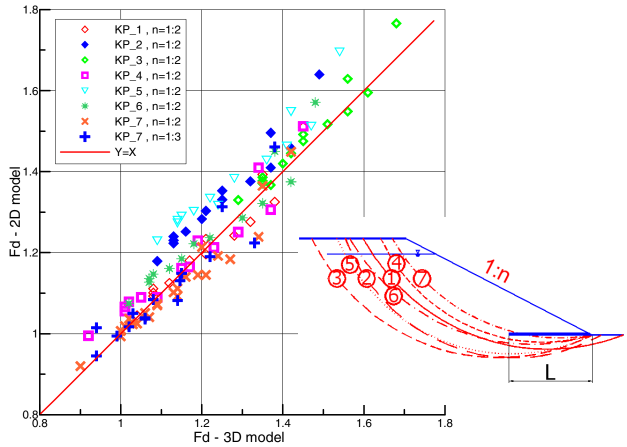

Figure 9 Factor of safety comparison.

2 EFFECT OF DRAINS ON THE FACTOR OF SAFETY INCREASE WITH TIME

The numerical model SEEP/W was used to calculate the transient seepage from the state of slope with no drains to the fully consolidated state after the drain installation, when the new steady state seepage regime is established. The analyses were performed with the equivalent hydraulic conductivity for the blanket drain kd corresponding to the drain lengths of L=50, 75, 100m and drain spacing of S=10, 20, 60, 100m for a 1:2 slope.

In order to compare the results obtained from the 2D seepage analyses presented here with the Nonveiller (1981) results from the 3D seepage analyses the value of the coefficient of consolidation c_v=10^{-3} (m^2/s) was selected for the slope material.

The coefficient of consolidation c_v is related to the oedometer (constrained) modulus by the following expression (3):

$$c_v = \frac{k \cdot M'}{\gamma_w} \quad (3)$$

In which M' –oedometer modulus (kPa), k – hydraulic conductivity (m/s), γ_w– unit weight of water (kN/m3)

Two functions are required for the transient analysis in the SEEP/W numerical model. The soil water retention characteristics (SWRC) and the hydraulic conductivity function (HCF). For the HCF the constant values of hydraulic conductivity for the soil and the equivalent hydraulic conductivity for the drain are selected. For the SWRC the volumetric water content is related to the pore pressure (or suction). At the pore pressure of zero (saturated state) the volumetric water content is equal to the porosity while for the positive pore pressures the slope m_w=1/M'of the SWRC is equal to the inverse of the oedometer modulus M'. At the desired times during the transient analysis the pressure head distributions from the SEEP/W model are imported into the SLOPE/W model in order to calculate the time dependent changes of the factor of safety for the critical failure surface.

The gain in the factor of safety at any time during the transient state is calculated by the normalized expression (4):

$$F_g = \frac{F_d - F_t}{F_d - F_0} \quad (4)$$

In which F_0 – factor of safety for the slope without drain, F_t– factor of safety at time t, and F_d – factor of safety at the end of consolidation when the new steady state seepage for the slope with drains is established.

Figures 10 and 11 present the gain in the factor of safety as a function of dimensionless time (5):

$$Tv = \frac{t \cdot c_v}{H^2} \quad (5)$$

In which t – time (sec), H – the total head difference in the problem (m), c_v– coefficient of consolidation (m^2/s).

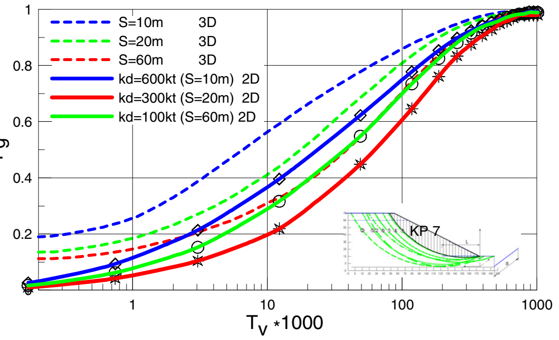

Figure 10 The gain in the factor of safety Fg versus the time factor Tv for slip surface 7 (critical slip surface) L=50m, S=10, 20, 60m

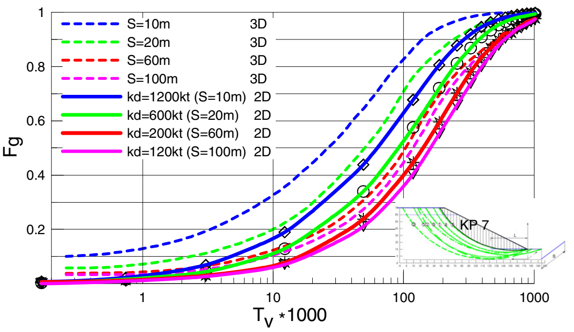

Figure 11 The gain in the factor of safety Fg versus the time factor Tv for slip surface 7 (critical slip surface) L=100m, S=10,20,60,100m

The results show a reasonable agreement between the analyses presented here and the work of Nonveiller (1981). It is interesting to note that the discrepancies between the two approaches are the most significant at early times and for the smallest drain spacing for which the Nonveiller (1981) solution gives an almost instantaneous increase in the factor of safety between 5 and 20%. For longer times and larger drain spacing the two solutions converge. The main reason for the observed discrepancies is not clear, but they are consistent with the differences in the seepage patterns observed in Figure 3 to 5.

3 CONCLUSIONS

The paper presents an algorithm that can be used to evaluate the development of stabilization effects with time for slopes for which the drilled drains are used as a remedial measure. The method uses two readily available numerical tools to find the increase in the factor of safety with time. While the analysis results are presented here in the form of dimensionless charts in order to compare them to the previously published solutions, the main advantage is that the algorithm can be used for the actual in situ conditions without the need to assume a homogeneous slope and simple geometry.

The methodology also suggests a procedure of modeling the 3D seepage pattern with the 2D model by defining the "equivalent" hydraulic conductivity for the drain material. A true 3D seepage and consolidation analyses would further improve the procedures presented here, and it is only a matter of time before such numerical tools will be available for routine applications. However, even if such tools were available, the complete 3D analyses might still be out of reach since it would require much more detailed description of site conditions that in many field cases is not available or economically feasible. The role of geotechnical engineers is then to develop a simplified, yet realistic, model which captures the most critical aspects of soil behavior while leaving out details that have secondary effects. The methodology presented here is developed in this spirit.

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