STUDY ON THE POTENTIAL EFFECT OF BLOCKAGE OF SUBSURFACE DRAINAGE BY SOIL NAILING WORKS

GEO REPORT No. 218

HALCROW CHINA LIMITED

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT
THE GOVERNMENT OF THE HONG KONG
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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet. Printed copies are also available for some GEO Reports. For printed copies, a charge is made to cover the cost of printing.

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R.K.S. Chan
Head, Geotechnical Engineering Office
December 2007

FOREWORD

This Special Study on the potential effect of blockage of subsurface drainage by soil nailing works has been carried out by Halcrow China Ltd on behalf of GEO.

All of the hydrogeological modeling and much of the reporting has been carried out by Dr Jimmy Jiao of the Department of Earth Science, Hong Kong University with assistance from Dr S Hencher, Mr Greg McGuire and Mr Martin Devonald of Halcrow China Limited. The input and advice from the Working Group of GEO and in particular Mr W K Pun, Chairman of the Working Group, Mr Y K Shiu, Dr W K Chang, Mr H C Chan and Mr T S Kwong is gratefully acknowledged.

Gerry Daughton
Project Director
Halcrow China Limited

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ABSTRACT

An investigation has been made into the potential effect of blockage of subsurface drainage by soil nailing works. Numerical models have been set up in both 2D and 3D for various geological settings, subjected to infiltration. Infiltration events modeled have included applying an average daily wet-season rainfall in Hong Kong until a steady state is achieved and applying intense rainfall over a 4-day period to simulate one of the major rainstorms in 1982. Various run off conditions were also modelled.

Models were initially run without nails to determine base conditions. Models were then conducted including nails represented as:

(1) discrete, low hydraulic conductivity elements (in 3D),

(2) discrete, low hydraulic conductivity elements (in 2D). "Pseudo-K" values were assigned to the nail elements as an average for the nail and surrounding ungrouted soil,

(3) grouted soil nail "horizons" to simulate lateral migration of grout so that the whole horizon had reduced hydraulic conductivity, and

(4) a general zone with hydraulic conductivity reduced by an order of magnitude (3D model).

In general it is concluded that under typical conditions, where there is little grout loss during the grouting operation, there should be no significant blockage of the drainage paths and therefore little or no adverse effect on slope stability.

It is found that only if excessive grout loss were to occur and this is responsible for reducing hydraulic conductivity over extensive zones or horizons would there be significant adverse consequences for slope stability.

It is recommended therefore that where excessive grout loss occurs during installation of soil nails, the cause should be investigated and, if necessary, measures taken to monitor rises in hydraulic head and to take action to drain the ground upstream of the nails.

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1. INTRODUCTION

1.1 Previous Studies on the Influence of Anomalous Hydraulic Conductivity Zones on Hydrogeology

A soil nail, together with the grout around the nail will generally provide a zone of lower hydraulic conductivity than the country soil into which the nail has been installed. The impact of zones of anomalous hydraulic conductivity much higher or lower than that of the background aquifer, on groundwater head distribution, pumping test data analysis, and parameter estimation in regional numerical models has been researched by several workers (e.g., Butler, 1988; Butler & McElwee, 1990; Butler & Liu, 1993; Jiao, 1993; Jiao, 1995; Jiao & Lerner, 1996; Jiao & Zheng, 1997). It is clear from these studies that the impact of such zones depends on the relative size of the zone of low or high hydraulic conductivity compared to that of the groundwater flow system. The position and extent of such zones will also affect the hydrogeological impact.

Butler (1988) and Butler & Liu (1993) derived analytical solutions for aquifers containing circular disk of anomalous properties. They concluded that the change in drawdown is sensitive to the hydraulic properties of a discrete portion of an aquifer only for a limited period. In the long term, drawdown is independent of properties of that discrete portion. Butler & McElwee (1990) conducted sensitivity analysis of hydraulic head to parameters in different aquifer zones under various pumping conditions and concluded that conventional pumping tests are of limited effectiveness for identifying the spatial distribution of aquifer properties.

This special study report has been carried out to ascertain, through numerical modelling, the potential damming effect on groundwater patterns of systematic soil nails with associated grouting. Most of analysis has been carried out using symmetrical 2D models with the hydraulic conductivity of the soil nailed zones either set very low to investigate potential damming or adjusted to allow for 3D flow around the nail themselves through the soil-nailed horizons. Models have been carried out for a variety of assumed geological settings. Verification analysis has been carried out in some cases using 3D models.

1.2 Soil Nailing Techniques in Hong Kong

Soil nailing is a technique commonly used in Hong Kong to improve slope stability. Figure 1 shows a possible configuration for soil nailing in a slope. The detailed configuration varies from slope to slope, depending on the geometry and soil properties of the slope. According to GEO Report No. 56 (Wong et al, 2000), the soil nail group may consist of a few to more than 10 rows of soil nails. The spacing between soil nails typically varies from 1 m to 2 m and the length of a nail can vary. To install a nail, a hole with a diameter of about 100 mm is commonly drilled, the nail inserted into the hole and then cement is injected under a low pressure to fill the annulus between the nail and the soil.

On occasions 3 to 5 times the theoretical annulus volume of grout and even more is injected during the grouting. The additional grout is probably lost down open joints, into voids in the colluvium/saprolite or into oversized holes.

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For most slopes in Hong Kong, downhill groundwater movement below the toe of the slope and through the slope surface in the form of seeps or springs are the main ways that infiltration and throughflow from above the slope is discharged. There is concern that, in a slope with extensive soil nailing and grout leak, the grouting injected around a nail may spread out widely, thereby filling in voids and fractures and blocking preferential flow paths such as natural soil pipes or fracture zones. The worst case scenario is that the soil nail zone might become a low permeability dam that blocks downhill movement of groundwater flow. The potential for soil nails to affect groundwater conditions adversely and thereby cause a reduction in Factor of Safety are the subjects of this special study.

2. TWO-DIMENSIONAL MODEL SETUP

2.1 Slope Configuration and Mesh Design

Seep/W V5.15 has been used to investigate the impact of soil nails on subsurface flow in slopes.

A basic slope configuration is shown in Figure 2. The soil nail layout and orientation are based on the typical settings in GEO Report No. 56 (Wong et al, 2000). The modelled zone is about 45 m wide by 30 m high. The vertical distance from the toe to the crest of the cut slope is 10 m.

To represent the location and orientation of the soil nails that intercept the slope surface at a certain angle accurately, the mesh design begins with the soil nail zone. This zone is modelled as a rectangular area with one side representing the slope surface. The soil nail zone is the focus of the model and is represented by fine elements of size 0.30 m × 0.37 m. Each soil nail is represented by a linear zone about 0.30 m wide and 11.4 m long (Figure 2).

After the mesh in the soil nail zone is generated, the rest of the model area is discretized into elements of various sizes. The general principle is that elements in and around the soil nail zone are fine but those away from the zone become gradually coarser. In that way the impact of the soil nails on groundwater flow is adequately simulated but the model remains computationally efficient.

The models conducted focus on the long-term impact of the soil nails on groundwater flow and hydraulic head in the slope for various configurations of soil nailing and hydrogeological conditions. For each model, two steady state flow conditions are simulated; one before soil nailing and the other after soil nailing. Some “observation points” A, B, C, and D are selected for the purposes of monitoring the detailed change in total head in the models (Figure 2).

2.2 Boundary Conditions

The impact of groundwater flow on slope stability in Hong Kong has been studied numerically since the 1980’s. A typical groundwater flow model to study the impact of pore water pressure on slope stability is a two-dimensional cross-sectional unconfined flow model. The model domain usually covers only a narrow superficial strip of the saprolite around the

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immediate vicinity of the potential slope failure area and the bottom boundary is chosen to coincide with the interface between saprolite and bedrock, which is assumed to be a no-flow boundary.

It may be adequate to choose such a small area for studying the engineering performance of soil and rock, but if groundwater flow through the potential failure area is to be studied, a much larger area, preferably one that includes the entire groundwater flow system of the hillslope, is needed (Nandy & Jiao, 2001; Jiao et al, 2004). Groundwater exists in a system with recharge, by-pass, and discharge areas. It is inappropriate to isolate a small portion of the system for groundwater flow modeling.

For modeling studies of groundwater flow in slopes, usually there are three options for boundary conditions: fixed-head, no-flow and specified flux (such as rainfall/infiltration) boundaries. A fixed-head boundary means that the boundary can take (or release) unlimited amounts of water from (to) the model domain when there is a source (sink) in the model. A fixed-head boundary near the toe may be a reasonable approximation if the toe is near the sea, a stream, or a major spring, but a fixed-head boundary near the crest of a landslide is physically unreasonable for most Hong Kong situations and may lead to misleading modeling results.

Experience in groundwater modeling has shown that errors in placing the upper boundary have a great impact on the modeling results. It is believed that the appropriate way to address the issue is to assume the upper boundary is at a water divide such that an entire hydrogeological system is simulated. In this case, the upper boundary can be represented by a natural boundary i.e. a no-flow boundary at the water divide, with only infiltration within the model boundary contributing to changes in head.

For this study, the lower boundary is set to be a fixed head boundary with head at the arbitrary level of +9 m. The ground surface is set with a constant flux to represent rainfall infiltration. The bottom boundary, which is located below the interface of the saprolite and bedrock, is an impermeable boundary.

2.3 Parameters

2.3.1 Infiltration Rate

The average annual rainfall in HK is 2210 mm with 1742mm occurring in the wet season (from May to September), which is about 80% of the annual rainfall. Because the aim of this study is to consider the influence of potential damming on slope stability in the wet season, the average rainfall in the wet season is considered in the model.

The rainfall intensity in the wet season is taken as 1.34×10^{-7} m/s with the infiltration rate at 50% of the rainfall intensity (GCO, 1984). Whilst this number might somewhat overestimate the infiltration, it is a reasonable assumption to simulate a relatively onerous hydraulic case for slope stability. Therefore, the infiltration used in the model is 6.7×10^{-8} m/s.

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2.3.2 Hydraulic Conductivity (K)

Throughout this study, the term hydraulic conductivity (K) is used in preference to permeability (k) as hydraulic conductivity (with dimension of L/T), is a parameter that depends on both the nature of the material and the liquid passing through it whereas permeability (with dimension of L^2) is a parameter dependent only on the geological material.

Three zones are included in the basic model with boundaries approximately parallel to the sloping ground above the crest of the cut slope. Various combinations of the hydraulic conductivity values have been applied to the zones thereby representing different conditions.

If all the zones are given the same K values, the model represents a uniform slope. If the three zones are given progressively lower hydraulic conductivity values with depth, the model represents an unconfined aquifer system, which is generally taken to be the typical situation for slopes in Hong Kong. For example, Zone 1 might be a given K of 10^{-5} m/s to represent colluvium or fill, Zone 2 is given a K of 10^{-6} m/s to represent completely decomposed igneous rock and Zone 3 is given a K of 10^{-8} m/s to represent bedrock. A perched water table scenario may be generated if a very low K zone is added between the first two layers. A confined, relatively high hydraulic conductivity (K) zone (HKZ) at depth may be represented in the model by setting the second layer in the 3 layer model to the highest hydraulic conductivity.

Each discrete soil nail zone including the grout zone is taken to have a low hydraulic conductivity of 10^{-9} m/s, i.e. one order of magnitude lower than the bedrock. Models have been run using various assumptions regarding the extent of grout leakage away from the nail annulus as discussed below.

3. 2D SIMULATION AND DISCUSSION OF VARIOUS MODELS

3.1 Introduction

A series of models have been conducted to investigate the potential effect of fully grouted nails on hydrogeological conditions for a variety of settings.

Many of these models have been run with two different assumptions for the hydraulic conductivity of the soil nails (in 2D), namely:

1) The horizons (planes) containing the lines of soil nails are taken to have K = 10^{-9} m/s. This is an extreme scenario representing the loss of grouting laterally (but not vertically) to block many of the groundwater pathways in that horizon,

2) The effect of grouting is restricted to the immediate location of each soil nail. In this case (the best case), the plane containing nails at each level can be taken as having a “pseudo-K” in 2D, with the “pseudo-K” used as a means to simulate the 3D case which is considered more realistic. The “pseudo-K” is calculated as a simple average K of the

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nail itself and that of the geological materials between the nails on a plan area basis (Appendix A).

3.2 Model 1: Effect of a Single Soil Nail Horizon on Flow in a Uniform Slope

In this model, the effect is simulated of single soil nail horizons, extending laterally in a slope of uniform K = 10^{-6} m/s. The nails are installed in each of the locations in turn (Figure 3). Four ‘observation’ points A, B, C, and D are selected for comparison. A and B are located at the lower part of the zone for possible soil nailing and C and D are located to the right and above this zone. Figure 4 shows the head increases at observation points A, B, C, and D with the nails installed at different locations compared to the head developed at the same locations with no nails installed. The detailed information is presented in Table 1.

Figure 4 shows that the effect of nail installation on head at Points C and D are quite similar. The highest head increase is for nails installed at location 3.

Heads at points A and B are most strongly influenced by soil nails installed directly above or below (Locations 5 and 6) as might be anticipated given the geometry of the situation.

Figure 5 shows how the groundwater flow pattern is modified by installing the nails at different locations. Compared to the flow pattern in the slope without soil nailing (Figure 5A), the groundwater flow in the unsaturated zone is somewhat disturbed when the soil nails are installed in Location 2 (Figure 5B). The flow below the water table is only slightly modified since the tips of the nails at this location have only just reached the water table. When the nails are installed at Location 4 (Figure 5C), which is largely below the water table, the flow in both saturated and unsaturated zones are significantly modified and the water table above the soil nails is considerably elevated. An unsaturated zone is observed below the nails and a perched water table is formed. Consequently two seepage zones are generated in the slope surface, one above the nail horizon and one at the toe of the slope. When the nails are installed at Location 6 (Figure 5D), the groundwater table is generally elevated. The majority of the groundwater flow is forced to pass through the region below the soil nail. The groundwater flow velocity is significantly increased in this region. This might, for this extreme scenario, lead to the generation of soil pipes in this region.

The model demonstrates that the change of total head in the slope in response to soil nailing can be quite complicated for this extreme scenario of fully grouted horizons. Overall, the head in the majority of the slope will be increased with adverse consequences for Factor of Safety, but the head in the immediate vicinity of the nails may be decreased, particularly if the observation point is located below and shadowed by the nail (e.g. point A).

3.3 Model 2: Effect of a Group of Soil Nails on Flow in a Uniform Slope

In this model all six nail horizons are installed in the slope of uniform hydraulic conductivity of K = 10^{-6} m/s. The nail loci represent lateral continuous horizons of low K. To understand the overall change of total head in the entire slope after soil nails are installed, the contours of head difference before and after soil nailing are plotted in Figure 6. The model shows that head is increased in the entire slope except for the area below the lowermost

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soil nail where total head is decreased. The increase in head in the area above the second nail is over 2 m. The area with most significant head increase is near the crest where the increase is over 4 m.

Figures 7A and 7B show flow nets and water table distributions before and after soil nailing, respectively. Detailed changes in head at observation points A, B, C, and D are presented in Table 2. The increase in the total head is more significant from B to D. The head at A actually decreases because it is closest to the discharge point (the toe) and because the multiple soil nails retard groundwater flow to this location.

Prior to installation of nails there is a water divide in the slope (Figure 7A). The infiltrated water to the left of the divide seeps out at the toe of the slope while the infiltrated water to the right of the divide flows to the left boundary of the model.

After installation of soil nails the flow pattern becomes more complicated. Multiple water tables or perched water tables develop and seepage velocity increases in the area below the soil nail zone.

Table 2B presents the total inflow (infiltration), outflow through the surface of the cut slope and outflow through the left boundary for the slope with and without soil nails. It can be seen that, after installation of soil nails, there is a minor increase in seepage through the slope surface whilst the discharge through the left boundary is decreased.

3.4 Model 3: Soil Nails in Uniform Slopes of Different Background Hydraulic Conductivities

To investigate the potential influence of soil nailing in slopes of different hydraulic conductivity, in model 3, three uniform slopes with background K = 10^{-5} m/s and 10^{-6} m/s, 5×10^{-7} m/s, respectively are simulated. The soil nailed zone is modelled with low permeability horizons. Figure 8 shows the simulation results. Detailed changes of heads at Points C and D are listed for comparison in Table 3. In this model, soil nails are taken to have a K of 10^{-9} m/s.

The simulation results show that the change in total head does not increase linearly with the decrease of hydraulic conductivity of the slope materials. The change in total head in response to soil nailing is low where the slope comprised material with high K = 10^{-5} m/s. This is probably because the water table is low and most of the nails are above the water table. When the background K = 10^{-6} m/s, the increase in total head with installation of nails is very significant. When K = 5×10^{-7} m/s, the increase in total head is still marked but less so than in the previous case because the head prior to soil nailing was already high.

In Figure 8C, when K = 5×10^{-7} m/s, the water table after soil nailing shows a depression in the water table with the groundwater flow dipping against the dip direction of the slope in the area above the soil nail zone. This apparent anomaly is a function of the whole model set up with uniform infiltration rate across the upper surface of the ground model.

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3.5 Model 4: Soil Nails in a Multi-layered Slope with Extensive Grout Loss

A typical slope in Hong Kong might consist of three layers comprising colluvium or fill over saprolite and over bedrock. Typical hydraulic conductivities for the three zones might be $K = 10^{-5}$ m/s, 10^{-6} m/s and 10^{-8} m/s, respectively. Soil nails are modelled as planes. Figures 9A and 9B show the flow nets and water table distributions before and after soil nailing, respectively for this model. As can be seen from the flow lines, the groundwater flow without soil nails mainly occurs in layers 1 and 2 and is more or less parallel to the layers of the slope. There is limited groundwater flow in the bedrock.

Overall, the water table after soil nailing is elevated by about 4 metres and becomes almost horizontal. Table 4 shows the detailed changes at observation points C and D.

Again the flow pattern is complicated after the soil nails are installed. Before soil nailing, a large portion of infiltrated water flows toward the left boundary (Figure 9A), but most of the water seeps out through the slope surface after soil nailing because the nails intercept the downslope flow (Figure 9B).

The hydraulic gradient in the region between the lowest nail and the bottom of the model is significantly increased. This may enhance the possibility for soil piping to occur in this region.

3.6 Model 4B: Soil Nails in a Multi-layered Slope with Little Grout Loss

As noted in the introduction to modeling (Section 3.1) the models reported above are for nailed horizons where the material between the nails, laterally, is assigned the same low K value of 10^{-9} m/s to simulate an extreme case with extensive lateral dispersion of grout. Each horizon containing nails therefore acts as an aquiclude. In reality this condition is unlikely and an attempt to simulate a reduced 3D effect in 2D mode has been attempted by adopting a ‘pseudo-K’ for the nail horizons, calculated as an average of the soil nail K plus intervening soil K, proportional to their area foot prints as explained earlier in 3.1.

Model 4 has therefore been re-run using soil nail pseudo-K values as indicated in Figure 9C. The K values are about 20% lower than the K for the background soil. In all other respects Model 4B is the same as Model 4.

Table 4B shows the calculated heads at points C and D and it can be seen that providing the soil nail grouted holes are discrete (no loss of grout locally), there will be little effect on the groundwater pattern. Figure 9D shows the flow patterns and water table after soil nailing for the three-layered slope. Figure 9D is generally similar to Figure 9A prior to soil nail installation and again demonstrates that the nails themselves (0.3 m diameter at 2 m spacing) will have little effect.

3.7 Model 5: Soil Nails in a Three-layer Slope with the Middle Layer having the Highest Hydraulic Conductivity

Model 5 comprises a slope consisting of three zones with $K = 10^{-6}$ m/s, 10^{-5} m/s and 10^{-8} m/s. Since the middle zone has the highest hydraulic conductivity, it may be a good

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drainage layer for the slope if this zone outcrops at the slope surface. In this case, the zone is beneficial to slope stability. However, if this zone is blocked at the toe of the slope, it is likely to have an adverse effect on slope stability since a highly confined aquifer may be formed, especially during the wet season.

As can be seen from Figure 10A, before soil nailing the groundwater flow in this zone is essentially parallel to layer surfaces but the groundwater flow in the top layer is almost perpendicular to the layer interface. All the groundwater flow is toward the left boundary. There is no seepage from the face because the water table is below the toe of the slope.

Figure 10B shows the flow net and water table distribution after soil nailing with extensive grout loss (using $K = 10^{-9}$ m/s). The third nail from the top plays the most important role in changing the flow pattern. As can be seen from the flow lines, most of the flow is intercepted by this soil nail which then directs the groundwater flow to the slope surface. An interesting feature is that appreciable seepage develops at the face above the third nail. Flow toward the left boundary is significantly reduced.

Overall, the water table after soil nailing is increased by about 8 m. Table 5 shows the detailed changes at observation points C and D. The increase in the head when there is a high K zone is more significant in all the cases than for previous models. The drainage through the high K zone has been effectively blocked by the soil nails and the nails direct the groundwater flow to seep out through the slope surface. Seepage can be observed along the whole slope surface of the soil nail zone, but the seepage above the third nail from the top is most significant.

Table 5B presents the total inflow (infiltration), outflow through the surface of the cut slope, and outflow through the left boundary for the slope with and without soil nails. Without the nails, water is entirely discharged through the left boundary. When the soil nails are installed, the seepage through the slope surface is 80% and the discharge through the left boundary is only 20%. The change is significant in this case.

3.8 Model 5B: Soil Nails in a Three-layer Slope with the Middle Layer having the Highest Hydraulic Conductivity but for Soil Nailing Works with Little Grout Loss

Model 5 has been re-run using the same soil nail pseudo-K values used in Model 4B (Figure 10C). The K values are about 20% lower than the K for the background soil.

Table 5C shows the calculated heads at points C and D which are slightly increased. Figure 10D shows the flow patterns and water table after soil nailing for the three-layer slope. Again Figure 10D is very similar to Figure 10A prior to soil nail installation demonstrating that the nails themselves have little effect.

3.9 Model 6: Impact of Soil Nail Orientation on the Buildup of Water Table

In Model 6, the impact of different soil nail orientations is investigated. The mesh system was redesigned for this model to simulate horizontal nails (Figure 11).

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Figures 12 A-C show the flow pattern in a uniform slope with K = 10^{-6} m/s and the flow patterns in the same slope with inclined or horizontal soil nails, respectively. Detailed changes of heads at points C and D are listed in Table 6. It is noted that the increase in the total head in response to nailing is much smaller for horizontal nails than when inclined nails are used.

A similar sensitivity study was carried out for a layered slope with K = 10^{-5} m/s, 10^{-6} m/s and 10^{-9} m/s. The results are shown in Figure 12 D-F and Table 7. In this case, it seems that the use of inclined nails will increase the total head more than the case where the slope is uniform. Generally, soil nails installed horizontally will have less impact on the groundwater flow within the slope compared with inclined soil nails.

3.10 Model 6B: Impact of Soil Nail Orientation in the Buildup of Water Table using Pseudo-K Values for Soil Nails

Model 6B is the same as the slope with uniform background soil (K = 10^{-6} m/s) in Model 6 except that the K for the soil nails is given a value of K = 8×10^{-7} m/s.

Table 7B shows the calculated heads at points C and D. The heads are slightly increased.

3.11 Model 7: Soil Nails in a Layered Slope with a Low Hydraulic Conductivity Zone

The model comprises a slope with of three main layers K = 10^{-5} m/s, 10^{-6} m/s, and 10^{-8} m/s and a relatively thin zone of low hydraulic conductivity sandwiched between the upper two layers. This zone that might represent a dyke in reality is about 2 m thick with a hydraulic conductivity of 10^{-8} m/s. All the soil nails are installed a minimum of 2 m above the toe of the slope (Figure 13).

As can be seen from Figure 14A, before soil nailing, two separate water tables are observed. There is a regional water table below the low K zone. Near the slope surface, a very small-scale water table is perched above the surface of the low K zone. Two seepage zones can be observed from the slope surface where the two water tables crop out. The regional water table is at the location of about 11 mPD.

Figure 14B shows the flow net and water table distribution after soil nailing with extensive lateral grout loss (10^{-9} m/s). The nails modify the flow pattern significantly. Multiple water tables are generated near the slope surface. The drainage through the second layer has been significantly blocked by the soil nails. Large amount of seepage appears on the slope surface, including the crest area of the slope. Flow toward the left boundary is considerably reduced.

With soil nails, in this worst case scenario the overall water table in the system is increased by over 7 m. The water table in the top layer is higher than the crest and higher than the water table in the second layer. Table 8 shows the detailed changes at observation points C and D. The increase in the heads at the two locations is over 40%.

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3.12 Model 7B: Soil Nails in a Layered Slope with a Low Hydraulic Conductivity Zone but for Soil Nailing Works with Little Grout Loss

Model 7 has been re-run using the soil nail pseudo-K values given in Figure 14C. The K values are about 20% lower than the K for the background soil. Model 7B is the same as Model 7 except for the values of hydraulic conductivity for the soil nails.

Table 8B shows the calculated heads at points C and D. The heads are slightly increased. Figure 14D shows the flow patterns and water table after soil nailing for the three-layer slope. Figure 14D is very similar to Figure 14A where no soil nail is installed.

3.13 Model 8: Soil Nails in a Uniform Slope with a Vertical Dyke of Very Low Hydraulic Conductivity

Model 8 comprises a slope with a uniform $K = 10^{-6}$ m/s and a vertical dyke of $K = 10^{-8}$ m/s. This dyke is 2 m thick. The configuration is shown in Figure 15. In addition to points C and D, point E, which is near the crest, has been selected to observe the detailed changes in head.

As can be seen from Figure 16A, the dyke causes a significant build-up in the water table upstream. The water table in the right part is over 10 m higher than that of the left. A seepage zone is generated along the area where the dyke intercepts the slope surface. While most of the water in the right part flows through the dyke and discharges to the left part of the slope, some water seeps out along the seepage zone.

Figure 16B shows the flow net and water table distribution after soil nailing (10^{-9} m/s) (assuming extensive grout loss). The flow system on the right is little affected because the nails are largely located in the left part of the slope. Conversely there is a significant increase in the water table in the left part of the slope. Multiple water tables are generated near the slope surface and considerable seepage occurs at the slope surface.

Table 9 shows that the increase in head at points C and D, located to the right of the dyke, are less than 2%. However, the increase in head at point E, which is located near the crest of the left part of the slope, is over 50%. If a lower bound, pseudo-K approach had been used in defining the K values for the soils, the influence of nailing would have been considerably reduced (i.e. negligible) as per the other models.

3.14 Model 9: Impact of Distance (L) from the Toe to the Left Boundary

A series of models has been run to test the sensitivity of the models to the distance assigned for the left boundary point beyond the slope toe. Using a uniform slope with a $K = 10^{-6}$ m/s the sensitivity to boundary point distances of 6.4 m, 8.0 m and 10.0 m, respectively, have been analysed. Figure 17 shows the results. Detailed changes of heads at points C and D are listed in Table 10.

When the distance (L) from the toe to the left boundary increases, the heads at points C and D in the slope with or without nails increase as shown in Table 10. This is because an increase in the distance means an increase in the length of flow path, which in turn will reduce

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the discharge to the left boundary, so that heads in the slope become elevated. However, the rise in head compared with the change of distance L is insignificant. Only a 0.7% increase in head is observed when the distance L is increased from 6.4 m to 10 m, i.e. an increased distance of 56%. This demonstrates that the head is not very sensitive to the distance from the toe to the left boundary.

When the distance (L) from the toe to the left boundary increases, the head increase at points C and D due to soil nailing is decreased, but the change with L is very small, compared to the change in L itself. This demonstrates that the total head increase due to soil nailing is not very sensitive to the distance between the toe and the left boundary. Figure 17 also shows that the general shapes of the flow nets are insensitive to distance L.

3.15 Model 10: Pseudo Hydraulic Conductivity in the Soil Nail Zone

For the various models described earlier, two extreme situations have been modeled. In one type of model the low hydraulic conductivity due to the nail + grout has been restricted to the nail itself (a 300 mm width zone). For these models, in 2D, an averaged “pseudo-K” was calculated for each horizon containing the nails by averaging the permeability of the nail and soil within the same horizon on a plan area basis. Such models simulate the no loss of grout scenario. In other cases, to test the sensitivity, the complete horizon containing each of the 300 mm nails was assigned the same low conductivity as the nail itself. This situation represents a scenario with considerable loss of grout.

For Model 10, the situation is considered where the grouting materials may spread out generally in the soil nail zone and reduce the overall hydraulic conductivity of that zone. To evaluate its effect on the groundwater flow system, the zone is given a pseudo hydraulic conductivity of $10^{-7.5}$ m/s (or 3.16×10^{-7} m/s) which equals the volumetric average of the K for the nails (10^{-9} m/s) and the K for background soil (10^{-6} m/s). The soil nail zone is represented in brown (Figure 18).

Figures 19A, B, and C show flow nets and water table distributions for the slope without soil nails, with soil nails, and with a soil nail zone of hydraulic conductivity modified by grouting, respectively. Detailed changes in head at observation points C and D are presented in Table 11. The increase in the total head is most significant when the hydraulic conductivity of the soil nail zone is modified by grouting.

Table 12 presents the total inflow (infiltration), outflow through the surface of the cut slope, and outflow through the left boundary for the slope without soil nails, with soil nails and with a soil nail zone of hydraulic conductivity modified by grouting. With soil nails only, the modification of the nails on the discharge through the left boundary and the slope surface is insignificant. However, when the soil nail zone is given a generally reduced pseudo hydraulic conductivity of $10^{-7.5}$ m/s, the total infiltration is reduced. The percentage of groundwater discharge in the form of seepage through the slope surface is also reduced but the groundwater discharge through the left boundary is increased.

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3.16 Model 11: Slope with and without Soil Nails under Severe Rainstorms (Uniform)

Previous models have been assessed assuming a steady state with rainfall infiltration assumed to be 6.7×10^{-8} m/s, which is based on the average rain fall during a typical wet season. Model 11 is designed to investigate the effect of increased infiltration due to severe rainstorm conditions. Only the case simulating extensive grout loss is investigated because the damming effect due to soil nailing works with little grout loss has been shown to be insignificant even for the study state based on the results of the studies on the previous models. The Model 11 layout is similar to Model 4 which includes three layers with hydraulic conductivities K = 10^{-5} m/s, 10^{-6} m/s and 10^{-8} m/s respectively. The nail horizons are taken to have K = 10^{-9} m/s.

A total four day rainfall of 654 mm, recorded at the Royal Observatory for the period 28 – 31 May 1982 was selected as the rainstorm for this modeling. This rainstorm represents an event that could be expected to occur perhaps once every 15 years (Tang, 1993). The intensity of this rainstorm is equivalent to 1.9×10^{-6} m/s. Assuming that only 50% of the rain will infiltrate the ground (GCO, 1984 at Section 4.2.2), an infiltration of 9.46×10^{-7} m/s is added to the model. No antecedent rainfall is modelled before the storm and the initial groundwater table is taken as flat and located at an elevation of 9 m.

Table 13 lists the detailed change of total head in response to rainfall at points A and D, which are below and above the soil nail zone, respectively. At point D there is a significant head increase in the case with soil nails. The response to rainfall becomes less proportionally towards the end of the rainstorm.

It is interesting to note that the head developed at point A is less in the case with soil nails. The reason is similar to that discussed regarding Model 1, i.e. the soil nail zone with reduced hydraulic conductivity restricts flow towards the toe region.

Figure 20A shows the change of water table in response to the storm at time = 0, 2, and 4 days. The water table starts to rise in the area near the toe because in this area the thickness of the unsaturated zone is small and the infiltrated rainwater can reach the water table quickly. The wetting front moves from left to right. This modeling result is very similar to that of Jiao et al (2005) using a separately developed research code.

The changes in water table during the rainstorm at point A with soil nails installed is shown in Figure 20B. In this case the water table increase is less marked because of the shadowing effect of the zone containing low K nail horizons and with lower overall hydraulic conductivity.

As a trial, the model has been run with continued rainfall. With time, the damming effect of the soil nail zone to the down-slope groundwater movement becomes more significant. Figures 20C and 20D present the simulated water table or saturated water body at time = 20 days. In the case with soil nails, the overall water table is much higher than the case without soil nails. Figures 20C and 20D indicate that the lower rock level remains largely unsaturated (above the initial head condition at +9m). In contrast, a complex water table is developed in the upper two soil layers above the bedrock. This phenomenon has been simulated and discussed in detail by Jiao et al (2005).

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From the above discussion, it can be concluded that, at the beginning of a storm, a slope with soil nails and extensive grouted zone may exhibit a lower rise in water table than the equivalent slope without soil nails because the soil nailed zone with low hydraulic conductivity reduces recharge to the groundwater table, especially near the toe of the slope. As rain continues, infiltrated rainwater along the upper part of the slope becomes important. If the downhill movement of the infiltrated water becomes blocked by the soil nail zone, a higher water table can be expected to develop in the slope.

3.17 Model 11B: Slope with and without Soil Nails under Severe Rainstorms (Non-uniform)

Model 11B is based on Model 11 but with non-uniform rainfall infiltration. The infiltration rates are taken to be 0%, 20% and 50% at the ground surfaces below the toe, at the cut slope and above the crest, respectively. These assumptions model the situation where the platform below the slope is paved (but not confining) and the steep cut slope has higher runoff.

Table 13B lists the detailed change of total head in response to rainfall at points A and D, which are below and above the soil nail zone, respectively. Compared to Table 13, the head increase at point A is much reduced because of the lower rainfall infiltration below the crest. At point D, the head increase is similar in each case because the infiltration rate above the crest is the same.

Figure 21A and 21B shows the change of water table or saturated water body in response to the storm at different times. Overall they are similar to Figure 20. At time = 2 and 4 days, there is a water mound near the toe, but the water table height is much smaller because the rainfall infiltration is much lower.

Figures 21C and 21D present the simulated water table at time = 20 days. In the case with soil nails, two separate saturated water bodies develop. The lower is regional groundwater with surface slightly modified through infiltration from the cut slope; the upper body is generated entirely by the infiltration from the upper slope surface. When the two water bodies eventually coalesce, the pressure in the slope would increase dramatically over a short time.

4. THREE-DIMENSIONAL MODEL SETUP

For 3D modeling studies the slope configuration, mesh design, boundary conditions and parameters have been input such that they may be compared to the 2D numerical case studies directly. Very fine elements of 0.3 m dimension have been used in order to develop a slope configuration similar to that adopted in the 2D modeling. Nevertheless it is very difficult to produce identical model layouts and, as such, some discrepancy is unavoidable between the 2D and 3D model configurations.

In order to prepare the input data files for the complicated mesh system required to model a cut slope with different soil layers and soil nails, the default FEMWATER source code has been modified using a series of FORTRAN codes written specifically for this study. The default FEMWATER setting requires the number of layers in the vertical dimension to be the same for the whole model domain in the x-y dimension. This has resulted in a cuboid model domain of 40 m × 25 m × 20 m (Figure 22) in size, which has been divided into

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106,330 elements (39 × 70 × 60) and 114,949 nodes. In order to reduce the numbers of nodes and elements, the height of the 3D model is selected as 25 m, instead of 33 m used in the 2D model.

As the number of elements and nodes for this study are significantly more than the limits allowed in the default FEMWATER code, the original code has needed to be modified and recompiled. This has been achieved using a series of FORTRAN codes that resolve the mesh file and adjust the coordinates of the nodes in the intended soil nail zone and allow inclined soil nails to be represented. An additional FORTRAN code has been written to specify the locations of the soil nails (seen as small red squares on the slope surface in Figure 22) and zones of different soils. The final mesh system is shown in Figure 22. Each soil nail is represented by a beam of about 11 m long with a 0.3 m × 0.3 m cross section. Consequently, the soil nail zone is represented by very fine elements. On the cut slope surface, there are 6 rows of soil nails and each row has 11 soil nails. To represent these soil nails, very fine elements have to be included in the soil nail zone and all the layers passing through the soil nail zone.

As in the 2D study, four “observation” points A(14,10,11), B(20,10,11), C(26,10,11) and D(26,10,17) (the number in the brackets are coordinates in metres) are chosen for detailed discussion. All these points are located on a cross section (I-II) through the middle of the slope. A and B are located at the lower part of the nail zone, C and D are located on the right and upper part of the nail zone, respectively.

5. 3D SIMULATION AND DISCUSSION OF VARIOUS MODELS

5.1 Model 12: Effect of a Group of Soil Nails on Flow in Uniform and Non-Uniform Slopes

Model 12 is of a uniform slope with hydraulic conductivity of 10^{-6} m/s. All other parameters, infiltration and boundary conditions are the same as those adopted for the 2D Model 2. Figures 23A and 23B show the simulated total head and water table distributions.

Subsequently 66 soil nails (6 rows and 11 columns) with discrete, localised hydraulic conductivity K of 10^{-9} m/s are installed in the uniform slope. The simulated total head after installation of the nails is shown in Figure 24A. The detailed heads at A, B, C, and D are shown in Table 14. The soil nails are shown to have very little effect on the total head distribution within the slope.

Similarly a slope of three layers with hydraulic conductivities K = 10^{-5} m/s, 10^{-6} m/s, 10^{-8} m/s, respectively has been studied. The total head distributions in the slope with and without soil nails are simulated. Figure 24B shows the total head distribution in the slope when soil nails are installed. Detailed heads at the observation points are listed in Table 15. Again, the discrete soil nails in the layered slope have little effect as shown similarly for the 2D models earlier using a pseudo-K approach (i.e. with nailed horizons having an averaged decrease in hydraulic conductivity of only about 20%).

5.2 Model 13: Effect of Soil Nail Zone with Low Hydraulic Conductivity

In an attempt to model the potential effect of the whole soil nail zone suffering a

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reduction in hydraulic conductivity due to grout migration from the soil nail, the whole nailed zone has been given a K of 10^{-7} m/s. Figure 25A shows the total head distribution in a uniform slope with such a soil nail zone. The detailed heads at the observation points are listed as Case 3 in Table 16. The head increase is very significant, e.g. the head increase at point D is more than 84%.

The model has been run again for a three layer slope of hydraulic conductivities K = 10^{-5} m/s, 10^{-6} m/s, 10^{-8} m/s, respectively, with a soil nail zone of K = 10^{-7} m/s. Figure 25B shows the total resultant head distribution in the layered slope. The detailed heads at the observation points are listed as Case 3 in Table 17. Again the head increase is significant, e.g. point D has a head increase of over 74%.

5.3 Model 14: 3D Slope with and without Soil Nails under Severe Rainstorms

As for the 2D case in Model 11, a severe rainstorm event has been taken as the input to Model 14 for the 3D case of three layers with hydraulic conductivities K = 10^{-5} m/s, 10^{-6} m/s, 10^{-8} m/s, respectively. An infiltration of 9.46×10^{-7} m/s has been applied to the full ground surface of the model. No rainfall has been assumed prior to the storm and the initial groundwater table has been taken as flat and located at an elevation of 9 m as per Model 11.

The modeling results show that the discrete soil nail zones have virtually no effect on the head distributions under the storm condition. Table 18 lists the detailed change of total head in response to rainfall at point D in the slope with and without soil nails.

Figure 26A and 26B are cross sections through the 3D model showing the water table at time = 4 days for the slope without and with the soil nails, respectively. The results are virtually identical to the 2D model illustrated in Figures 20A and 26B. The water table starts to rise in the area near the toe because in this area the thickness of the unsaturated zone is small and the infiltrated rainwater can reach the water table quickly. This result is very similar to that of Model 11, although the results from 2D and 3D models are not entirely comparable due to slightly different slope heights and model setup.

5.4 Model 14B: 3D Slope with and without Soil Nails under Severe Rainstorms (Non-Uniform)

Model 14B is similar to Model 14 but rainfall infiltration is taken as non-uniform. The infiltration rates are 0%, 20% and 50% at the ground surfaces below the toe, at the cut slope and above the crest, respectively.

The modeling results show that the soil nails have virtually no effect on the head distributions under storm conditions. As an example, Table 19 lists the detailed change of total head in response to rainfall at point D in the slope with and without soil nails. By limiting the infiltration on the cut slope and below the toe there is little build up in water at the slope toe (unlike Model 14).

Figures 27A and 27B show the water table at time = 4 days for a layered slope without and with soil nails.

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5.5 Model 15: Comparison of 2D and 3D Models

Finally, a 2D model (Figure 28) with the same slope height as the 3D model has been designed to examine the comparability of the 2D and 3D model results. Figure 23B shows the water table in a uniform 3D slope with hydraulic conductivity K = 10^{-6} m/s and discrete soil nails K = 10^{-9} m/s. In the 2D model, each soil nail horizon is given a hydraulic conductivity of K = 8×10^{-7} m/s, a pseudo-K calculated by averaging the discrete nail zone K and the soil K within the same horizon laterally. It is found that water tables in Figure 28 and Figure 23B are very similar but a careful examination of the two water tables shows that the water table calculated from the 2D model is slightly higher. The water table in Figure 23B is close to or below the ground surface but in Figure 28 a seepage zone can be seen from the cut slope surface.

Table 20 presents the heads at points A to D (along cross section I-II in Figure 22) from the 3D model and the heads at the locations closest to the corresponding points calculated from the 2D model. Although it is difficult to compare the results from the two models because configurations, discretisation, numerical algorithms and the representation of soil nails used in the two models are not precisely the same, it seems that the 2D model with pseudo-K representation of the influence of soil nails overestimates the impact of the soil nails to some degree. However, both the 2D and 3D models show that the effect on the water table due to discrete soil nailing with little loss of grout is negligible.

6. INFLUENCE ON SLOPE STABILITY

6.1 Introduction

The findings from this study show that, in general, the installation of fully grouted soil nails at typical spacings of about 2 m centres without excessive grout loss are going to have little effect on the hydrogeological conditions in a slope and therefore little negligible adverse influence on stability with respect to blocked drainage. This is true of the variety of geological settings that have been modeled in this study.

Other models in which each discrete soil nail horizon has been taken as an aquiclude with a low hydraulic conductivity of 10^{-9} m/s deal with the scenario of extensive loss of grout. In one 3D model (Model 13), the whole nailed zone has been modeled with hydraulic conductivity reduced from 10^{-6} m/s to 10^{-7} m/s.

These models which simulate the conditions where grout might migrate away from the soil nails to block water pathways laterally and extensively, do show that such conditions could give rise to adverse changes in the hydrogeology of slopes.

To investigate this effect, slope stability analyses have been carried out on several of the models used in the hydrogeological modeling. The three conditions analysed are:

(1) slope with groundwater due to modeled rainfall event but no nail installation,

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(2) slope with nails installed but limited effect on groundwater (findings from the pseudo-K models), and

(3) slope with horizons and zones of low hydraulic conductivity giving rise to significantly worse groundwater conditions.

It is to be appreciated that where there is excessive grout loss that permeates voids within the ground, whilst there may be adverse hydrogeological effects, there may also be some compensatory improvements in shear strength and moduli whilst this is a possibility, as if a deliberate attempt had been made to improve the ground through grouting, it is considered that this potential benefit cannot normally be relied upon in any quantifiable way and has therefore been conservatively discounted in the stability analysis.

Results from slope stability analyses are presented in detail in Appendix B.

6.2 Models 4 and 4B

Comparative analyses have been carried out using SLOPE/W on the three steady state outcomes from Models 4 and 4B, i.e. without nails, with nails (using a pseudo-K) and worst case scenario with nails and excessive grout loss (using discrete elements with permeability = 10^{-9} m/s). The complex head distributions shown in the hydrogeological models have been smoothed for the purpose of the exercise. The ground model adopted for stability analysis of Models 4 and 4B is shown in Figure 29. The soil shear strength parameters adopted for stability analysis have been selected in line with typical values for Hong Kong soils as presented in Table 8 of Geoguide 1 (GEO, 1993). The main groundwater table is affected by the grouting works in the worst case scenario as shown in Figure 29. Details of these analyses are presented in Appendix B, Figures B1 and B2 and a summary of the results is presented in Table 21.

It can be seen that, for the pseudo-K case, the typical soil nail arrangements recommended in GEO Report No. 56 are sufficient to increase the minimum F of S from 0.71 to 1.4 for this model. However, in the event of excessive grout loss leading to significant blockage, the F of S could be reduced by about 33% compared to the pseudo-K case giving a minimum F of S just less than unity.

6.3 Models 5 and 5B

Similar comparative analyses have been carried out for Models 5 and 5B. The ground model adopted for stability analysis, including effect on the groundwater level in the worst case scenario, for Models 5 and 5B is shown in Figure 30. Details of these analyses are presented in Appendix B, Figures B3 and B4 and a summary of the results is presented in Table 21.

As for Models 4 and 4B, for the pseudo-K case, the typical soil nail arrangements in GEO Report No. 56 are sufficient to increase the minimum F of S from 0.95 to 1.79 for this model. However, in the event of excessive grout loss the F of S could be reduced by about 49% compared to the pseudo-K case, giving a minimum F of S just less than unity.

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6.4 Models 7 and 7B

The ground model adopted for the comparative stability analysis of Models 7 and 7B is shown in Figure 31. In this case the main groundwater table is somewhat less affected than the previous models, however, a perched water table also develops above the low permeability layer. Details of these analyses are presented in Appendix B, Figures B5 and B6 and a summary of the results is presented in Table 21.

Again, for the pseudo-K case, the typical soil nail arrangements in GEO Report No. 56 are sufficient to increase the F of S from 0.93 to 1.65. Due to the reduced effect on the main groundwater table for this model even in the event of excessive grout loss, the F of S, whilst reduced by about 7%, would still achieve the required minimum F of S of 1.4 (1.53).

6.5 Models 8 and 8B

The ground model adopted for the comparative stability analysis of Models 8 and 8B is shown in Figure 32. In this model the groundwater behind the low permeability zone is already high prior to soil nailing and is relatively unaffected by soil nail installation. However, in the worst case scenario there is also a significant build up of groundwater in front of the low permeability zone. Details of these analyses are presented in Appendix B, Figures B7 and B8 and a summary of the results is presented in Table 21.

For this particular model, the typical soil nail arrangements in GEO Report No. 56 only increase the minimum F of S from 0.92 to 1.2 for the pseudo-K case. In the event of excessive grout loss the minimum F of S is reduced further, by about 31% (0.83).

7. ADDITIONAL 2D SIMULATION

Following completion of the draft Study Report, comments were received during the presentation of the findings of this study at the LPM Liaison Meeting in October 2005. As a result an additional model was run to study the case where a large through-flow of underground water affects the 2D model. Model 3B (see Figure 8), a uniform slope with background $K = 10^{-6}$ m/s, was selected to undertake this additional modelling. Details of the modifications made to, and comparisons with, the original model are given in Appendix C.

The additional modelling showed there was an overall increase in the water levels prior to soil nailing as a result of adopting a fixed head upper boundary, but also showed that the soil nails had little or no affect on the relative groundwater levels in the slope, providing that there is no significant lateral migration of grout (ie the pseudo-K case)

8. PRACTICAL IMPLICATIONS

This study shows that soil nailing and associated grouting will generally not have any significant adverse affect on the hydrogeological regime. This is because the overall hydraulic conductivity of the soil nailed zone is only reduced by perhaps 20 or 30% when a soil nailed horizon is considered in plan. The effect would be even less if considered volumetrically.

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It has also been demonstrated however that if there was considerable grout loss so that the soil nailed zone is generally made less permeable (as if one were deliberately trying to grout the ground to form a cut off) then there may be an adverse effect and there could be an unacceptable reduction in factor of safety if the potential benefit of the grout loss on the shear strength of the soil mass is ignored. The fact that soil nails are generally grouted under low pressure means that excessive loss of grout will generally be associated with infill to highly permeable pathways or voids with potential detrimental effects.

It is suggested that:

(1) The reasons for any excessive grout loss during soil nailing should be investigated, as the damming effect of excessive grout loss may impact on the stability of the upslope as well as the subject slope,

(2) In the event of excessive grout loss from a high proportion of soil nails, albeit locally in a zone, piezometers should be monitored to check for higher head than allowed for in design,

(3) In geological settings where loss of grout might be anticipated to adversely affect hydrogeological conditions, preferred practice would be to place piezometers immediately behind the anticipated extent of the soil nailed zone, in order that long term monitoring can be undertaken prior to and after soil nailing.

(4) In the event that excessive hydraulic heads are developed, drains should be designed to draw down the excessive head. As a general rule raking drains should be designed to draw down water from behind the nailed zone.

9. CONCLUSIONS

1. Numerical models of effect of fully grouted soil nails (with little grout loss during construction) on groundwater flow and hydraulic head distribution in a slope indicate that impact is insignificant.

2. Comparison of results from 2D and 3D models indicate that a 2D model using an area-based, average, pseudo-K parameters for soil nailed horizons can give reasonable representations of 3D conditions comprising discrete grouted nails with low K in a high K soil mass.

3. The influence of soil nails can be significant where grout escapes laterally to affect larger volumes of the country rock. This is demonstrated by 2D models where lateral grout spreading is represented by soil nail horizons of low

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hydraulic conductivity and by 3D models in which the spread of grout is represented by soil nail zones of low hydraulic conductivity.

4. Overall the hydraulic head may be increased due to soil nailing (with excessive grout loss), but head at locations near the toe of the slope may be only slightly increased or even reduced because of shadow effects from the horizons limiting through flow. The crest above the soil nail zone or the area upslope of the soil nail zone has the most significant head increase.

5. In a multilayered slope with bedrock at shallow depth below the toe, soil nailing (with excessive grout loss) can lead to much greater head increase than a uniform slope of typical K (K = 10^{-6} m/s), especially when the soil nails penetrate into the bedrock, as discussed concerning Models 2 and 3.

6. Where a highly conductive zone through a slope becomes blocked, this can lead to a high head increase as demonstrated in Model 5.

7. It follows inevitably that in the event of excessive grout loss and extensive blockage of flow paths, there may be a reduction in Factor of Safety as a result of an increased groundwater table. That reduction may be partially recompensed by an unintended increase in the strength of the mass, but such a benefit is considered unquantifiable.

8. Excessive loss of grout should be investigated, especially where numerous adjacent nails exhibit such loss such that an extensive zone with low K might develop.

9. Whilst it is unlikely that such grout loss will be linked to permeation grouting, if that seems to be the case, care should be taken to monitor head behind the soil nails so affected and appropriate drainage measures adopted to remedy the situation.

A specific slope geometry and soil nail pattern was adopted for this study to allow comparison of the impact of the grouting operation between different assumed geological sections in both 2D and 3D. Generally the heterogeneity of real slopes cannot accurately be modelled, however, the above serves as an useful illustration of the likely effects of grouting on the hydrogeological conditions within a slope. It is likely that different slope geometries and soil nail patterns will have different effects/impacts on the hydrogeological regime and stability of each specific slope. However, as demonstrated in this report, the effects of the soil nailing and grouting operation are likely to be insignificant regardless of the configuration adopted.

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Table 1 – Detailed Changes in Total Head (m) when a Soil Nail is installed at Different Locations (Model 1)

Location	Head Change at A	Head Change at B	Head Change at C	Head Change at D
1	-0.03	0.01	0.394	1.271
2	-0.051	0.028	0.662	1.412
3	-0.103	0.038	1.016	1.614
4	-0.327	-0.204	0.955	1.309
5	-0.664	1.403	0.782	0.919
6	0.775	0.724	0.428	0.509

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Table 2 – Detailed Changes of Total Head (m) after Six Soil Nails are installed (Model 2)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
A	11.5	11.0	-0.5	-4.5
B	12.5	13.5	1.0	8.0
C	13.2	15.0	1.8	13.7
D	13.5	16.6	3.1	22.9

Table 2B – Total Inflow, Outflow through the Surface of the Cut Slope, and Outflow through the Left Boundary for the Slope with and without Soil Nails (Model 2) (unit: m^2/s over unit width)

	No Nail	With Nails
Total inflow	3.17×10^{-6}	3.12×10^{-6}
Outflow through cut slope surface (%)	1.30×10^{-6} (41.0%)	1.34×10^{-6} (42.9%)
Outflow through left boundary (%)	1.87×10^{-6} (59.0%)	1.78×10^{-6} (57.1%)

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Table 3 – Detailed Changes of Total Head (m) at Points C and D for Soil Nailing in Uniform Slopes of Different Hydraulic Conductivities (Model 3)

K	Head at Point C				Head at Point D			
	No Nail	With Nail	Increase	% Increase	No Nail	With Nail	Increase	% Increase
10^{-5}m/s	9.57	9.96	0.39	4.1	9.61	10.11	0.50	5.2
10^{-6} m/s	13.20	15.01	1.82	13.8	13.54	16.50	2.96	21.9
5x 10^{-7}m/s	15.96	17.04	1.08	6.8	16.62	19.34	2.72	16.4

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Table 4 – Detailed Changes of Total Head (m) after Six Soil Nails are installed in a Layered Slope (Model 4)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	15.4	18.1	2.7	17.5
D	15.7	20.1	4.4	28.2

Table 4B – Detailed Changes of Total Head (m) after Six Soil Nails are installed in a Layered Slope using Pseudo K (Model 4B)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	15.4	15.5	0.1	0.65
D	15.7	15.8	0.1	0.64

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Table 5 – Detailed Changes of Total Head (m) after Six Soil Nails are installed in a Slope with a High K Zone (Model 5)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	10.5	16.7	6.2	59.4
D	10.5	18.0	7.4	70.3

Table 5B – Total Inflow, Outflow through the Surface of the Cut Slope, and Outflow through the Left Boundary for the Slope with and without Soil Nails (Model 5) (unit: m^2/s over unit width)

	No Nail	With Nails
Total inflow	3.43×10^{-6}	3.31×10^{-6}
Outflow through cut slope surface (%)	0 (0%)	2.65×10^{-6} (80%)
Outflow through left boundary (%)	3.43×10^{-6} (100%)	0.65×10^{-6} (20%)

Table 5C – Detailed Changes of Total Head (m) after Six Soil Nails are installed in a Slope with a High K Zone using Pseudo K (Model 5B)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	10.51	10.54	0.03	0.29
D	10.55	10.58	0.03	0.28

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Table 6 – Detailed Changes of Total Head (m) in a Uniform Slope with Inclined or Horizontal Nails (Model 6)

Points	Head without Nail	Head with Inclined Nail	Head Increase at C	% Increase
C	13.20	15.01	1.82	13.76
D	13.54	16.50	2.96	21.89
Points	Head Without Nail	Head With Horizontal Nail	Head Increase at C	% Increase
C	13.25	14.33	1.08	8.13
D	13.59	15.33	1.75	12.85

(Note: without nails the head at C =13.20 in the slope mesh designed for the inclined nails which is slightly different from C = 13.25 in the slope mesh designed for the horizontal nails. This is because the two mesh systems are very different and the location for C in the two systems is not exactly the same)

Table 7 – Detailed Changes of Total Head (m) in a Layered Slope with Inclined or Horizontal Nails (Model 6)

Points	Head without Nail	Head with Inclined Nail	Head Increase at C	% Increase
C	15.44	17.94	2.51	16.23
D	15.71	19.69	3.98	25.31
Points	Head Without Nail	Head With Horizontal Nail	Head Increase at C	% Increase
C	15.51	17.18	1.67	10.76
D	15.79	18.28	2.49	15.74

Table 7B – Detailed Changes of Total Head (m) in a Uniform Slope with Horizontal Nails using Pseudo K (Model 6B)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	13.20	13.29	0.09	0.68
D	13.54	13.63	0.09	0.66

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Table 8 – Detailed Changes of Total Head (m) after Soil Nails are installed in a Slope with a Low K Zone (Model 7)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	12.8	18.0	5.2	40.1
D	13.0	19.2	6.2	47.5

Table 8B – Detailed Changes of Total Head (m) after Soil Nails are installed in a Slope with a Low K Zone using Pseudo K (Model 7B)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	12.85	12.82	-0.03	-0.23
D	13.02	13.00	-0.02	-0.15

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Table 9 – Detailed Changes of Total Head (m) after Soil Nails are installed in a Slope with a Vertical Low K Zone (Model 8)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
C	23.0	23.3	0.3	1.2
D	23.2	23.6	0.4	1.7
E	13.2	20.4	7.2	55.0

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Table 10 – Detailed Changes of Total Head (m) at Points C and D for Soil Nailing in an Uniform Slope with varied Distance (L) from the Toe to the Left Boundary (Model 9) (for L = 6.4, 8.0, and 10.0 m)

Distance (m) from Toe to Left Boundary	Head at Point C				Head at Point D			
	No Nail	With Nail	Increase	% Increase	No Nail	With Nail	Increase	% Increase
6.4	13.04	14.95	1.91	12.8	13.38	16.44	3.06	22.8
8.0	13.20	15.01	1.82	13.8	13.54	16.50	2.96	21.9
10.0	13.27	15.07	1.79	13.5	13.62	16.56	2.94	21.6

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Table 11 – Detailed Changes of Total Head (m) at Points C and D (Model 10)

Location	Head Without Nail	With Nail			With Nail and Pseudo K		
		Head	Change	Change %	Head	Change	Change %
C	13.2	15.0	1.8	13.8	15.6	2.4	18.1
D	13.5	16.5	3.0	21.9	17.2	3.6	26.8

Table 12 – Total Inflow, Outflow through the Surface of the Cut Slope, and Outflow through the Left Boundary for the Slope without Soil Nails, with Discrete Nails, and with 'Nail plus a pseudo K for the Soil Nail Zone' (Model 10) (unit: m^2/s over unit width)

	No Nail	With Nails	With Nails + Pseudo K
Total Inflow	3.17×10^{-6}	3.12×10^{-6}	$2.98 \times 10\text{-}6$
Outflow through cut slope surface (%)	1.30×10^{-6} (41.0%)	1.34×10^{-6} (42.9%)	$-1.09 \times 10\text{-}6$ (36.6%)
Outflow through left boundary (%)	1.87×10^{-6} (59.0%)	1.78×10^{-6} (57.1%)	$-1.89 \times 10\text{-}6$ (63.4%)

Table 13 – Changes of Total Head (m) at Points A and D in a Layered Slope with and without Soil Nails during Rainstorm Conditions (Model 11) (% Change relates to the Initial Head of 9 m)

Time (day)	Head At A				Head At D			
	Head with Nail		Head without Nail		Head with Nail		Head without Nail	
	Head	% Change	Head	% Change	Head	% Change	Head	% Change
1	9.6	7	9.8	9	10.3	14	9.7	8
2	10.2	13	10.5	17	11.4	26	10.4	16
3	10.6	17	11.0	22	12.2	36	11.0	22
4	10.8	20	11.3	26	12.9	43	11.5	28

Table 13B – Changes of Total Head (m) at Points A and D in a layered Slope with and without Soil Nails during Rainstorm Conditions using Pseudo K (Model 11B) (% Change relates to the Initial Head of 9 m)

Time (day)	Head At A				Head At D			
	Head with Nail		Head without Nail		Head with Nail		Head without Nail	
	Head	% Change	Head	% Change	Head	% Change	Head	% Change
1	9.2	2	9.3	3	10.2	14	9.6	7
2	9.4	4	9.6	6	11.3	26	10.3	15
3	9.6	7	9.9	10	12.2	35	10.9	21
4	9.8	9	10.3	14	12.9	43	11.4	26

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Table 14 – Total Head (m) at A, B, C, and D in a Uniform 3D Slope (Model 12)

Brief Description of Models	Head at A	Head at B	Head at C	Head at D
Uniform slope	10.231	10.250	10.193	10.983
With nails	10.231	10.252	10.195	11.003

Table 15 – Total Head (m) at A, B, C, and D in a Layered 3D Slope (Model 12)

Brief Description of Models	Head at A	Head at B	Head at C	Head at D
Layered slope	10.911	11.012	11.035	11.615
With nails	10.920	11.026	11.051	11.642

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Table 16 – Total Head (m) at A, B, C, and D for a Soil Nail Zone of Low Hydraulic Conductivity in a Uniform 3D Slope (Model 13)

Case	Brief Description of Models	Head at A	Head at B	Head at C	Head at D
1	Uniform slope	10.231	10.250	10.193	10.983
2	With nails	10.231	10.252	10.195	11.003
3	With nail zone ($K = 10^{-7}$ m/s)	13.022	16.698	18.811	20.258

Table 17 – Total Head (m) at A, B, C, and D for a Soil Nail Zone of Low Hydraulic Conductivity in a Layered 3D Slope (Model 13)

Case	Brief Description of Models	Head at A	Head at B	Head at C	Head at D
1	Layered slope	10.911	11.012	11.035	11.615
2	With nails	10.920	11.026	11.051	11.642
3	With nail zone ($K = 10^{-7}$ m/s)	12.525	16.777	19.449	20.291

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Table 18 – Detailed Changes of Total Head (m) at Point D for Soil Nailing in a Layered 3D Slope with and without Soil Nails under Uniform Rainstorm Conditions (Model 14)

Time (day)	Without Nail	With Nail
1	9.162	9.161
2	9.560	9.561
3	10.172	10.176
4	10.890	10.898

Table 19 – Detailed Changes of Total Head (m) at Point D for Soil Nailing in a Layered 3D Slope with and without Soil Nails under Non-uniform Rainstorm Conditions (Model 14B)

Time (day)	Without Nail	With Nail
1	9.127	9.128
2	9.457	9.460
3	9.965	10.972
4	10.554	10.565

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Table 20 – Comparison of the Total Head (m) obtained from 3D and 2D Modelling of a Uniform Slope (Model 15)
[The numbers in the brackets are coordinates (m)]

3D Results		2D Results	
A(14, 11)	10.231	A'(13.9, 11.6)	11.550
B(20, 11)	10.252	B'(19.6, 10.7)	12.195
C(26, 11)	10.195	C'(26.3, 10.8)	12.642
D(26, 17)	11.003	D'(26.2, 16.9)	13.065

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Table 21 – Summary of Stability Analysis for Various Models

Model No.	Condition	Minimum Factor of Safety		
		Before soil Nailing	After Soil Nailing	
			pseudo-K case	worst case (% reduction*)
4 (4B)	Unconfined three layer slope (eg typical saprolite with colluvial cover)	0.71	1.40	0.94 (-32.9%)
5 (5B)	Confined three layer slope (eg high permeability shear zone within saprolite soil)	0.95	1.79	0.92 (-48.6%)
7 (7B)	Low permeability zone within uniform soil (eg persistent clay seams within saprolite soil)	0.93	1.65	1.53 (-7.3%)
8 (8B)	Confined case due to vertical zone of low permeability (eg low permeability dyke within saprolite soil)	0.92	1.2	0.83 (-30.8%)

Soil nail layout is based on the recommendations of GEO Report No. 56 for the typical slope height of the above models, as adopted in the groundwater modeling for this Study

* reduction in F of S is in comparison to the ‘pseudo-K’ case

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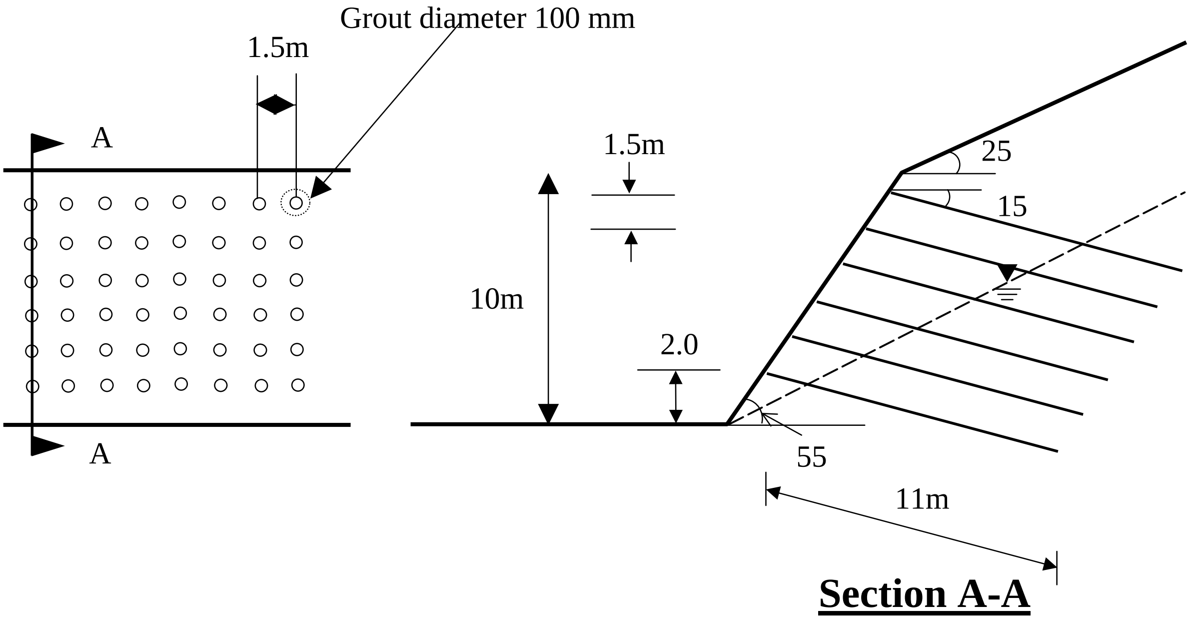
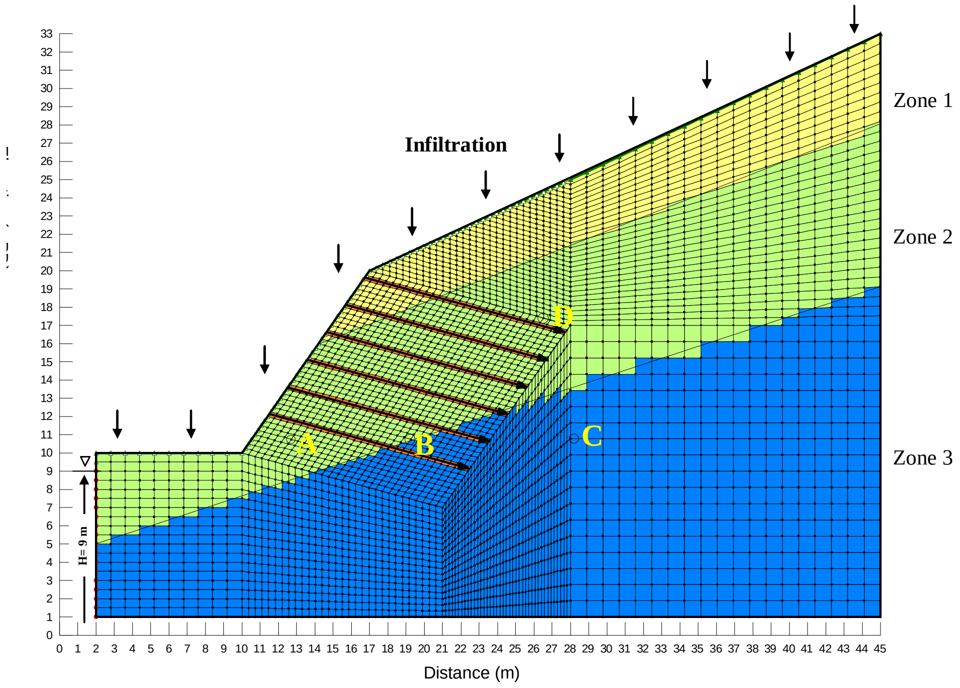


Figure 1 – Configuration of Soil Nailing in Slopes



A uniform infiltration is applied to the ground surface. The head at the left boundary is fixed, with a piezometric surface at 9 m. Other boundaries are set to be no flow boundaries. The three zones represent colluvium or fill, saprolite and bedrock. The red lines represent soil nails. Locations A, B, C and D are monitored as the model is run

Figure 2 – Basic Slope Configuration used in this Study

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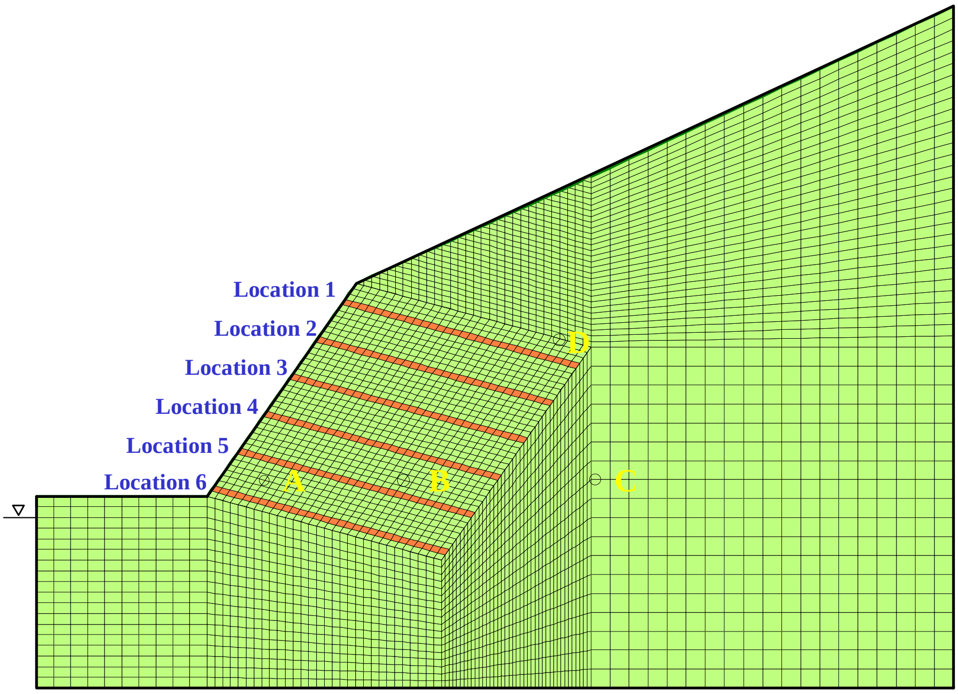


Figure 3 (Model 1) – Possible Six Locations for a Single Soil Nail in a Uniform Slope

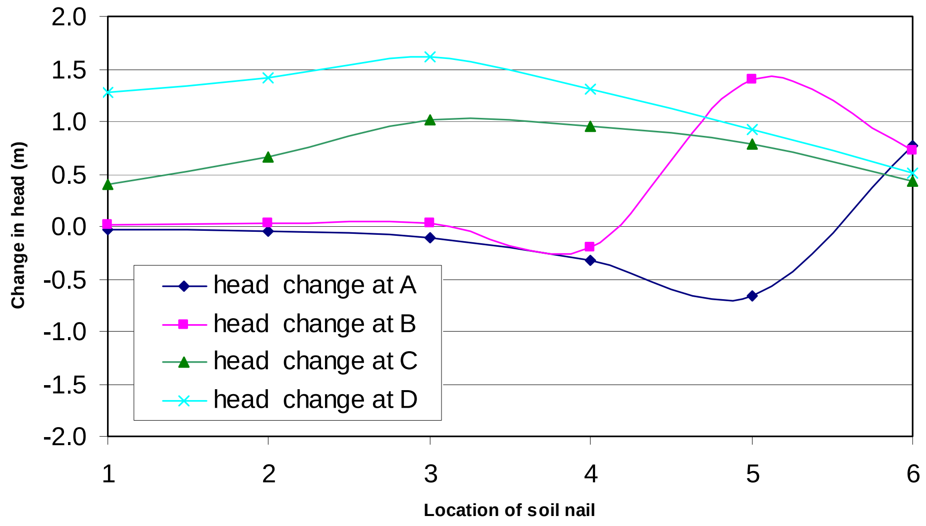
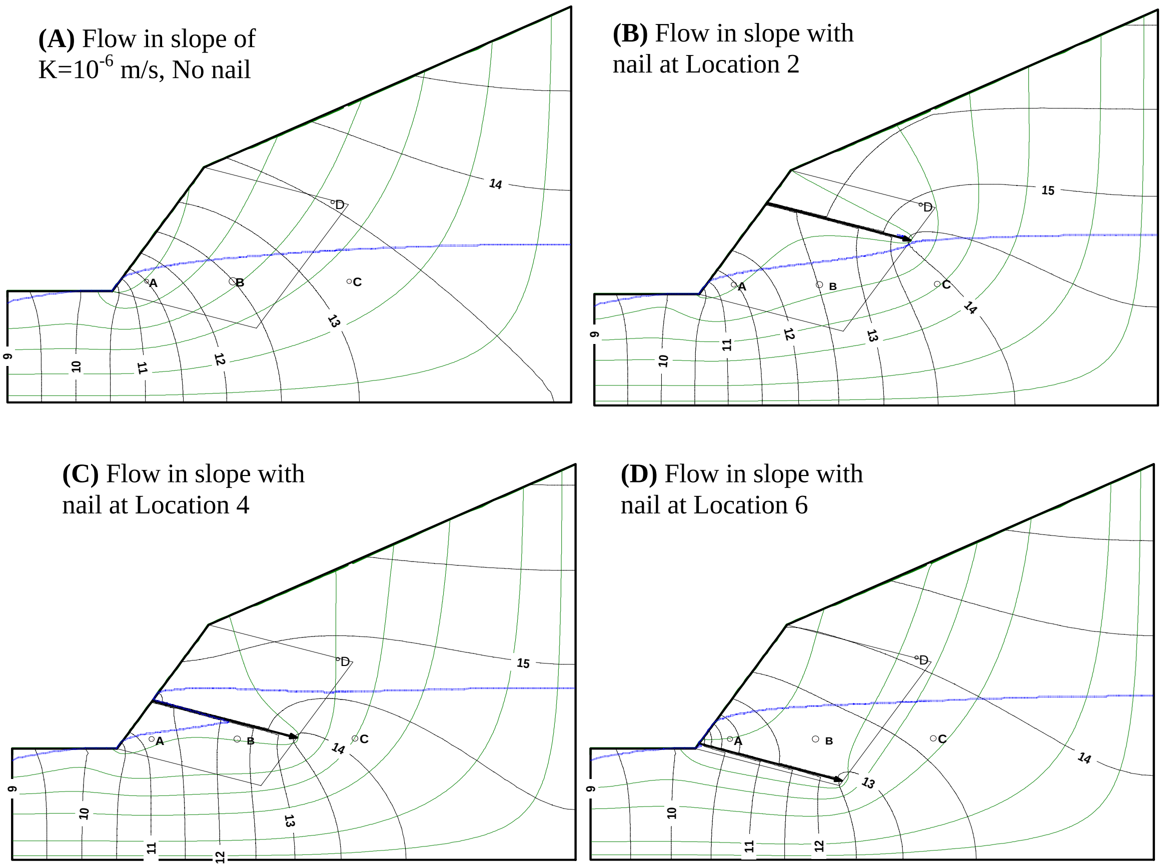


Figure 4 (Model 1) – Changes of Total Head in the Slope at Observation Points A to D after a Soil Nail is installed at different Locations



Note that a perched water table (blue line) and two seepage zones are generated and that the head below the nail can be reduced when the groundwater flow is blocked by the nail (Location 4, Figure 5C).

Figure 5 (Model 1) – (A) Flow net with no Soil Nail; (B) Nail installed at Location 2; (C) Nail installed at Location 4; (D) Nail installed at Location 6

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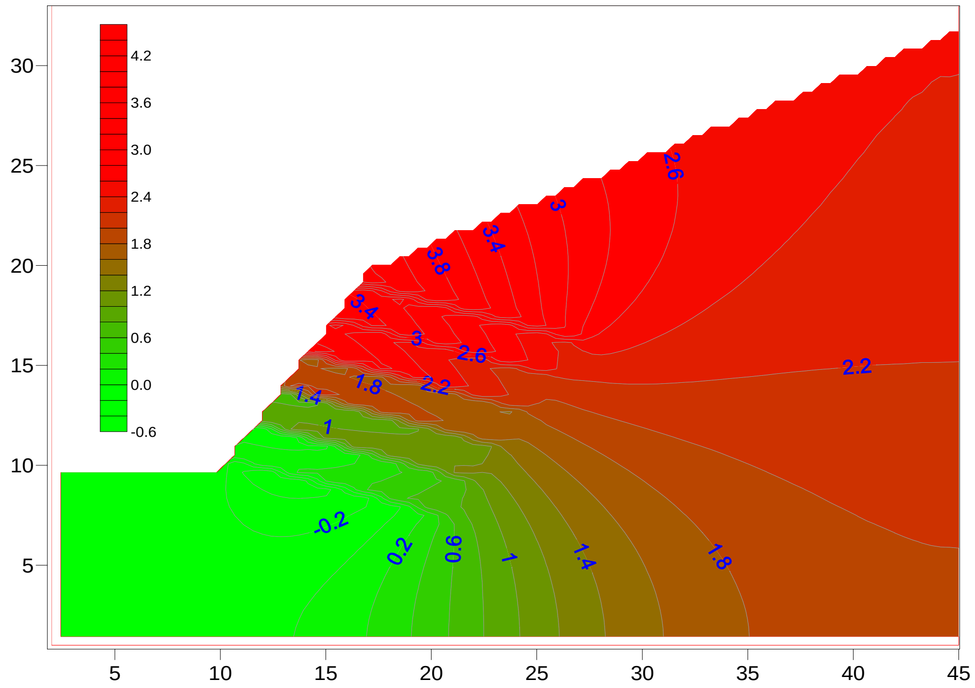

Figure 6 (Model 2) – Contours of Change of Total Head (m) in the Slope
with a Group of Soil Nails

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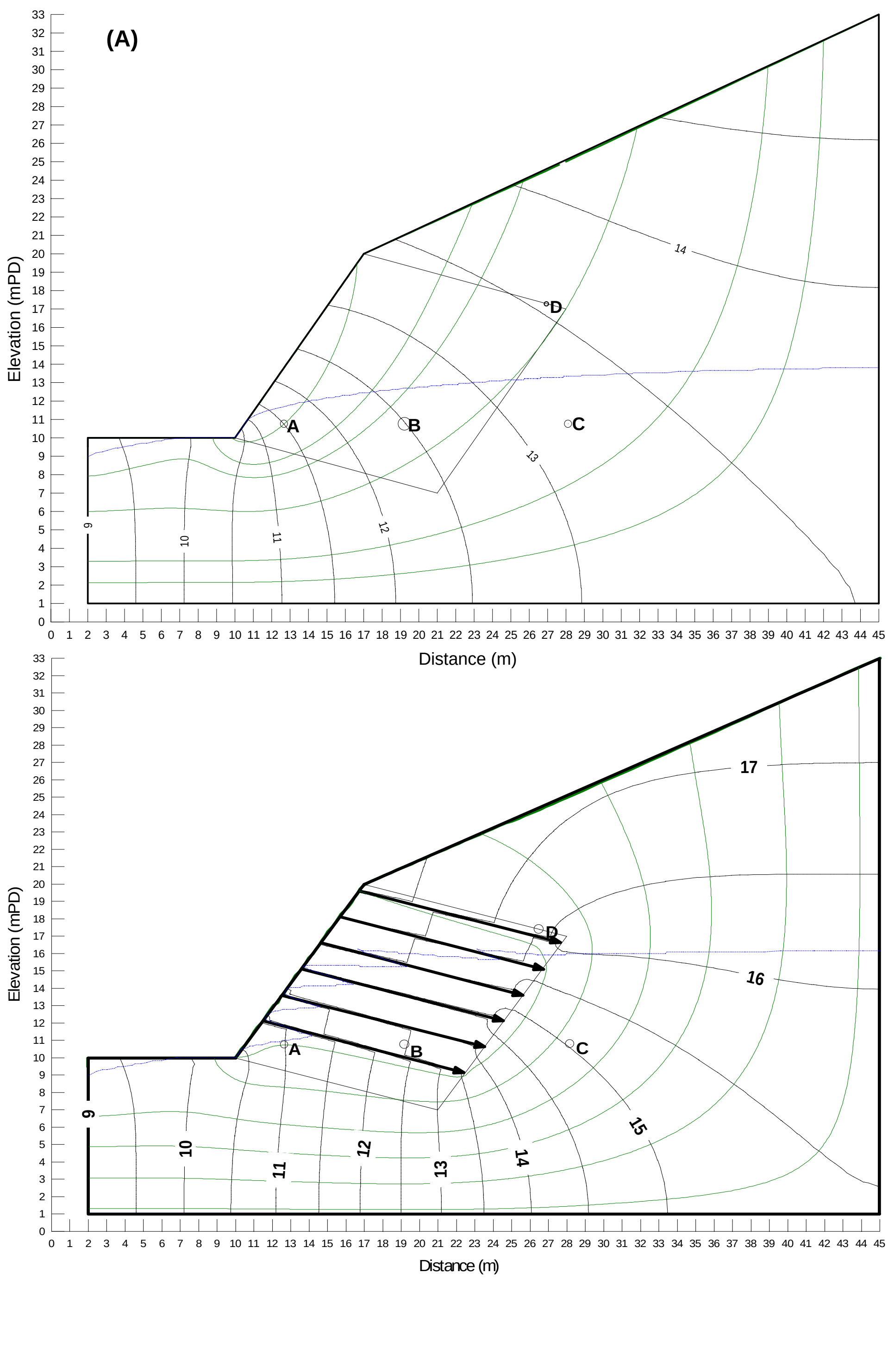

Figure 7 (Model 2) – Uniform Slope with K =10^{-6} m/s before (A) and after (B) Soil Nailing

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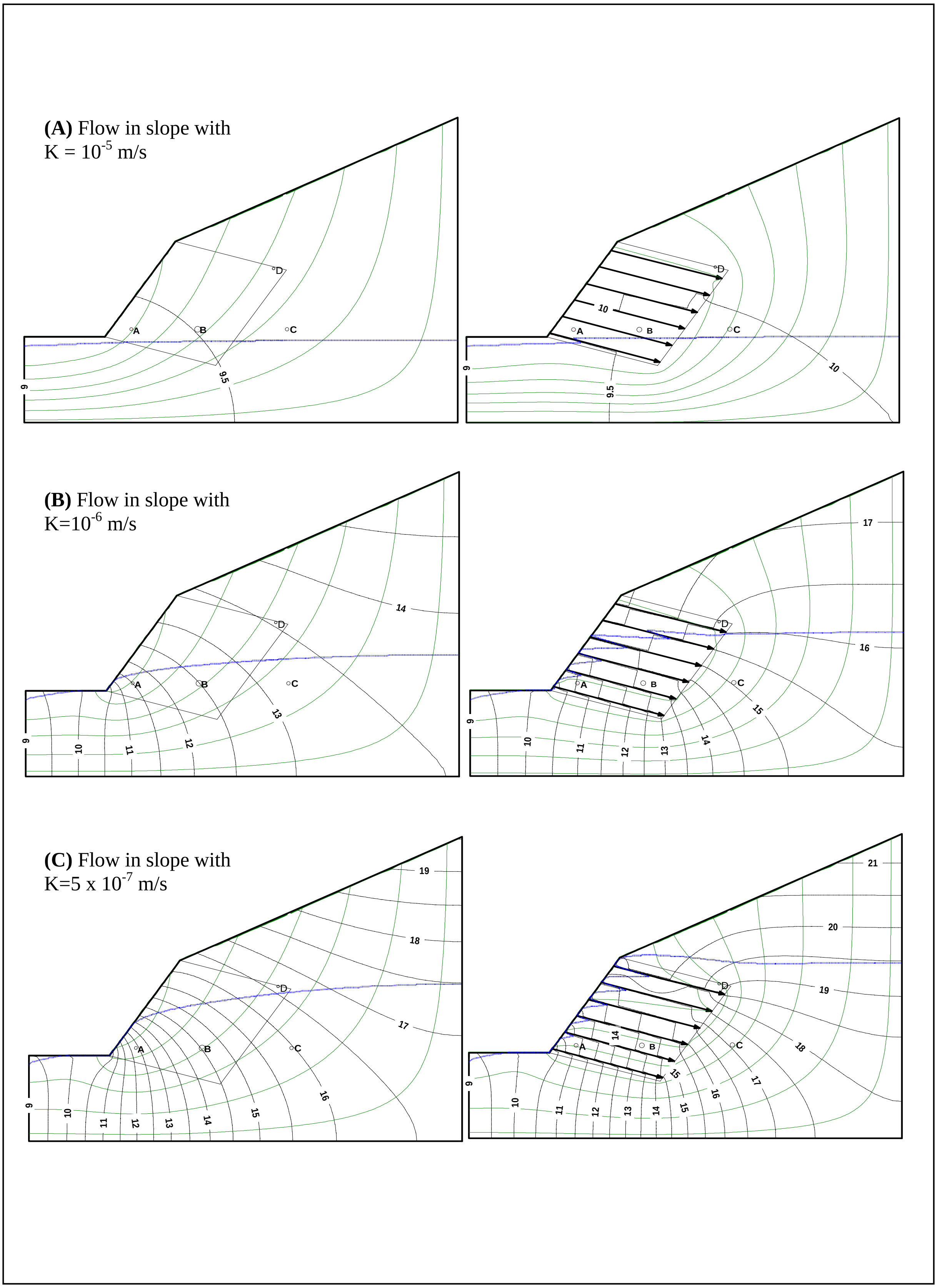

Figure 8 (Model 3) – Comparison of Flow Patterns and Water Tables before (left) And After (right) Soil Nailing for a Uniform Slope with K = 10^{-5} m/s (A), 10^{-6} m/s (B), 5×10^{-7} m/s (C)

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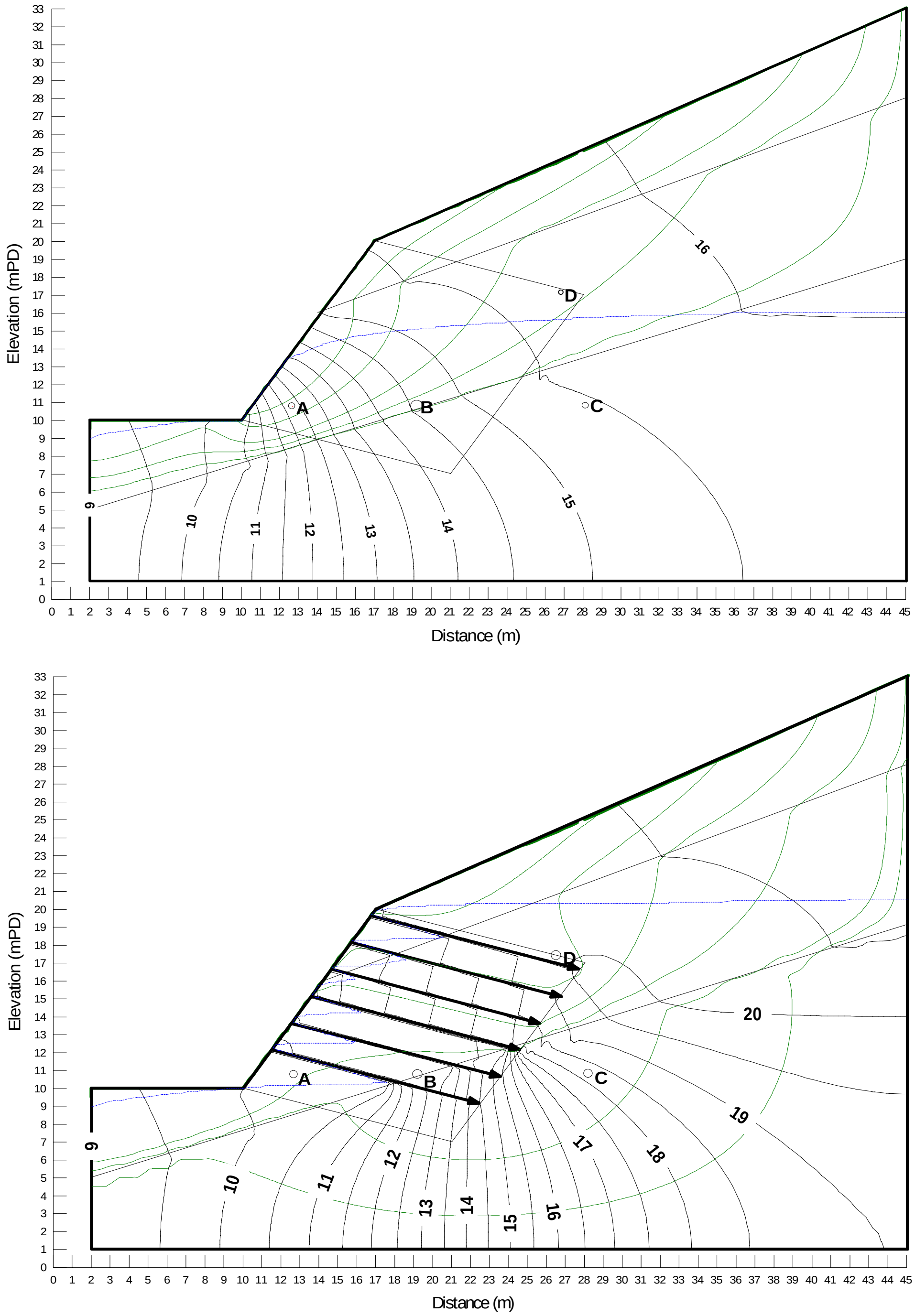

Figure 9 (Model 4) – Comparison of Flow Patterns and Water Tables before (A) and after (B) Soil Nailing for a Three-layer Slope

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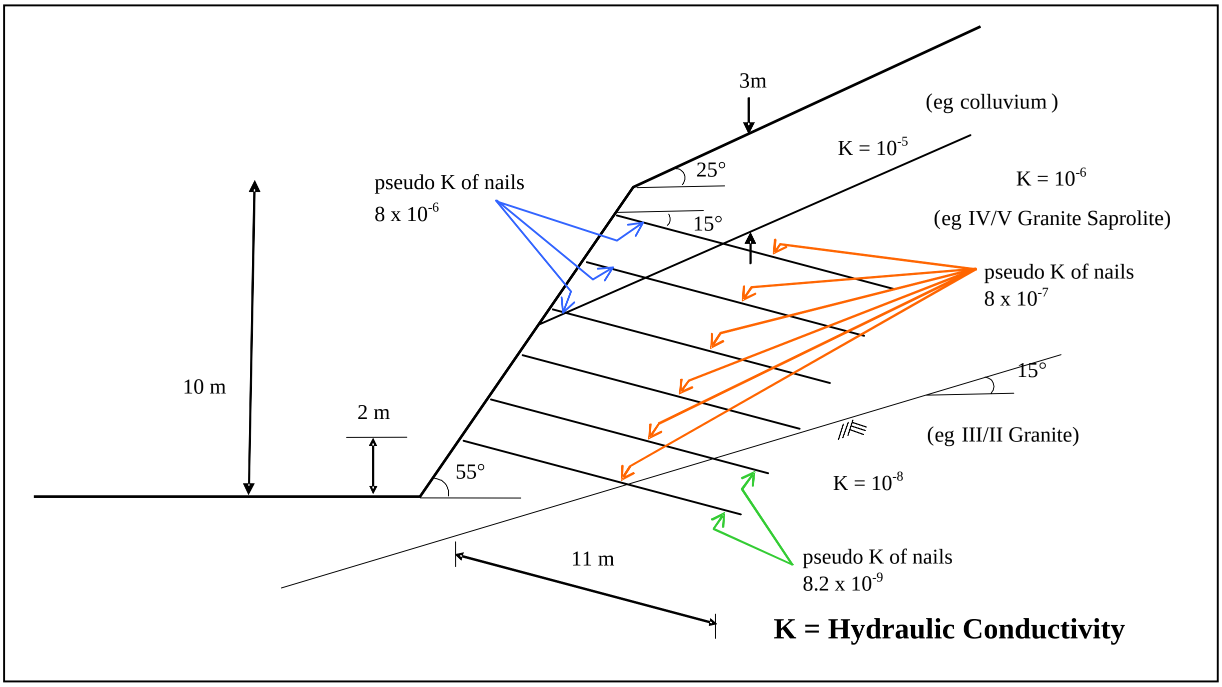


Figure 9C – Pseudo K (m/s) calculated for Model 4B

(Values calculated with regard to Area Footprint of Nails in Plan within the Parent Soil)

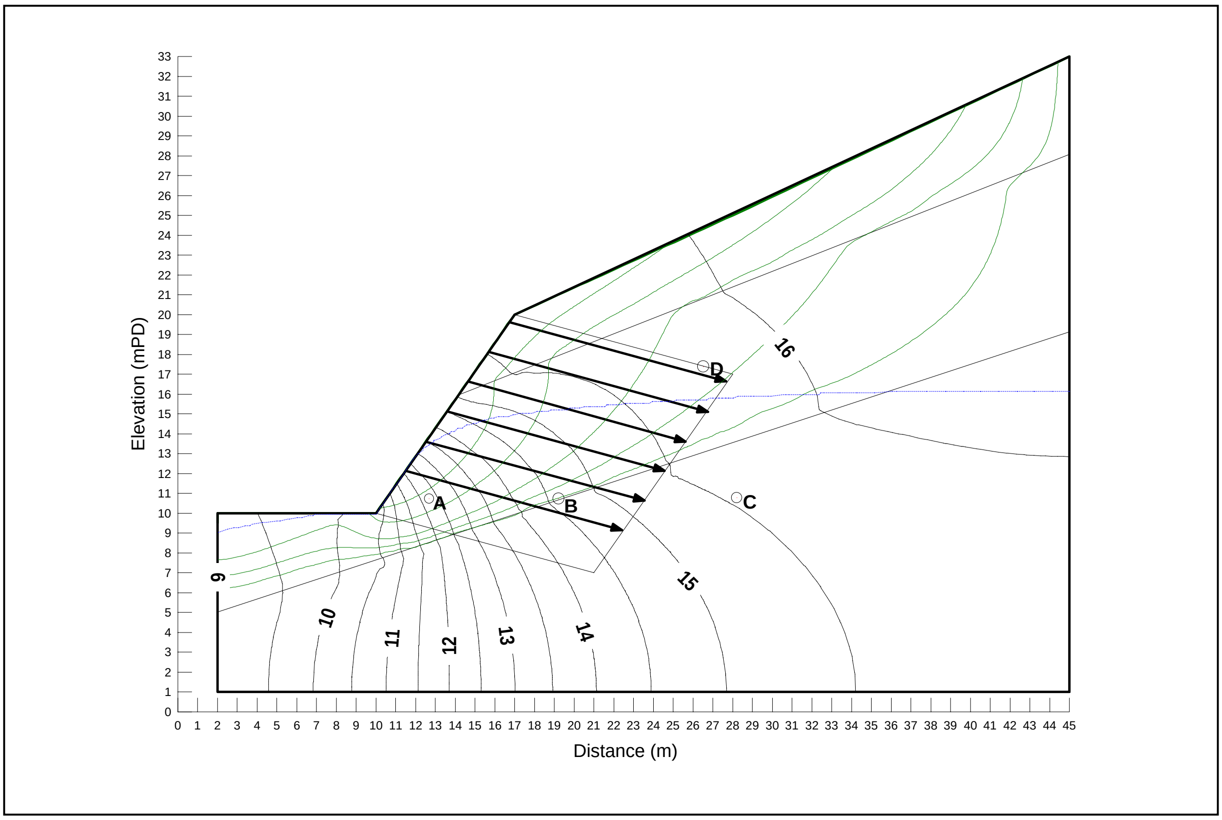
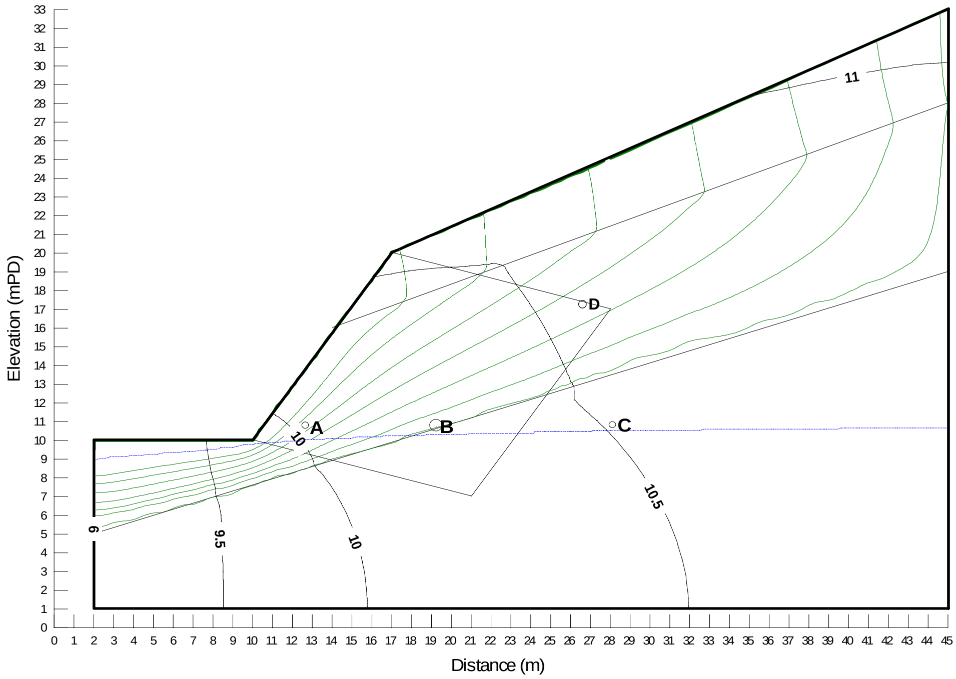


Figure 9D (Model 4B) – Flow Patterns and Water Table after Soil Nailing for a Three-layer Slope using Pseudo K



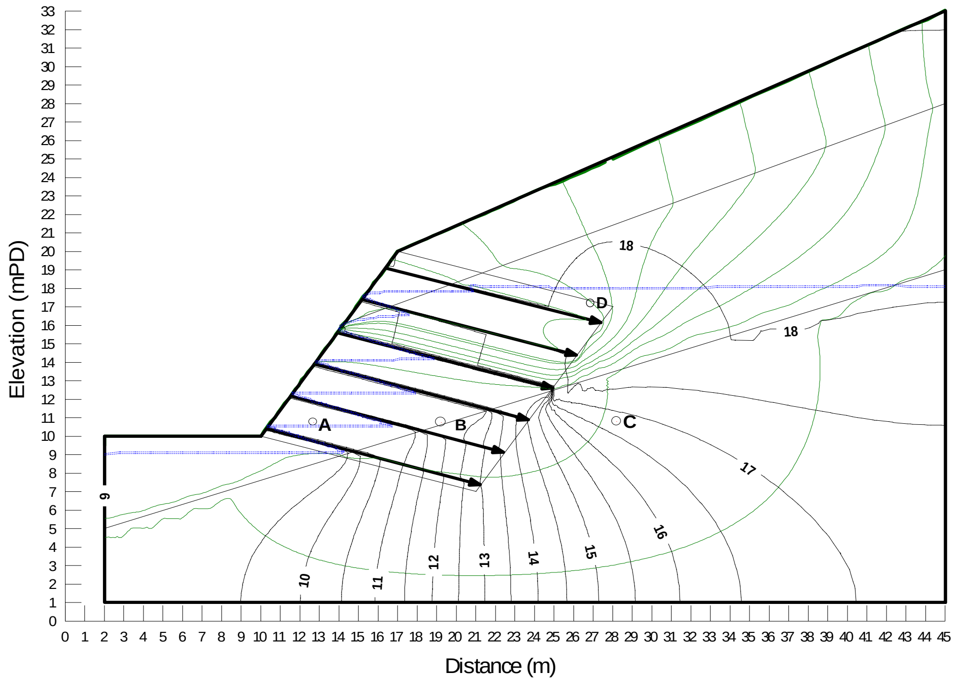


Figure 10 (Model 5) – Comparison of Flow Patterns and Water Tables before (A) and after (B) Soil Nailing for a Three-layer Slope with the Highest Hydraulic Conductivity Zone in the Middle

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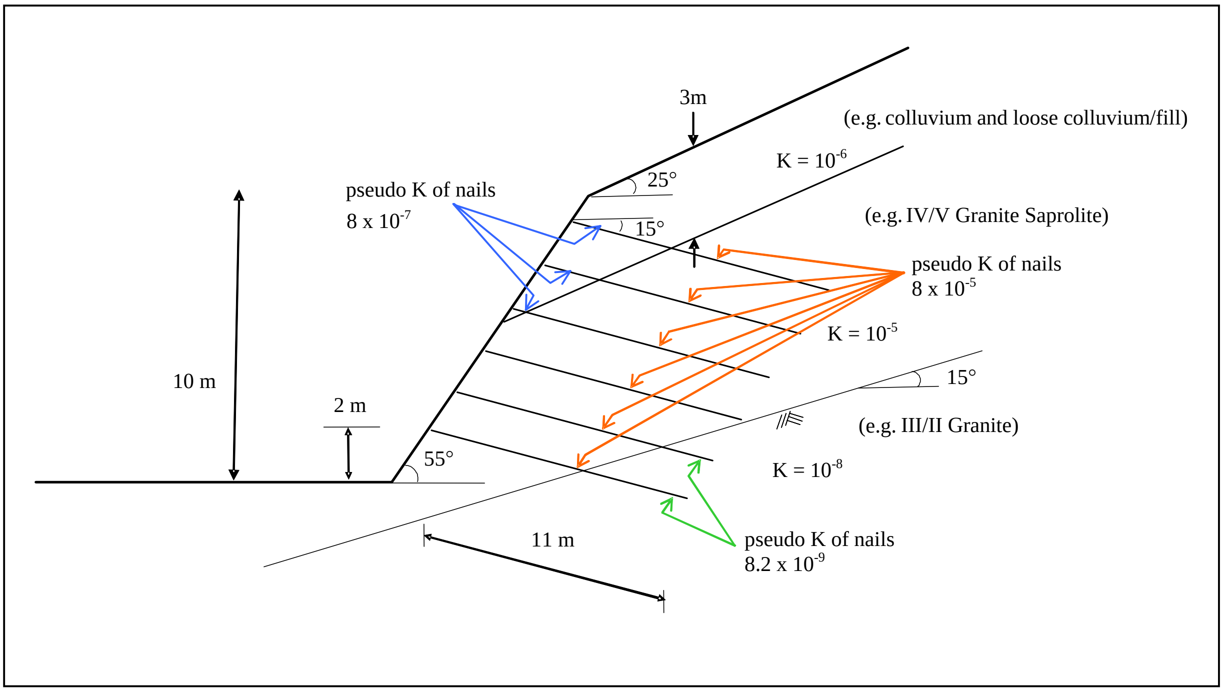

Figure 10C – Pseudo K (m/s) calculated for Model 5

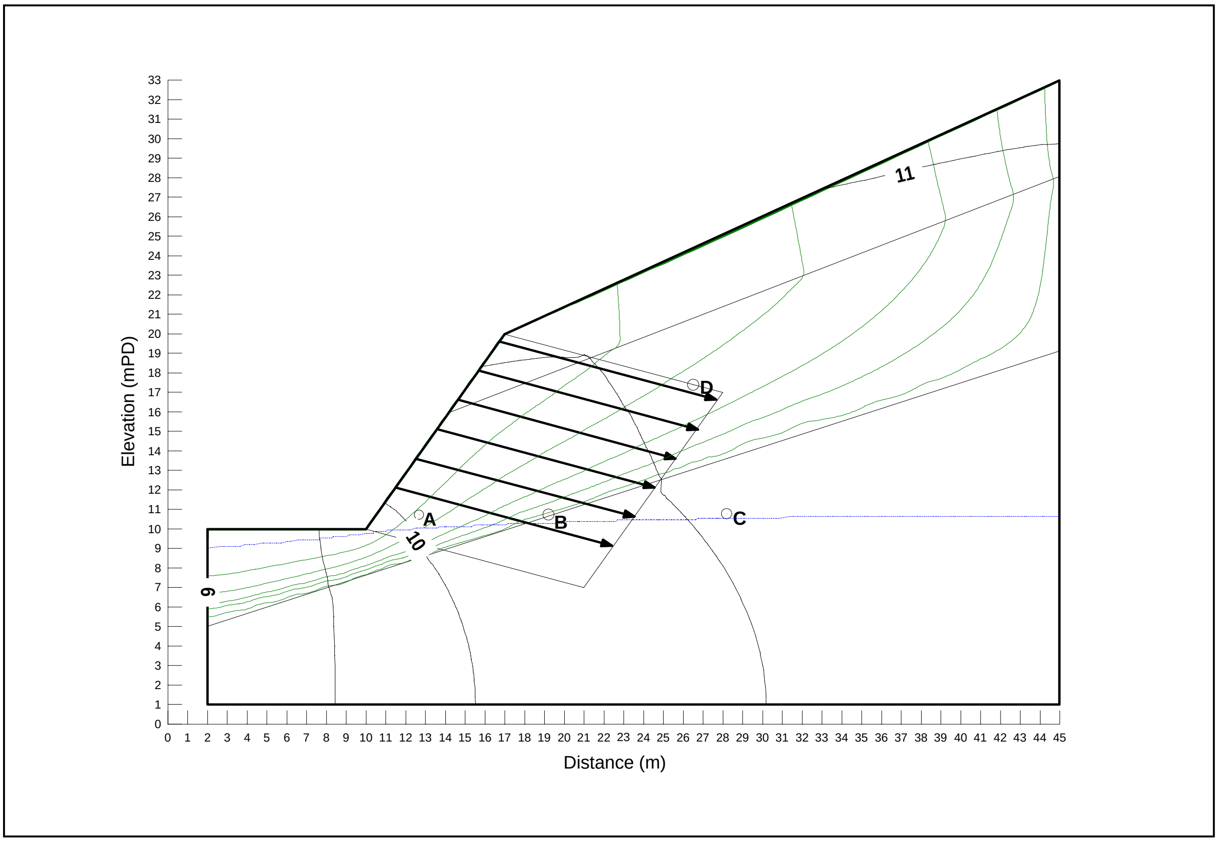

Figure 10D (Model 5B) – Flow Patterns and Water Table after Soil Nailing for a Three-layer Slope with Highest Hydraulic Conductivity Zone in the Middle using Pseudo K

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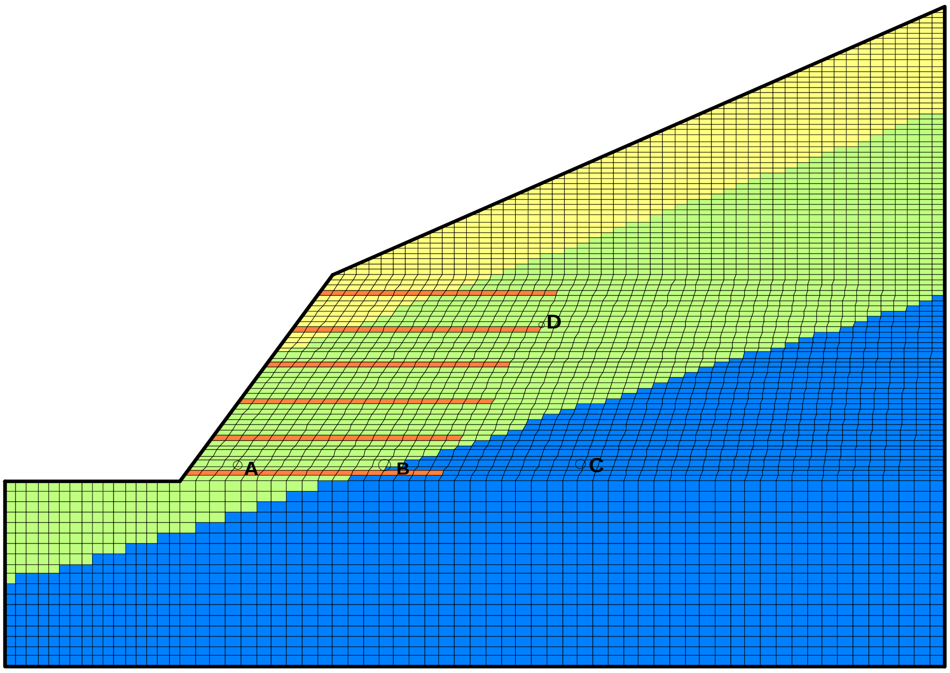

Figure 11 (Model 6) – Horizontal Nails and Mesh System in a layered Slope or Uniform Slope if all the Zones are given the Same Hydraulic Conductivity

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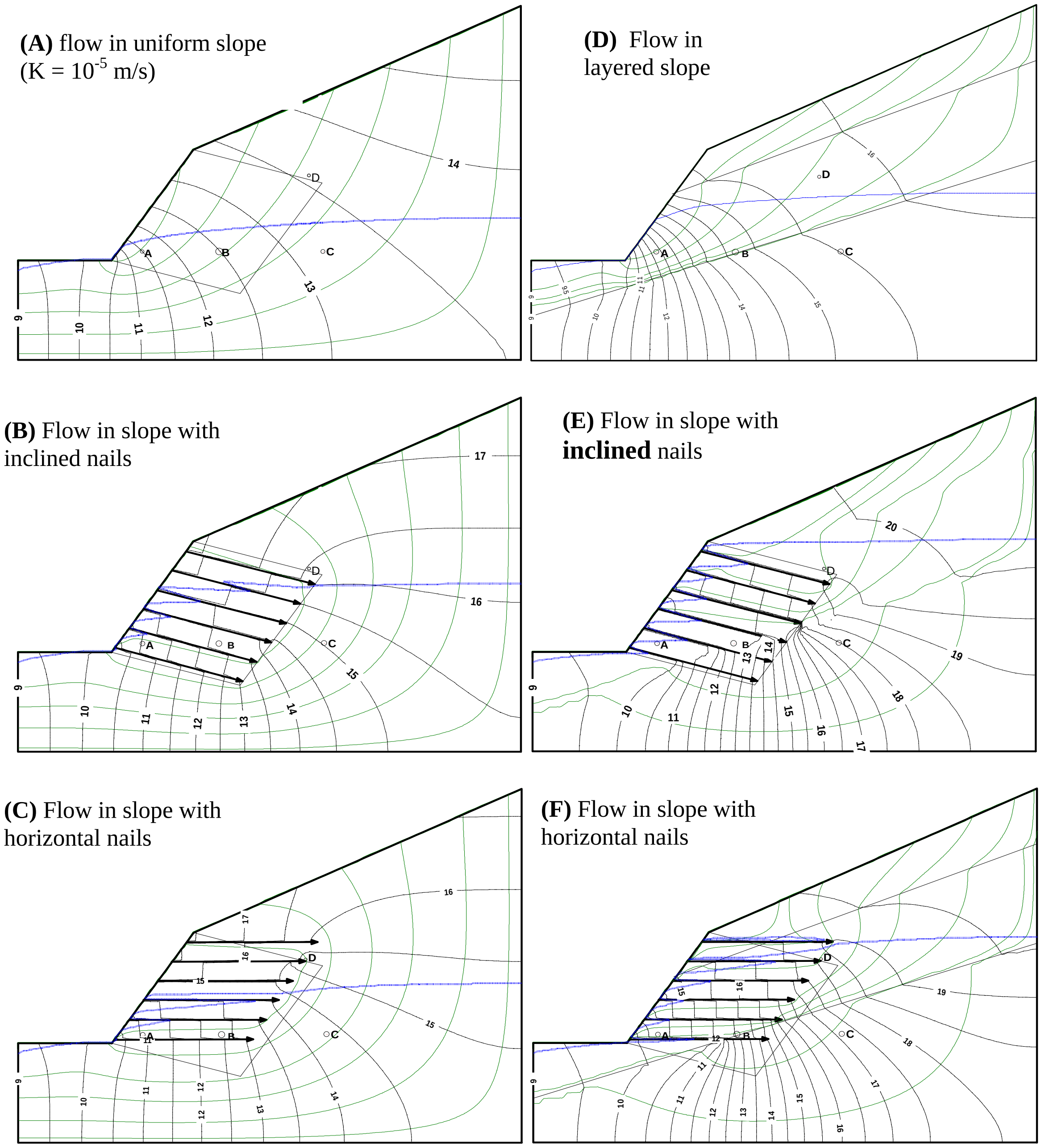

(A) – (C): no nail, inclined nail, and horizontal nail in a uniform slope; (D) – (F) no nail, inclined nail, and horizontal nail in a layered slope

Figure 12 (Model 6) – Comparison of Changes in Flow Patterns in a Uniform Slope (left) And a Three-layer Slope (right) in response to Inclined or Horizontal Soil Nails

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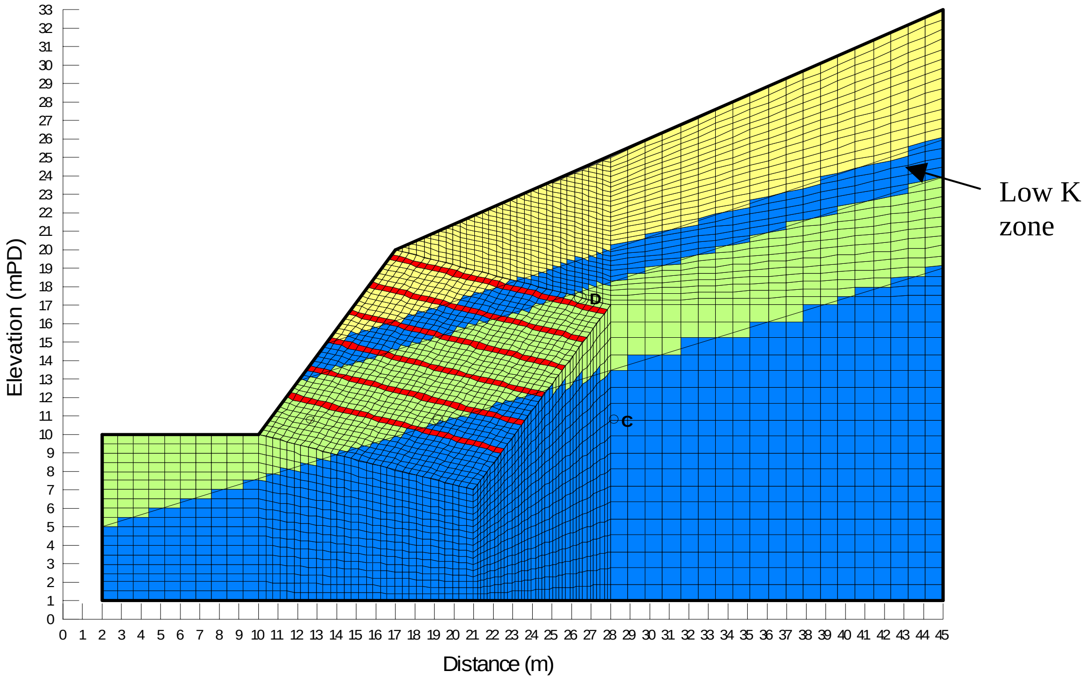

Figure 13 (Model 7) – Soil Nails and Mesh System in the Layered Slope with Thin Zone of Low Hydraulic Conductivity

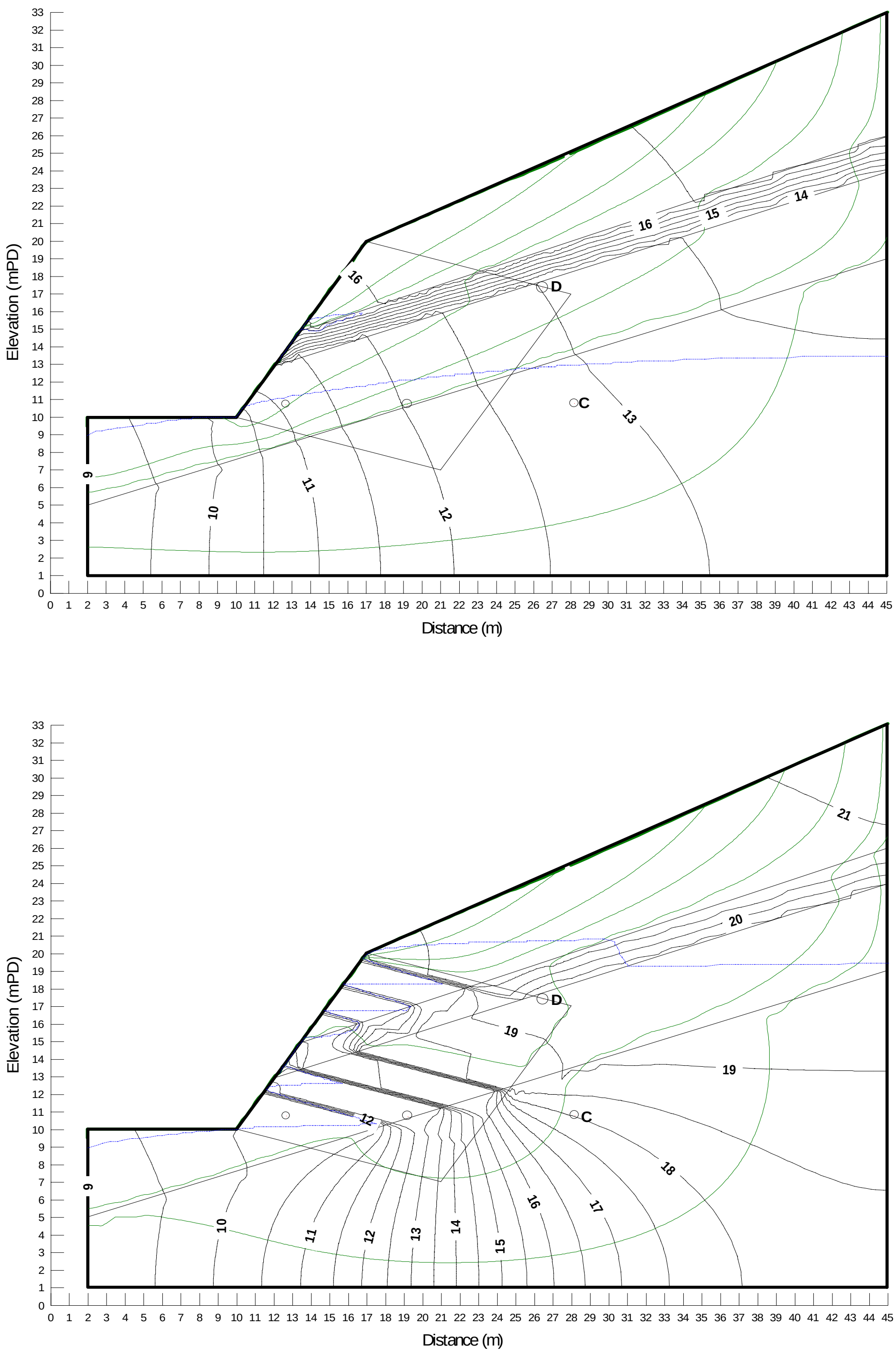

Figure 14 (Model 7) – Comparison of Flow Patterns and Water Tables before (A) and after (B) Soil Nailing for a Slope with Thin Zone of Low Hydraulic Conductivity

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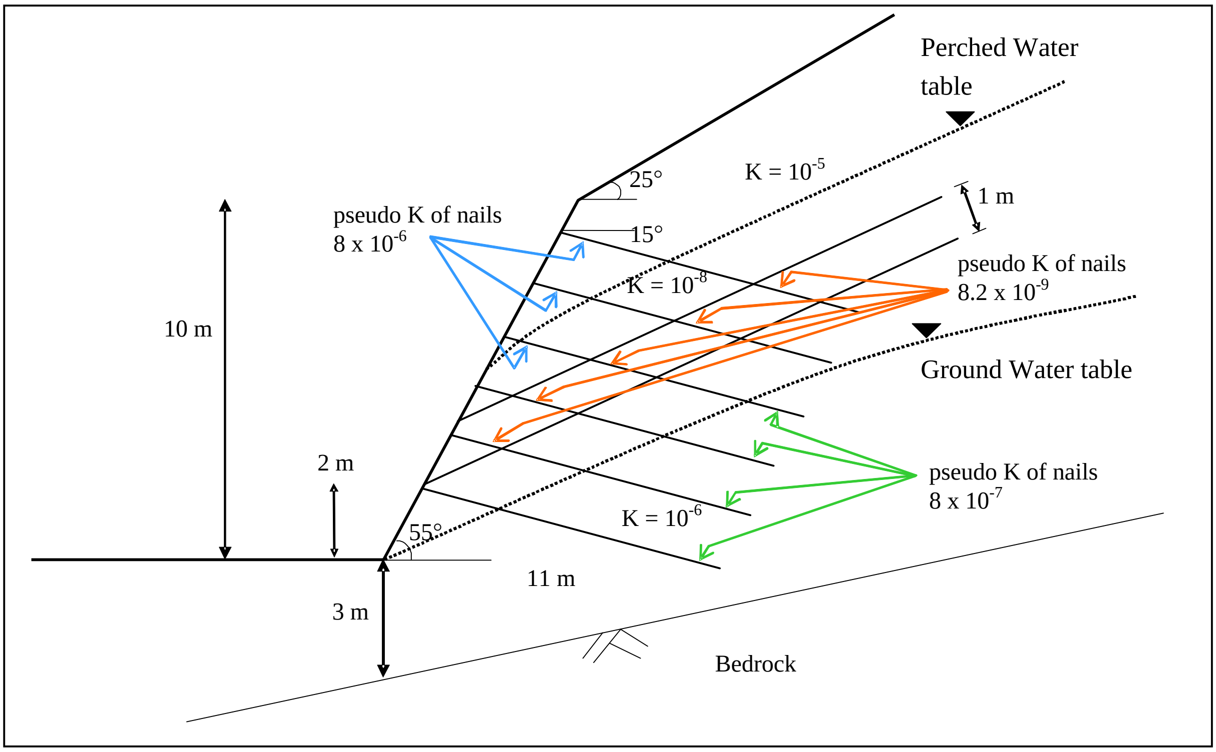

Figure 14C – Pseudo K (m/s) calculated for Model 7B

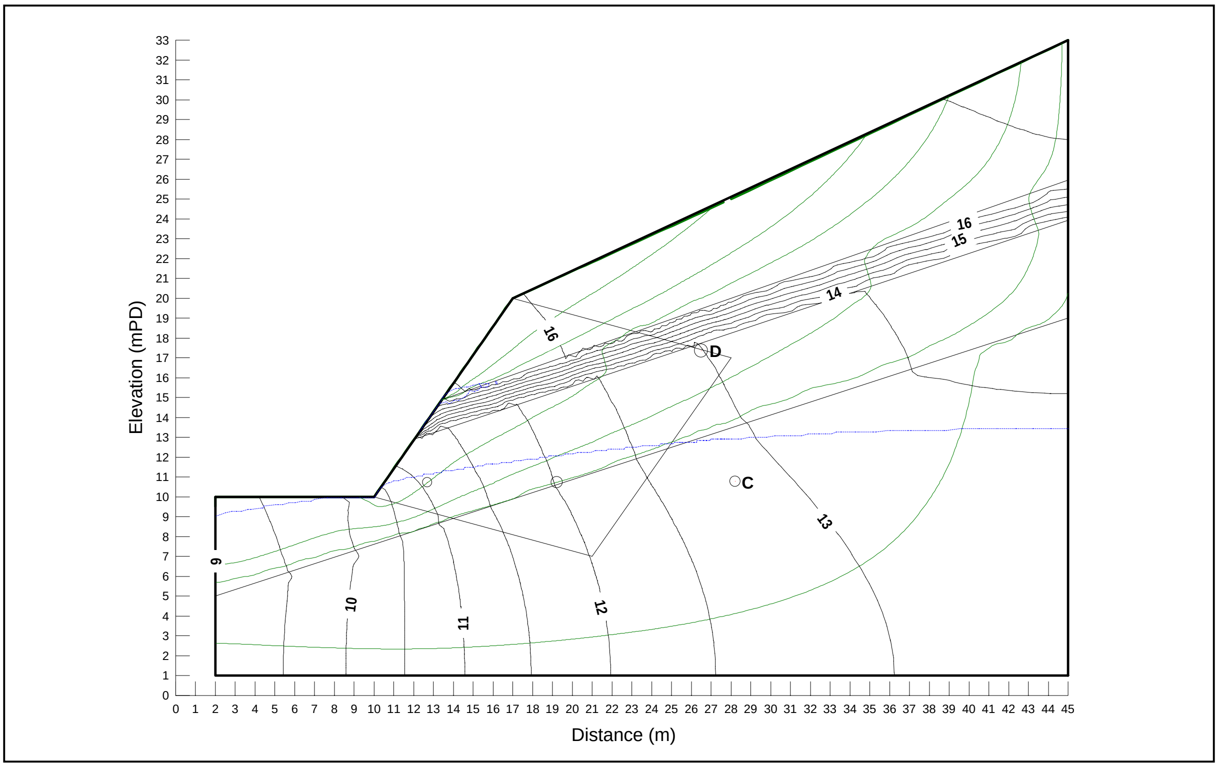

Figure 14D (Model 7B) – Flow Patterns and Water Table after Soil Nailing for a Three-layer Slope with a Thin Zone of Low Hydraulic Conductivity using Pseudo K

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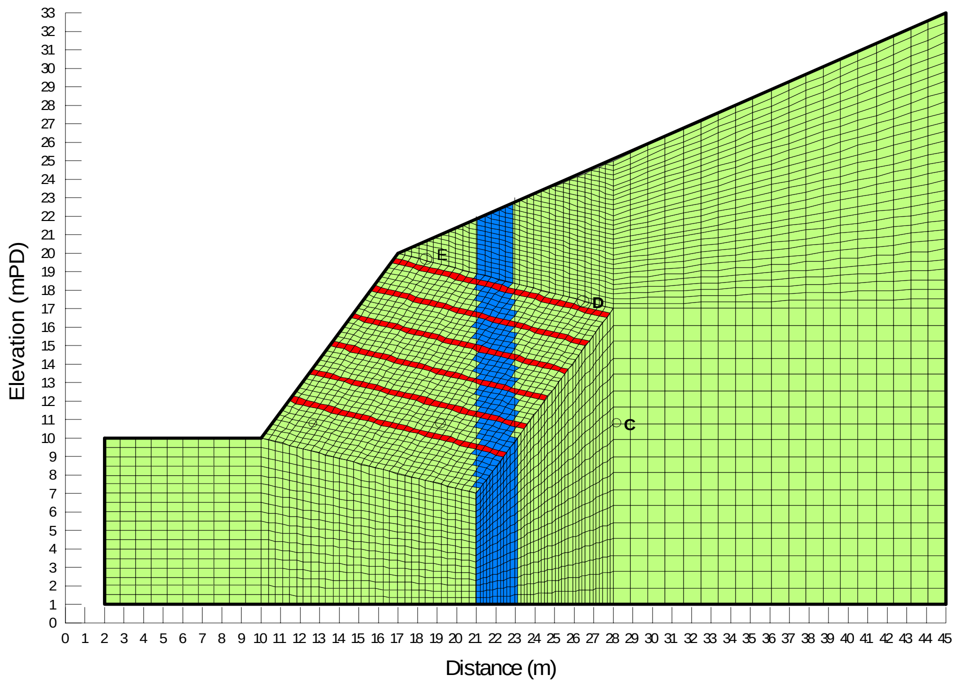

Figure 15 (Model 8) – Soil Nails and Mesh System in a Uniform Slope with a Vertical Dyke of Low Hydraulic Conductivity

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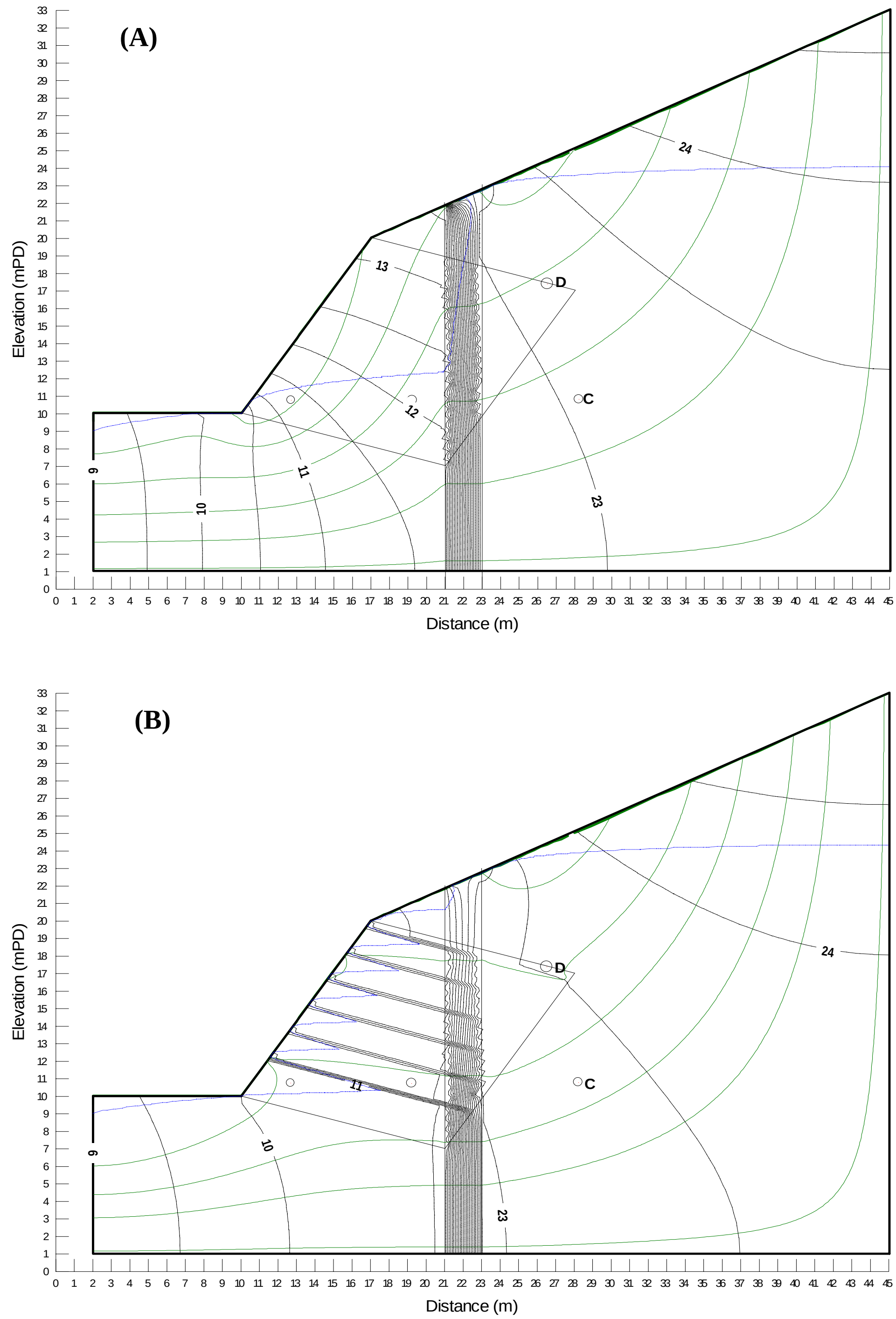

Figure 16 (Model 8)– Comparison of Flow Patterns and Water Tables before (A) and after (B) Soil Nailing for a Slope with a Vertical Dyke of Very Low Hydraulic Conductivity

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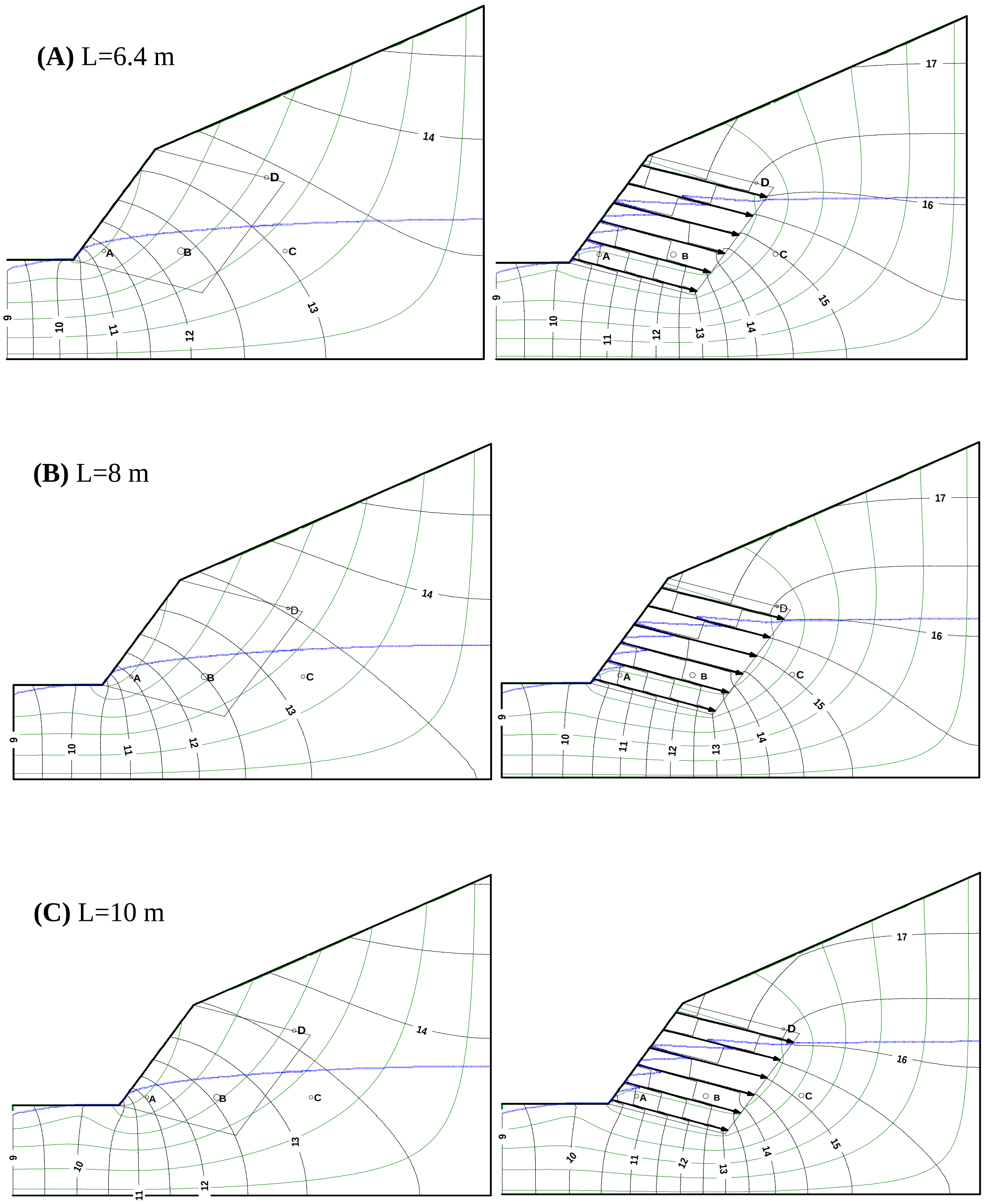

Where L = 6.4 m (A), 8.0 m (B), and 10.0 m (C)

Figure 17 (Model 9) – Comparison of flow patterns and water tables before (left) and after (right) soil nailing for a uniform slope with K $=10^{-6}$ m/s and varied distance from the toe to the left boundary

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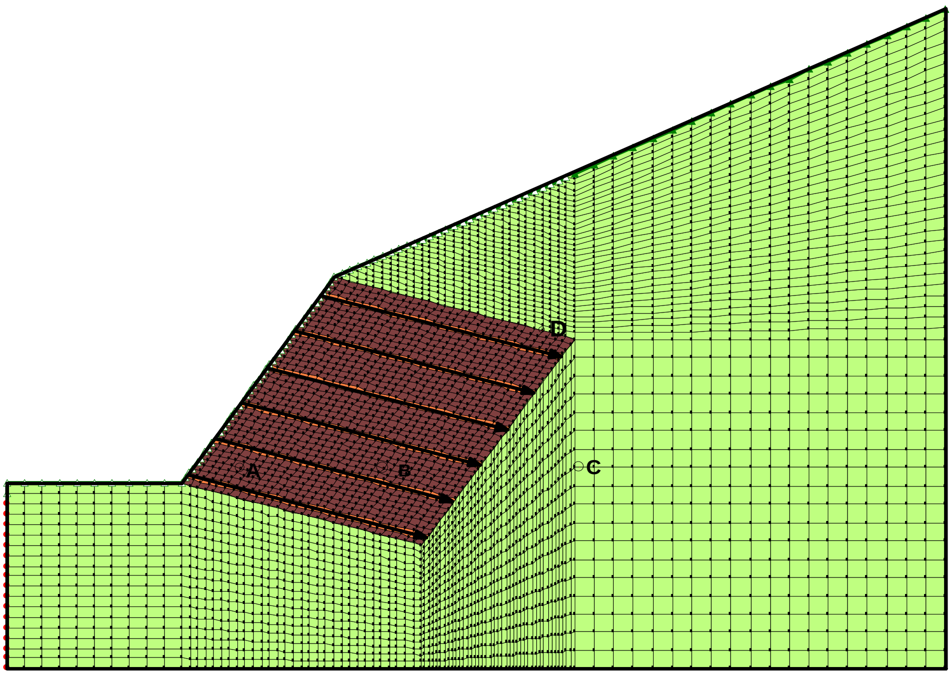

Soil nail zone, shown in brown, is given a Pseudo K of $10^{-7.5}$ m/s

Figure 18 (Model 10) – Soil Nail Zone with a Pseudo Hydraulic Conductivity in a Uniform Slope

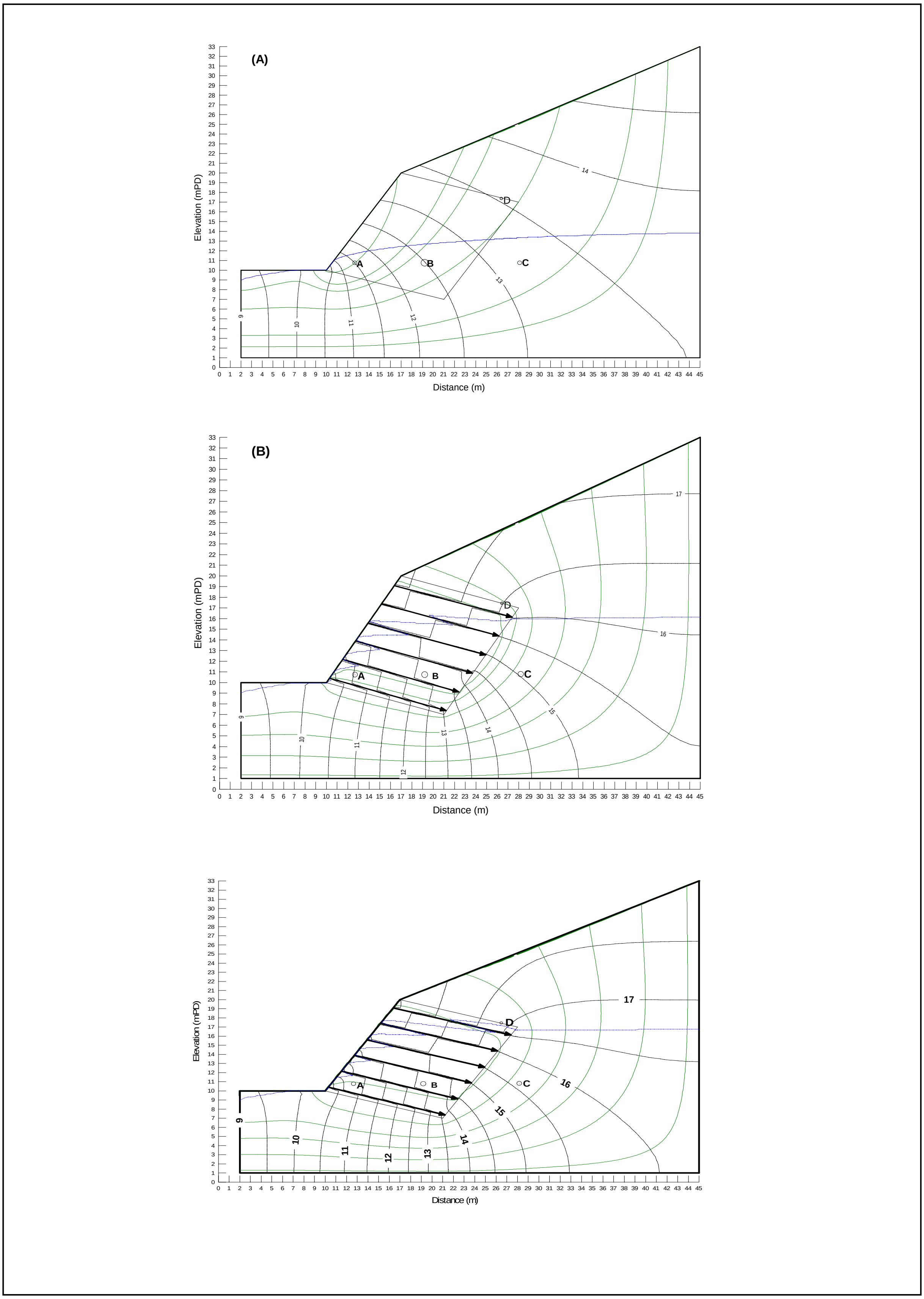

Figure 19 (Model 10) – Flow Pattern in a Uniform Slope, without Soil Nails (A), with Discrete Soil Nails (B) and with Soil Nail Zone of pseudo K (C)

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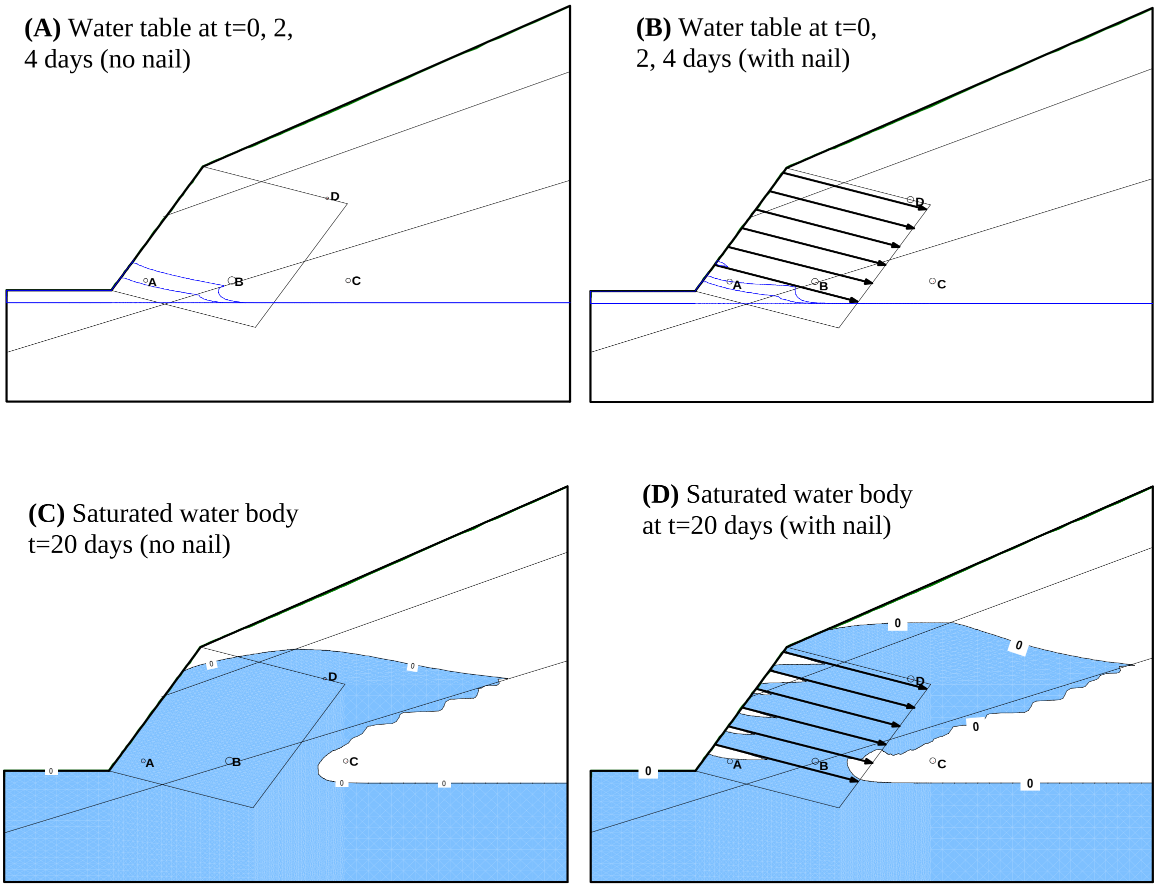

Figures A and B show the water table at time = 0, 2, 4, days and Figures C and D show the water table or saturated water body at time = 20 days, the number 0 on the boundary indicates pressure =0.

Figure 20 (Model 11) – Comparison of Water Tables in a Layered Slope with (right) and without (left) Soil Nails under Rainstorm Conditions

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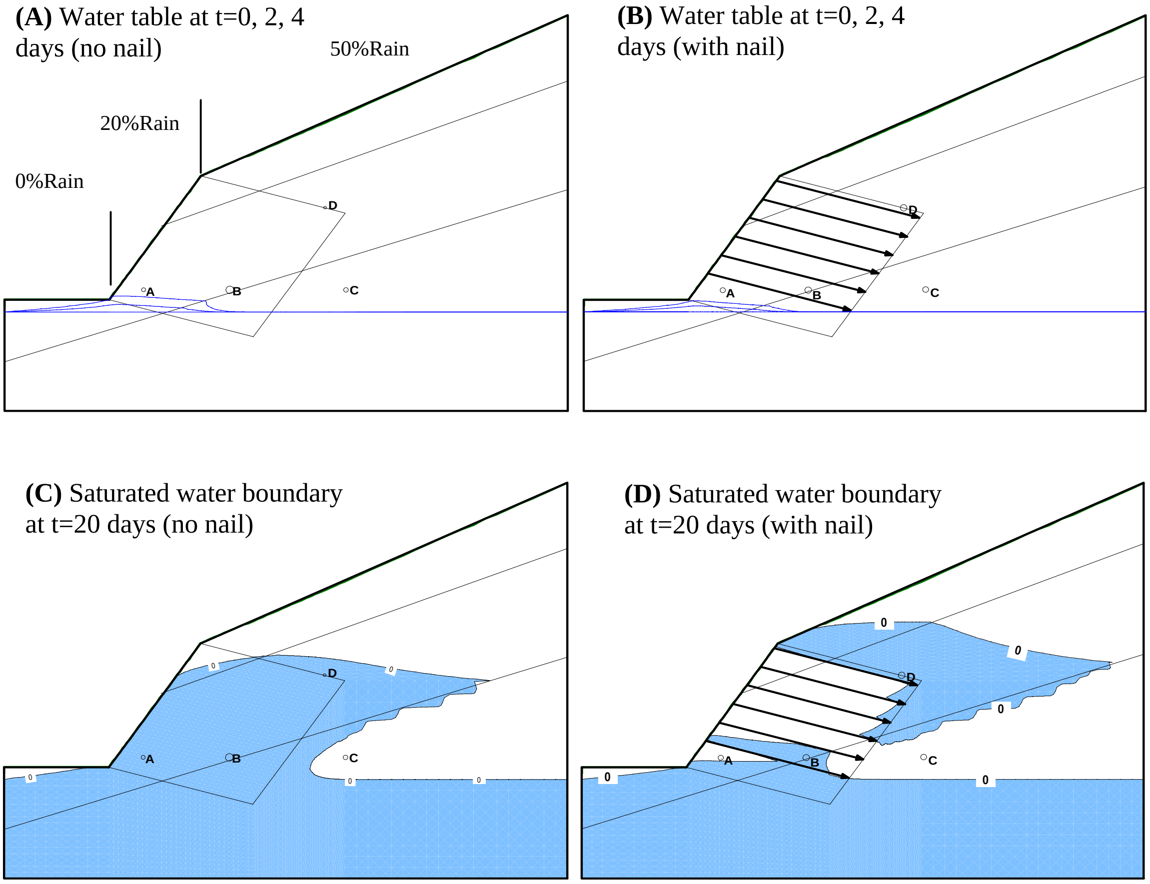

Figures A and B show the water table at time = 0, 2, 4, days; Figures C and D show the water table or saturated water body at time = 20 days, the number 0 on the boundary indicates pressure = 0.

Figure 21 (Model 11B) – Comparison of Water Tables in a layered Slope with (right) and without (left) Soil Nails under Rainstorm Conditions using Pseudo K

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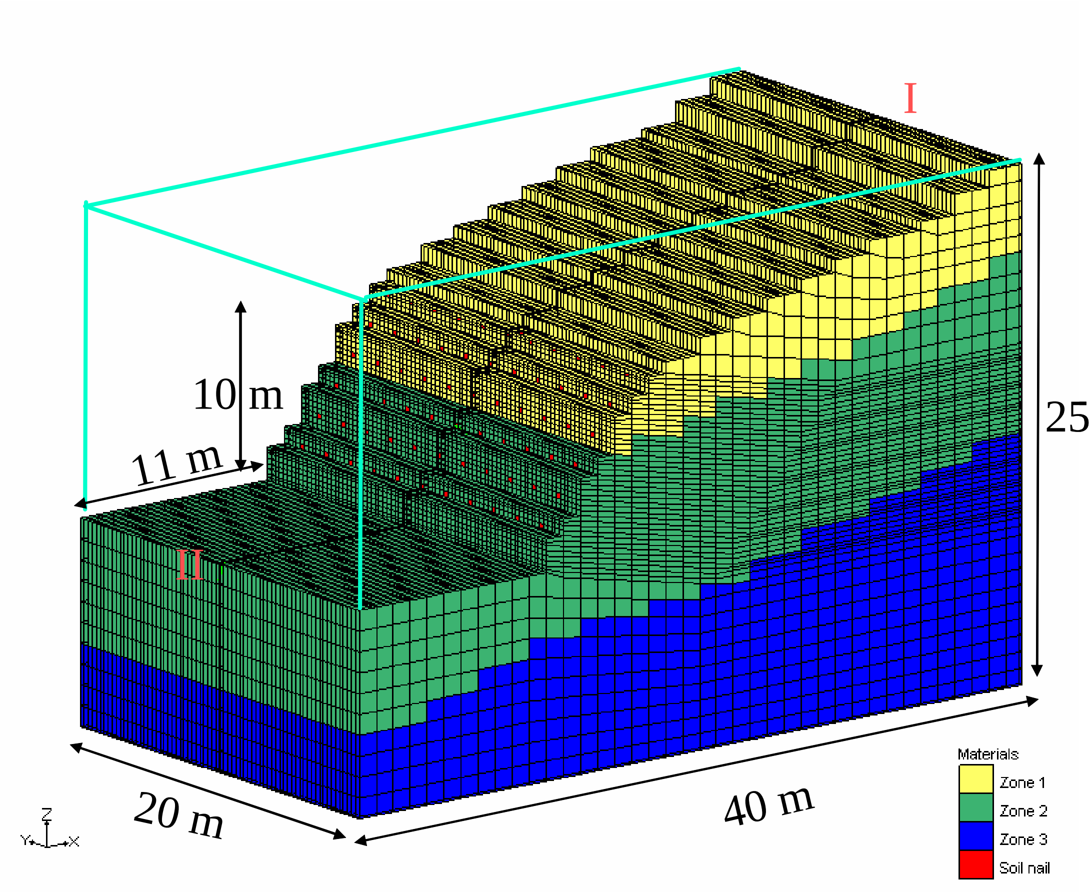

Figure 22 – The Finite-element System used for 3D Modelling in this Study

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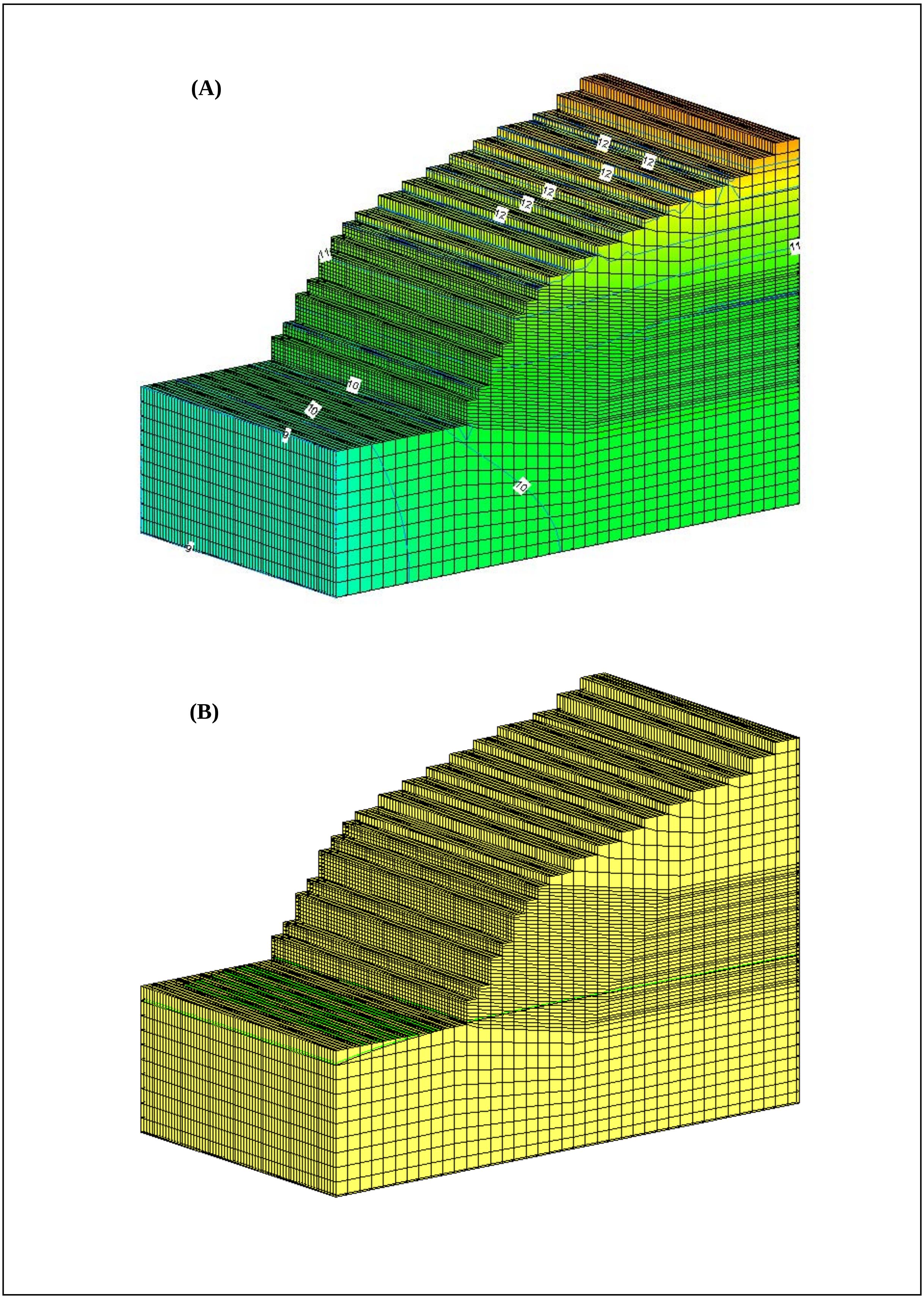

Figure 23 (Model 12) – Simulated Total Head Distribution (A) and Water Table (B) in a Uniform 3D Slope

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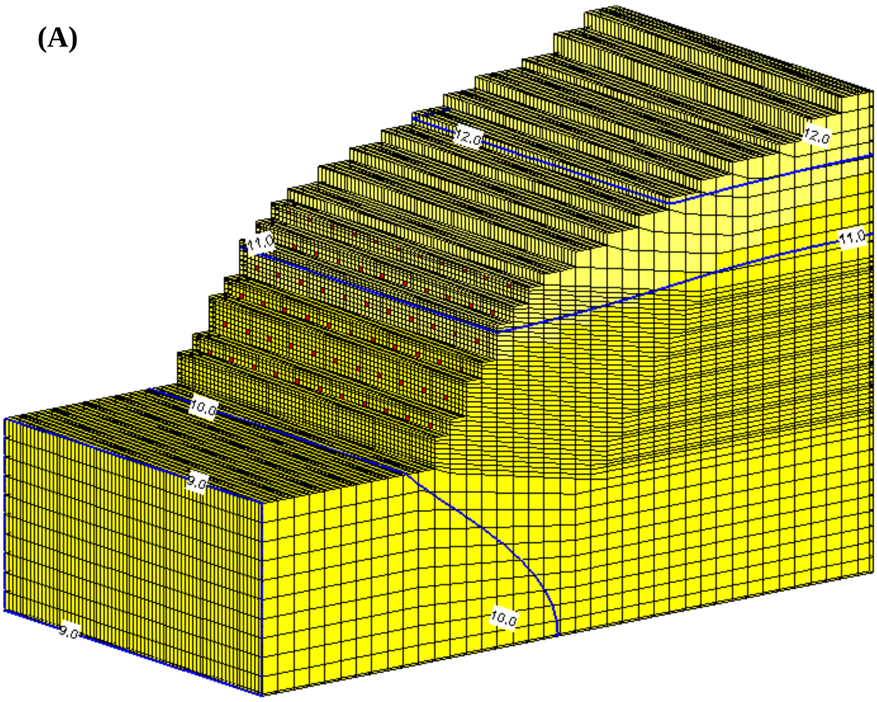

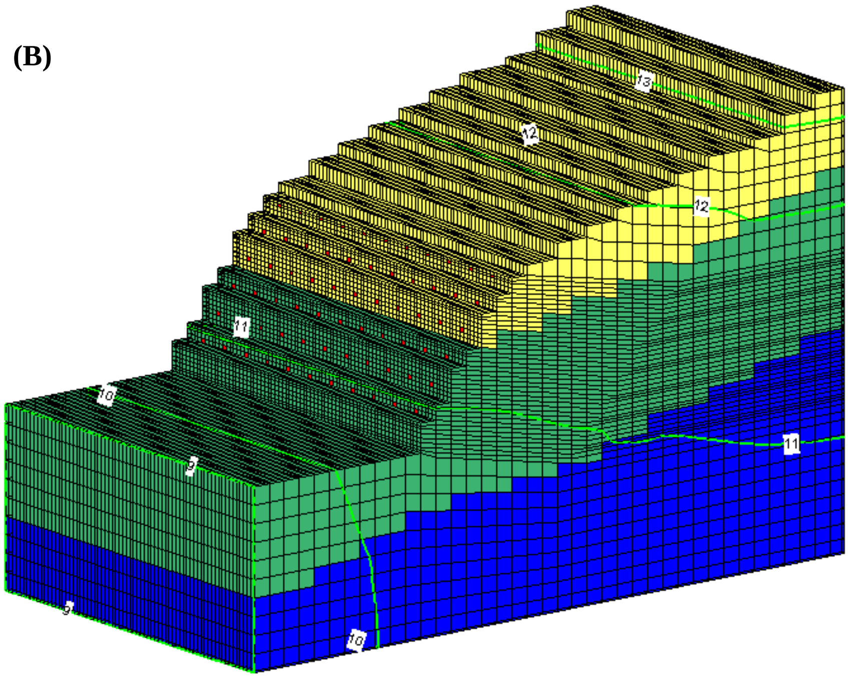

(The small red squares shown on the slope surface are the soil nail locations)

Figure 24 (Model 12) – Simulated Total Head Distributions in a Uniform 3D Slope with Soil Nails (A) and a Layered 3D Slope with Soil Nails (B)

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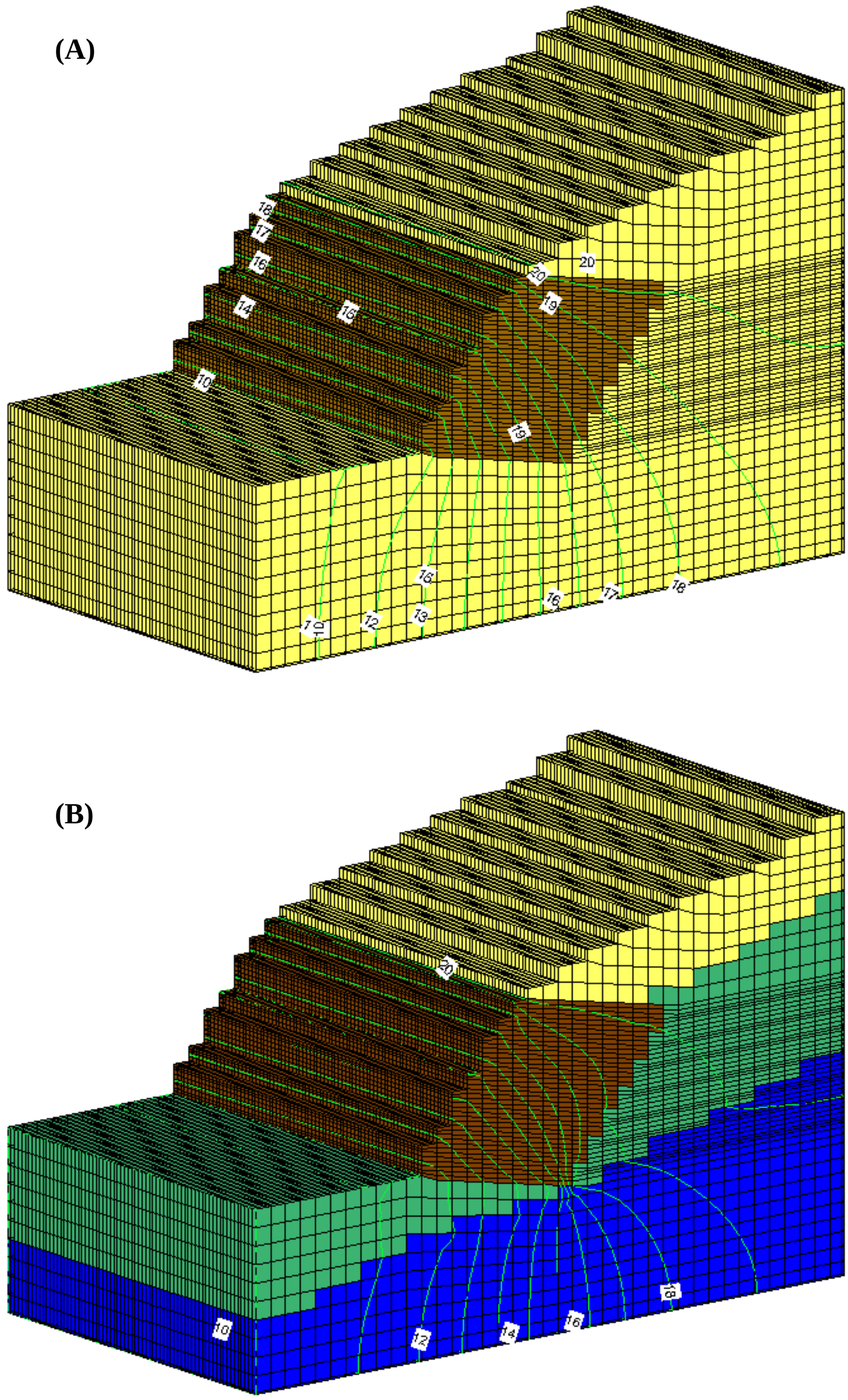
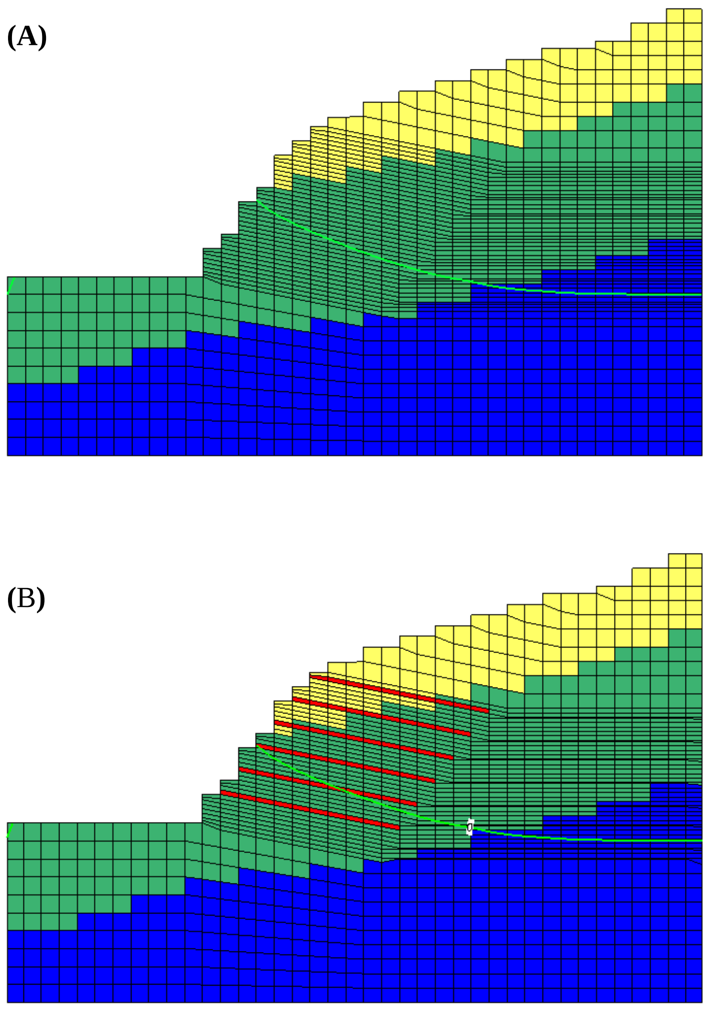


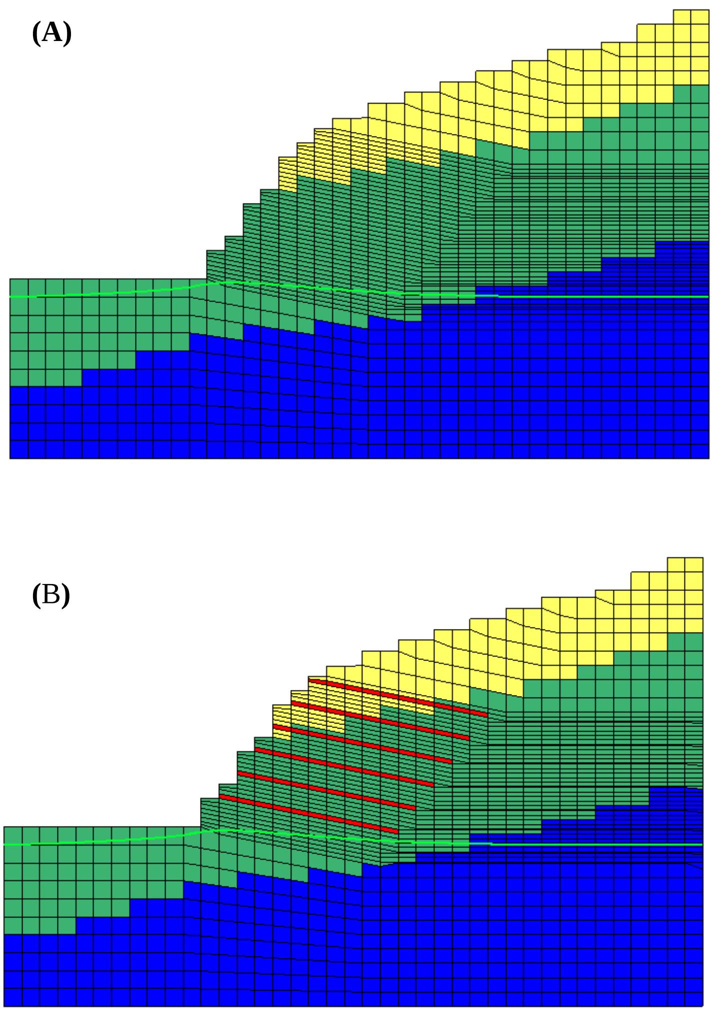
Figure 25 (Model 13) – Simulated Total Head Distributions for a Soil Nail Zone with low Hydraulic Conductivity in a Uniform 3D Slope (A) and a Layered 3D Slope (B)



Red Bars represent the Soil Nails

See Figure 22 for location of cross section

Figure 26 (Model 14) – Water Table along Cross Section I-II in a layered 3D Slope without (A) and with (B) Soil Nails after Four Days of Rainstorm Conditions



Red Bars represent Soil Nails

See Figure 22 for Location of cross section

Figure 27 (Figure 14B) – Water Table along Cross Section I-II in a layered 3D Slope without (A) and with (B) Soil Nails after Four Days of Non-uniform Rainstorm Conditions.

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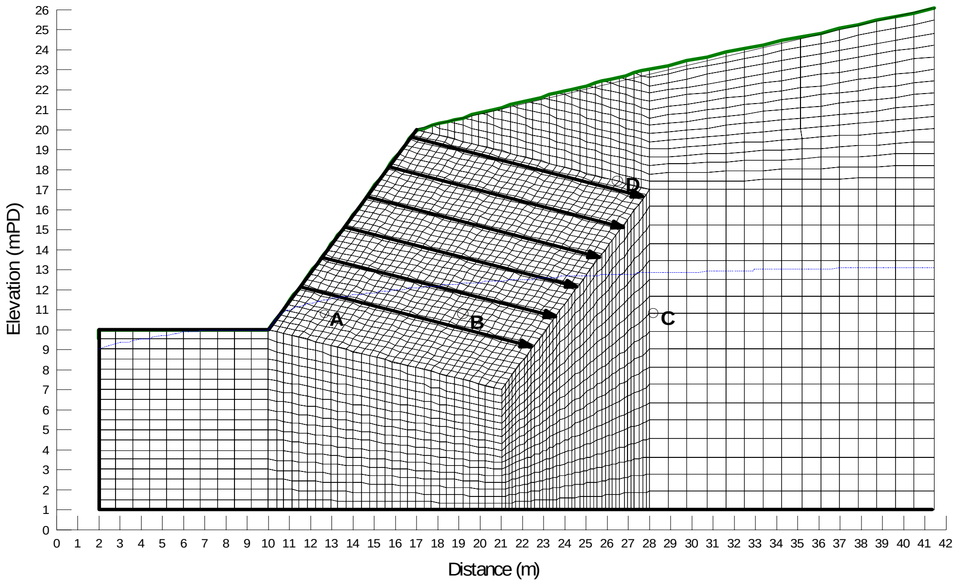

Figure 28 (Model 15) – 2D Model for Comparison with the 3D Model for a Uniform Slope with Soil Nails (ie Figure 23B)

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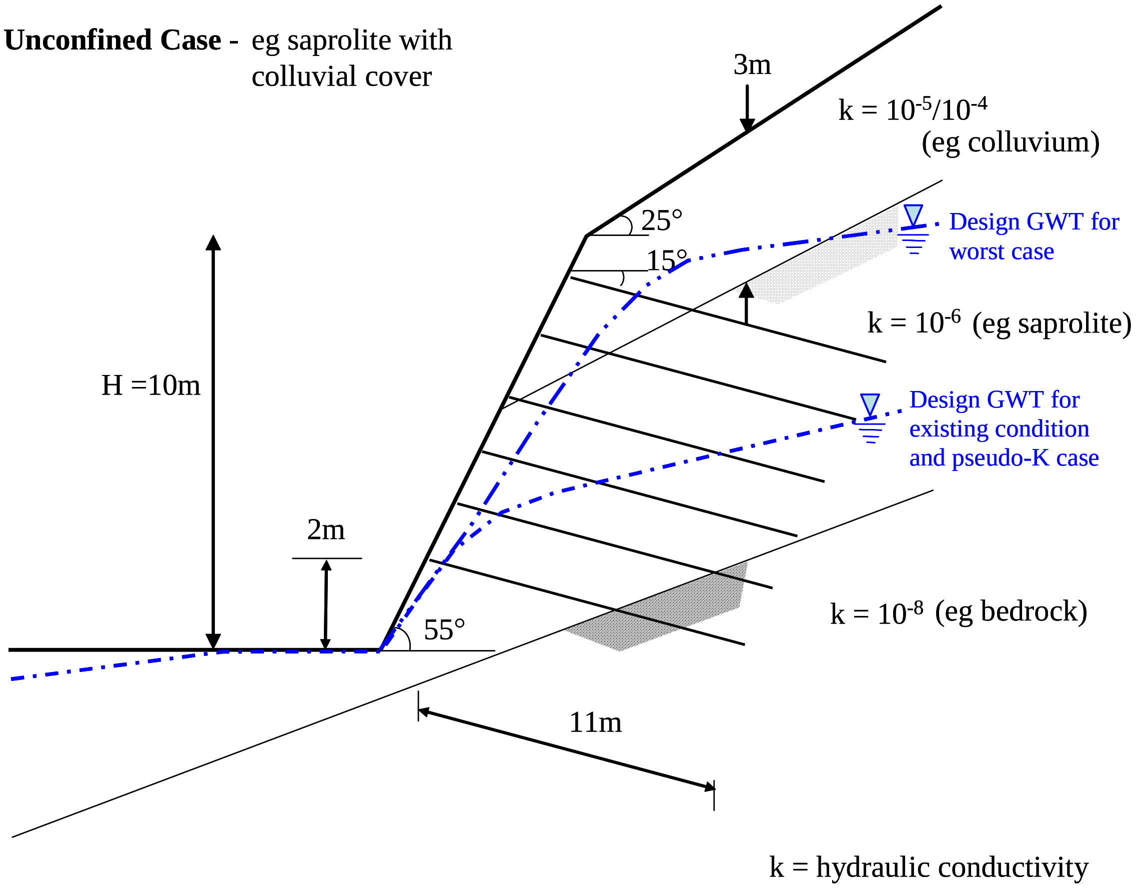

Figure 29 – Cross Section for Stability Analysis of Model 4 / 4B

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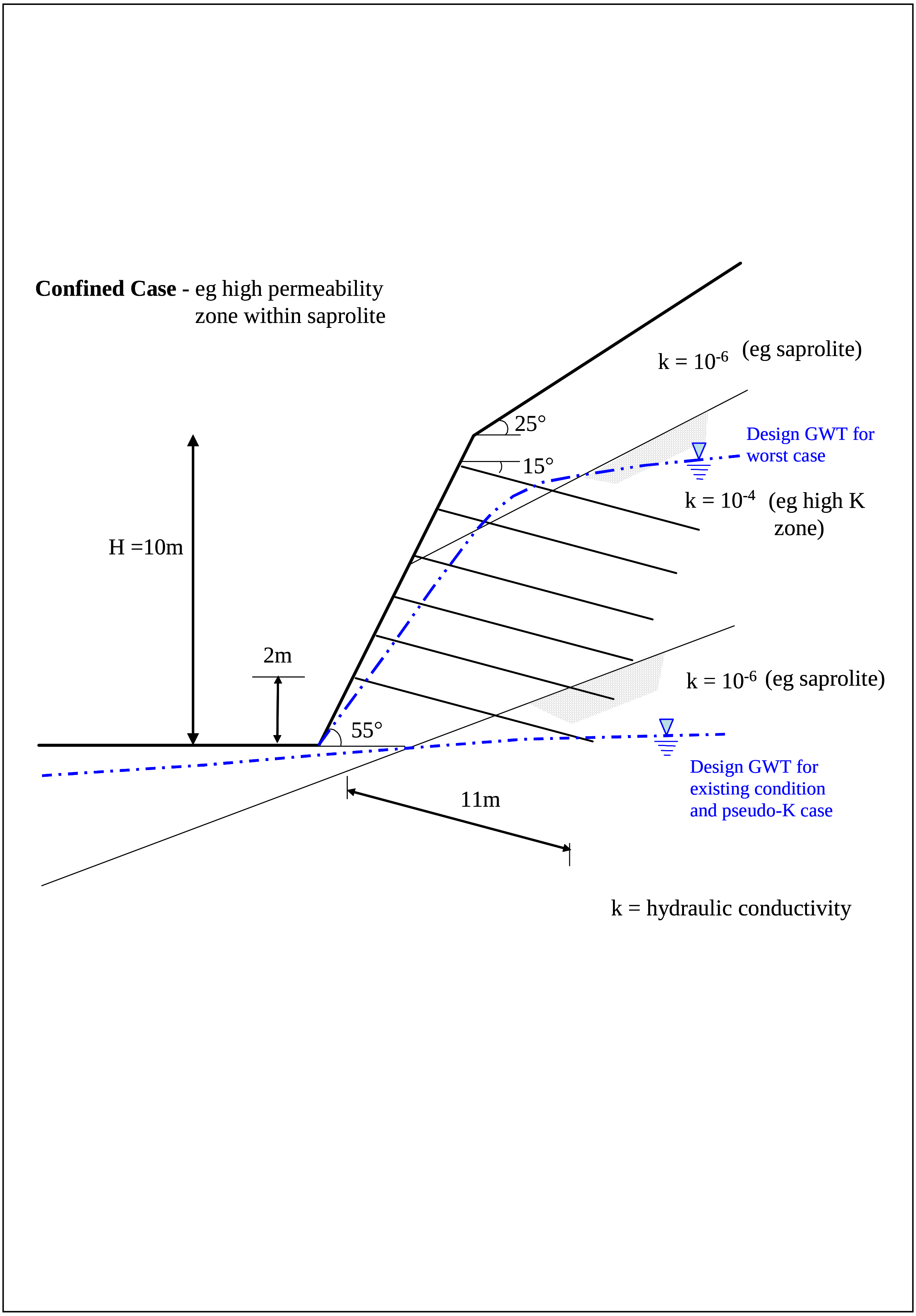

Figure 30 – Cross Section for Stability Analysis of Model 5 / 5B

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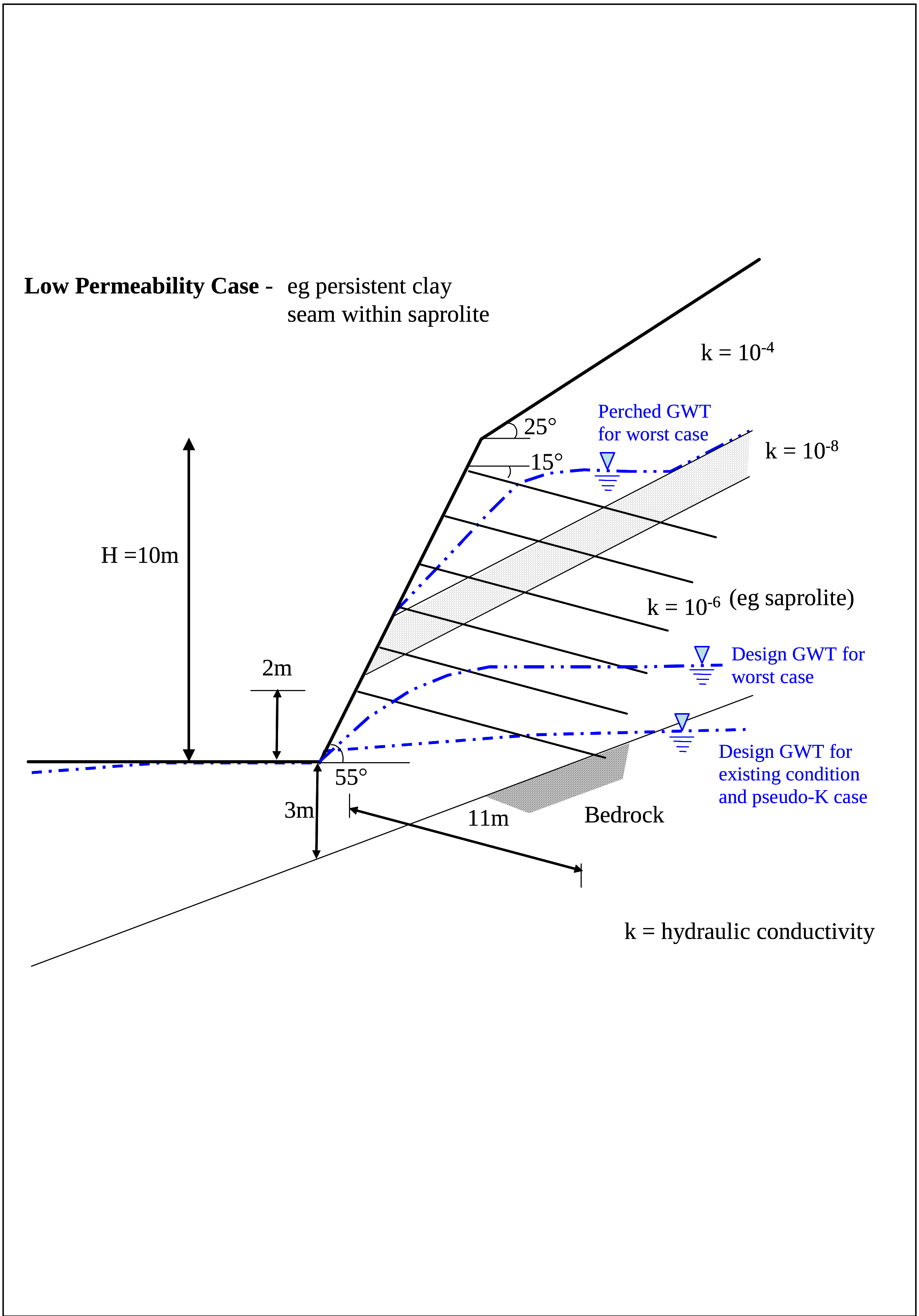

Figure 31 – Cross Section for Stability Analysis of Model 7 / 7B

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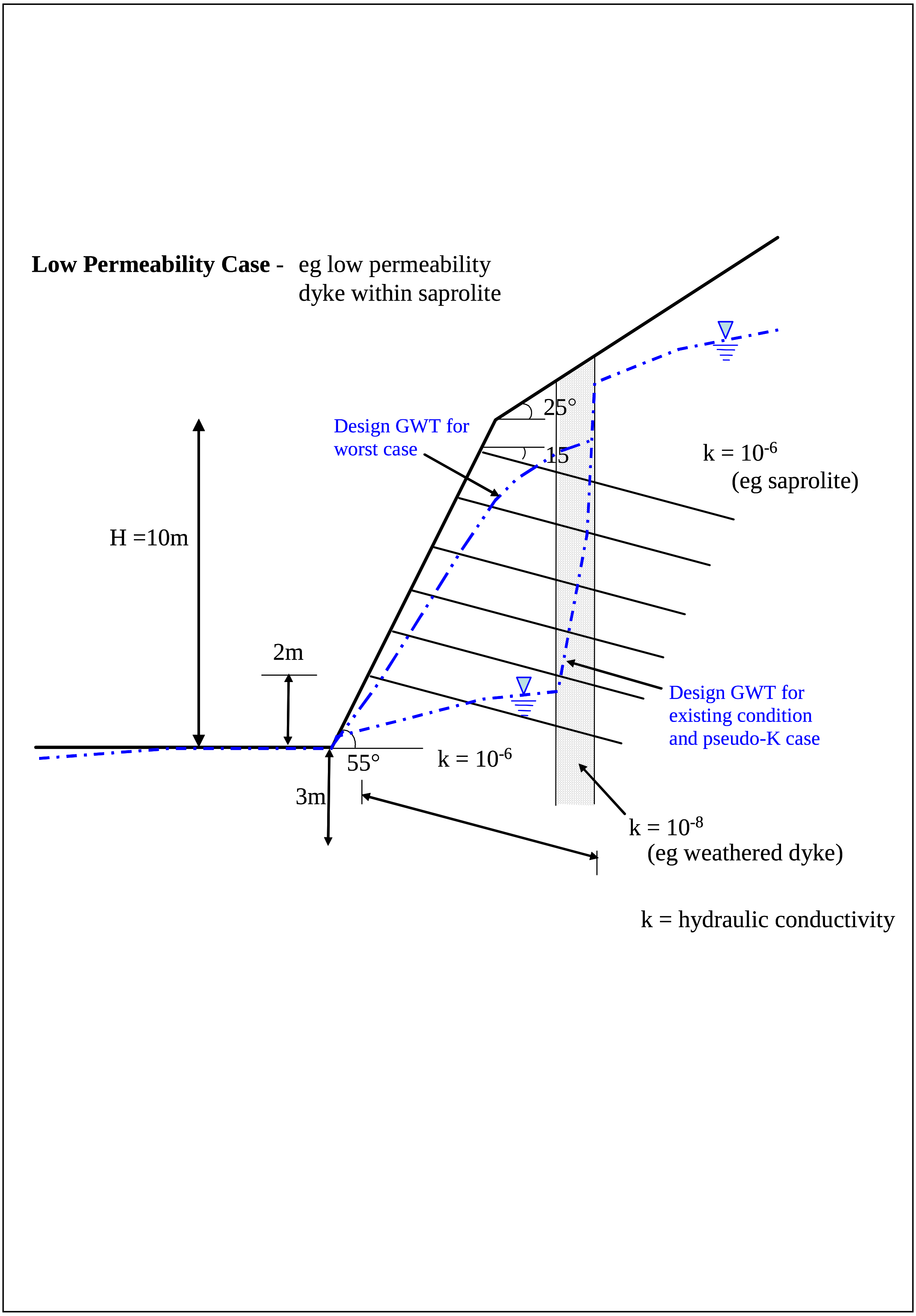

Figure 32 – Cross Section for Stability Analysis of Model 8 / 8B

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APPENDIX A

PSEUDO-K CALCULATION SHEETS

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Calculation of Psuedo-Kx between consecutive nails using an Area Based Equation (Figure A)

Equation used $$\frac{\mathbf{(An.Kn)+(As.Ks)}}{\mathbf{(An + As)}}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-4}}$

		π	r	
Area of Soil Nail	πr^2	3.14152	0.15	0.0706842
K of Soil Nail	$1\text{x}10^{-9}$			
	An.Kn	**7.06842E-11**		

Area of Soil Between Nails (1.5 x 0.3)-Area of soil nail 0.379316

As.Ks **3.79316E-05**

Therefore $\frac{\text{(An.Kn)+(As.Ks)}}{\text{(An + As)}} = \frac{\mathbf{7.07E\text{-}11 \quad + \quad 3.79E\text{-}05}}{\mathbf{0.45}}$

Kx = **8.42926E-05**

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Calculation of Psuedo-Ky between consecutive nails using an Area Based Equation (Figure B)

Equation used $$\frac{(An.Kn)+(As.Ks)}{(An + As)}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-4}}$
Height of slope = 10 m and contains 6 rows of nails
Soil strip width 1.5 m

		length	with		
Area of Soil Nail		1	0.3	0.3	
K of Soil Nail	$1x10^{-9}$				
	An.Kn	**3E-10**			
Area of Soil Between Nails		1	1.5 =1*1.5-0.3		**1.2**
	As.Ks	**0.00012**			

Therefore $\frac{(An.Kn)+(As.Ks)}{(An + As)}$ = $\frac{\mathbf{3E\text{-}10} \quad \mathbf{+} \quad \mathbf{0.00012}}{\mathbf{1.5}}$

Ky = **8.00002E-05**

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Calculation of Psuedo-Kx between consecutive nails using an Area Based Equation (Figure A)

Equation used $$\frac{\mathbf{(An.Kn)+(As.Ks)}}{\mathbf{(An + As)}}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-5}}$

		π		r	
Area of Soil Nail	πr^2	3.14152		0.15	0.0706842
K of Soil Nail	$1x10^{-9}$				
	An.Kn	**7.06842E-11**			

Area of Soil Between Nails (1.5 x 0.3)-Area of soil nail 0.379316

As.Ks **3.79316E-06**

Therefore $\frac{(An.Kn)+(As.Ks)}{(An + As)}$ = $\frac{\mathbf{7.07E\text{-}11 + 3.79E\text{-}06}}{\mathbf{0.45}}$

Kx = **8.4294E-06**

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Calculation of Psuedo-Ky between consecutive nails using an Area Based Equation (Figure B)

Equation used $\dfrac{(An.Kn)+(As.Ks)}{(An + As)}$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-5}}$
Height of slope = 10 m and contains 6 rows of nails
Soil strip width 1.5 m

		length	with		
Area of Soil Nail		1	0.3	0.3	
K of Soil Nail	$1x10^{-9}$				
	An.Kn	**3E-10**			
Area of Soil Between Nails		1	1.5 =1*1.5-0.3		**1.2**
	As.Ks	**0.000012**			

Therefore $\dfrac{(An.Kn)+(As.Ks)}{(An + As)}$ = $\dfrac{\mathbf{3E\text{-}10} \quad \mathbf{+} \quad \mathbf{0.000012}}{\mathbf{1.5}}$

Ky = <u>**8.0002E-06**</u>

Calculation of Psuedo-Kx between consecutive nails using an Area Based Equation (Figure A)

Equation used $$\frac{(An.Kn)+(As.Ks)}{(An + As)}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity **10^{-6}**

		π	r	
Area of Soil Nail	πr^2	3.14152	0.15	0.0706842
K of Soil Nail	$1x10^{-9}$			
	An.Kn	**7.06842E-11**		

Area of Soil Between Nails (1.5 x 0.3)-Area of soil nail 0.379316

As.Ks **3.79316E-07**

Therefore $\frac{(An.Kn)+(As.Ks)}{(An + As)} =$ $$\frac{\mathbf{7.07E-11 + 3.79E-07}}{\mathbf{0.45}}$$

Kx = **8.43081E-07**

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Calculation of Psuedo-Ky between consecutive nails using an Area Based Equation (Figure B)

Equation used $$\frac{(An.Kn)+(As.Ks)}{(An + As)}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-6}}$
Height of slope = 10 m and contains 6 rows of nails
Soil strip width 1.5 m

		length	with		
Area of Soil Nail		1	0.3		0.3
K of Soil Nail	$1x10^{-9}$				
	An.Kn	**3E-10**			
Area of Soil Between Nails		1	1.5 =1*1.5-0.3		**1.2**
	As.Ks	**0.0000012**			

Therefore $\frac{(An.Kn)+(As.Ks)}{(An + As)} = \frac{\mathbf{3E\text{-}10} + \mathbf{1.2E\text{-}06}}{\mathbf{1.5}}$

Ky = **<u>8.002E-07</u>**

Calculation of Psuedo-Kx between consecutive nails using an Area Based Equation (Figure A)

Equation used $$\frac{\mathbf{(An.Kn)+(As.Ks)}}{\mathbf{(An + As)}}$$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity $\mathbf{10^{-8}}$

		π	r	
Area of Soil Nail	πr^2	3.14152	0.15	0.0706842
K of Soil Nail	1×10^{-9}			
	An.Kn	**7.06842E-11**		

Area of Soil Between Nails (1.5 x 0.3)-Area of soil nail 0.379316

As.Ks **3.79316E-09**

Therefore $\frac{(An.Kn)+(As.Ks)}{(An + As)}$ = $\frac{\mathbf{7.07E\text{-}11 \quad + \quad 3.79E\text{-}09}}{\mathbf{0.45}}$

Kx = **8.58632E-09**

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Calculation of Psuedo-Ky between consecutive nails using an Area Based Equation (Figure B)

Equation used $\dfrac{(An.Kn)+(As.Ks)}{(An + As)}$

An	Area of nail
Kn	Hydraulic conductivity of the soil nail
As	Area of soil
Ks	Hydrualic conductivity of the soil

Soil nail spacing is 1.5 m
Soil Nail Hydraulic conductivity is 10^{-9}
Soil Hydraulic conductivity **10^{-8}**
Height of slope = 10 m and contains 6 rows of nails
Soil strip width 1.5 m

		length	with		
Area of Soil Nail		1	0.3	0.3	
K of Soil Nail	$1x10^{-9}$				
	An.Kn	**3E-10**			
Area of Soil Between Nails		1	1.5 =1*1.5-0.3		**1.2**
	As.Ks	**0.000000012**			

Therefore $\dfrac{(An.Kn)+(As.Ks)}{(An + As)} = \dfrac{\mathbf{3E\text{-}10} \quad \mathbf{+} \quad \mathbf{1.2E\text{-}08}}{\mathbf{1.5}}$

Ky = **<u>8.2E-09</u>**

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APPENDIX B

RESULT OF STABILITY ANALYSIS FOR VARIOUS MODELS

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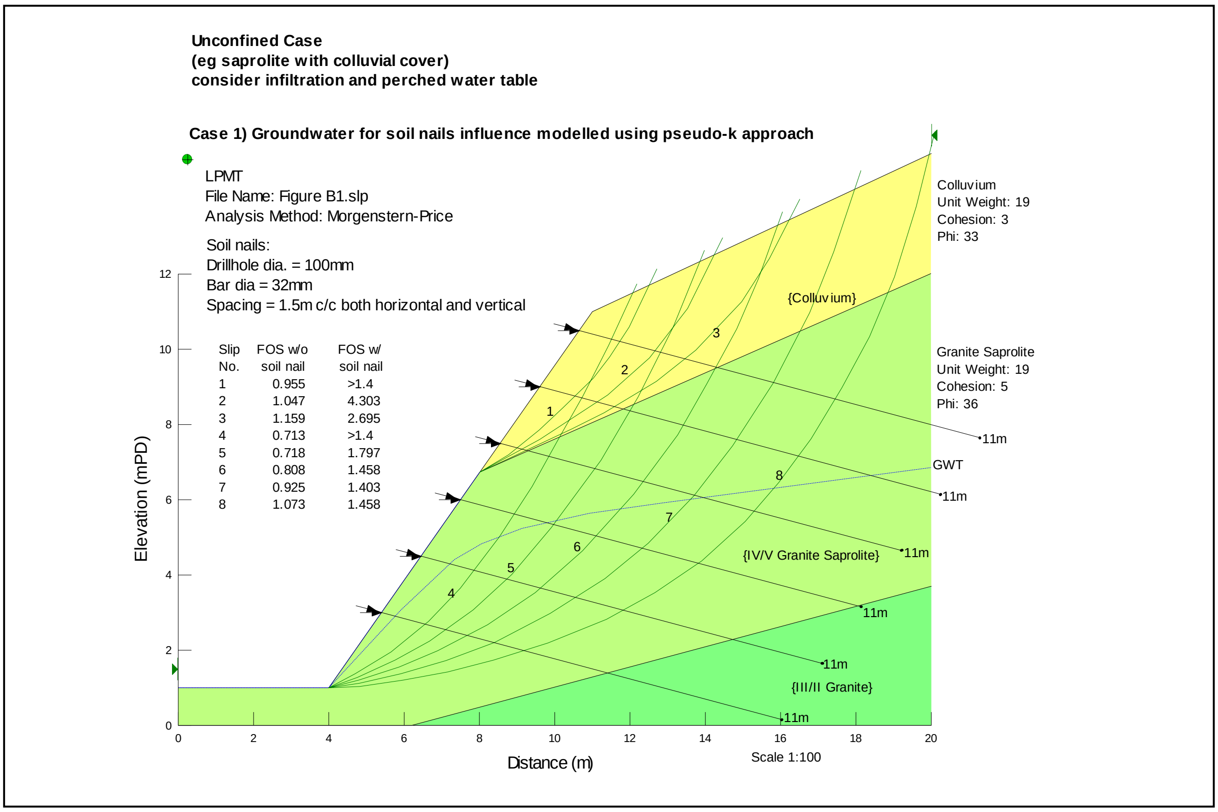

Figure B1 – Stability Analysis of Model 4 Before and After Soil Nailing

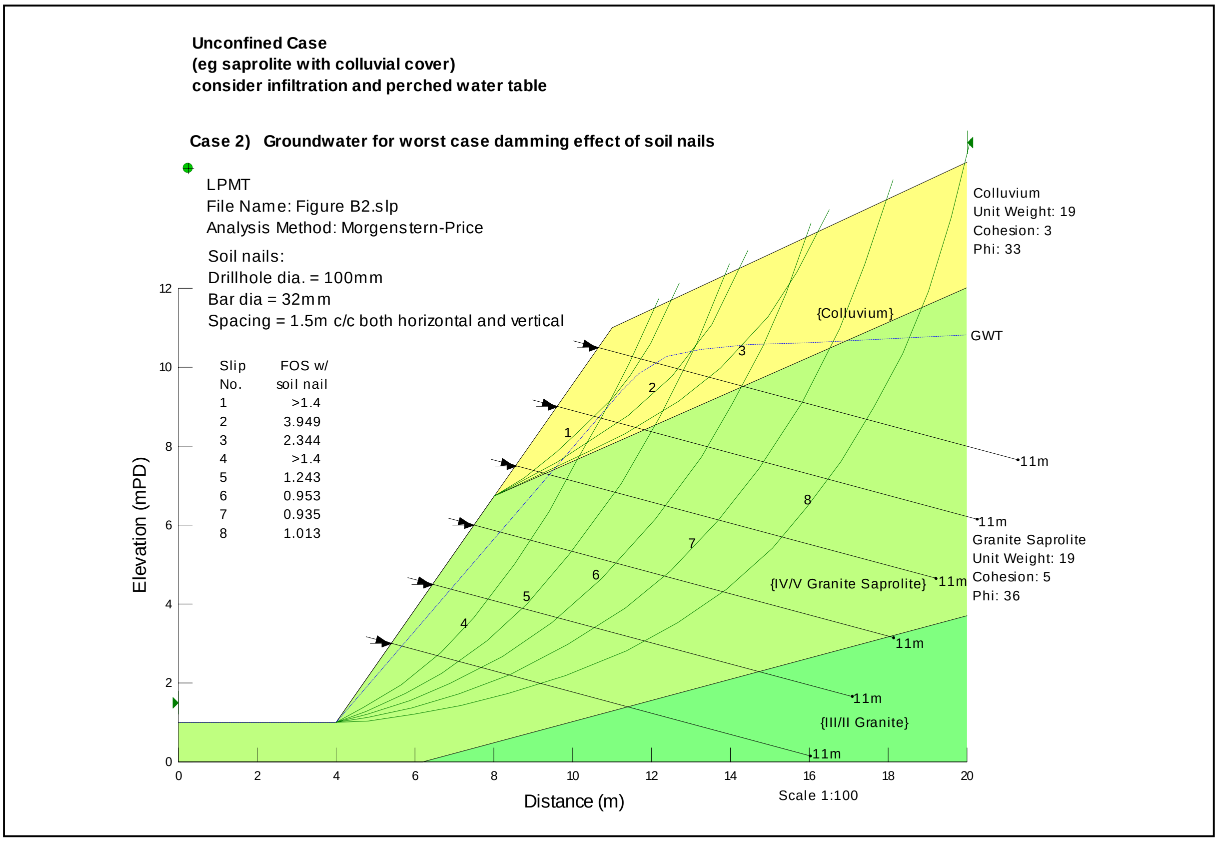

Figure B2 – Stability Analysis of Model 4B Assuming a Worst Case Groundwater Due to Damming Effect of Soil Nails

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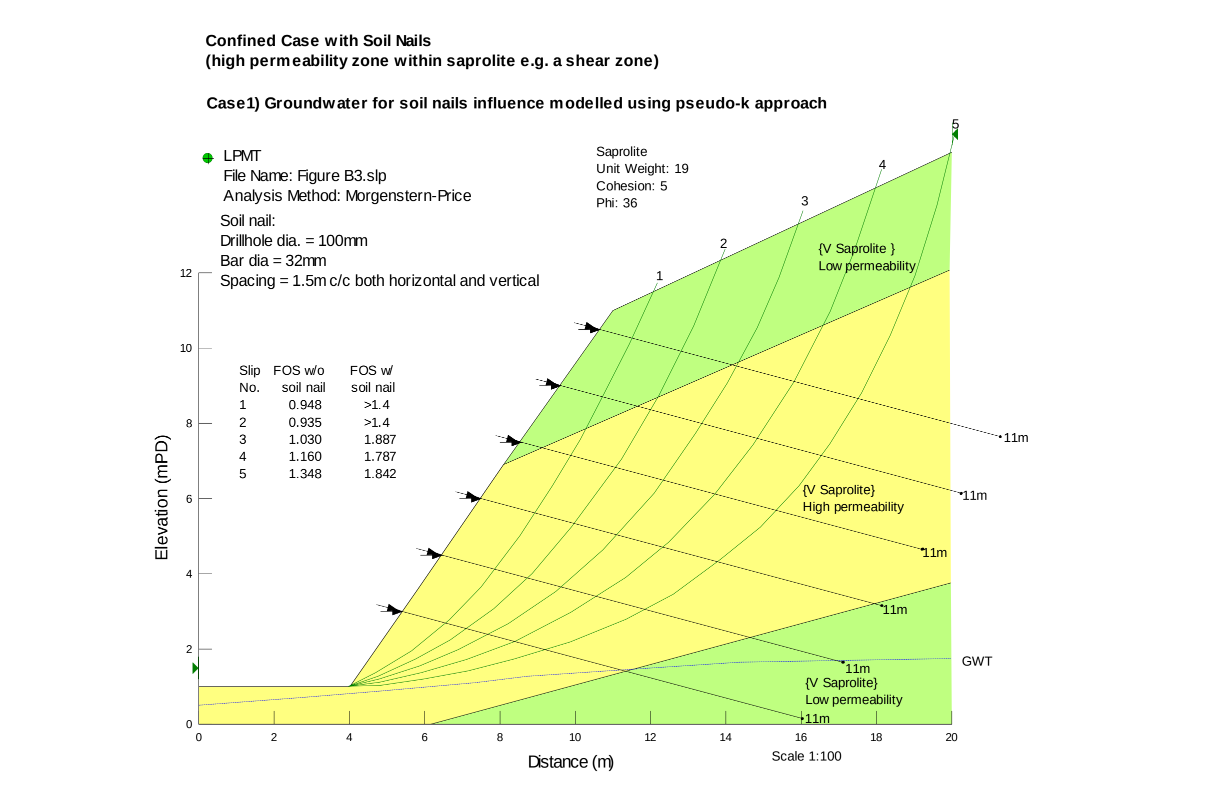

Figure B3 – Stability Analysis of Model 5 Before and After Soil Nailing

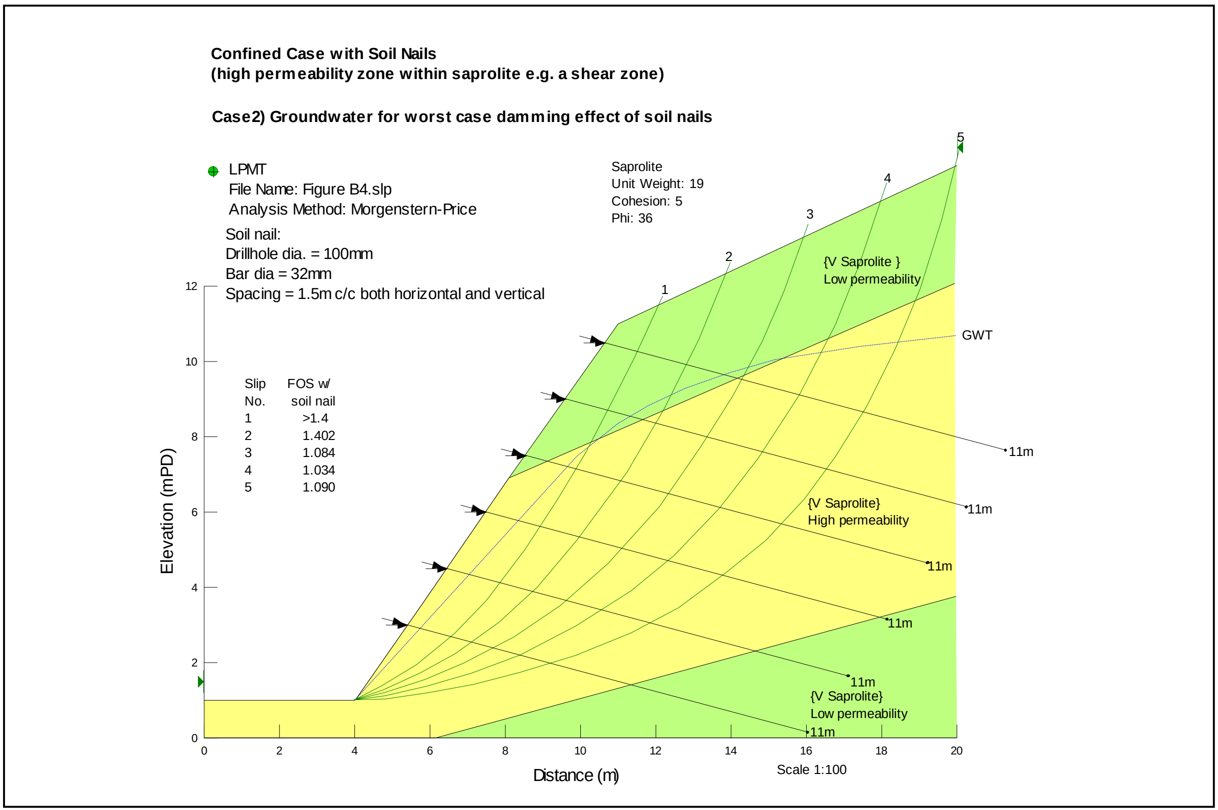

Figure B4 – Stability Analysis of Model 5B Assuming a Worst Cast Groundwater Due to Damming Effect of Soil Nails

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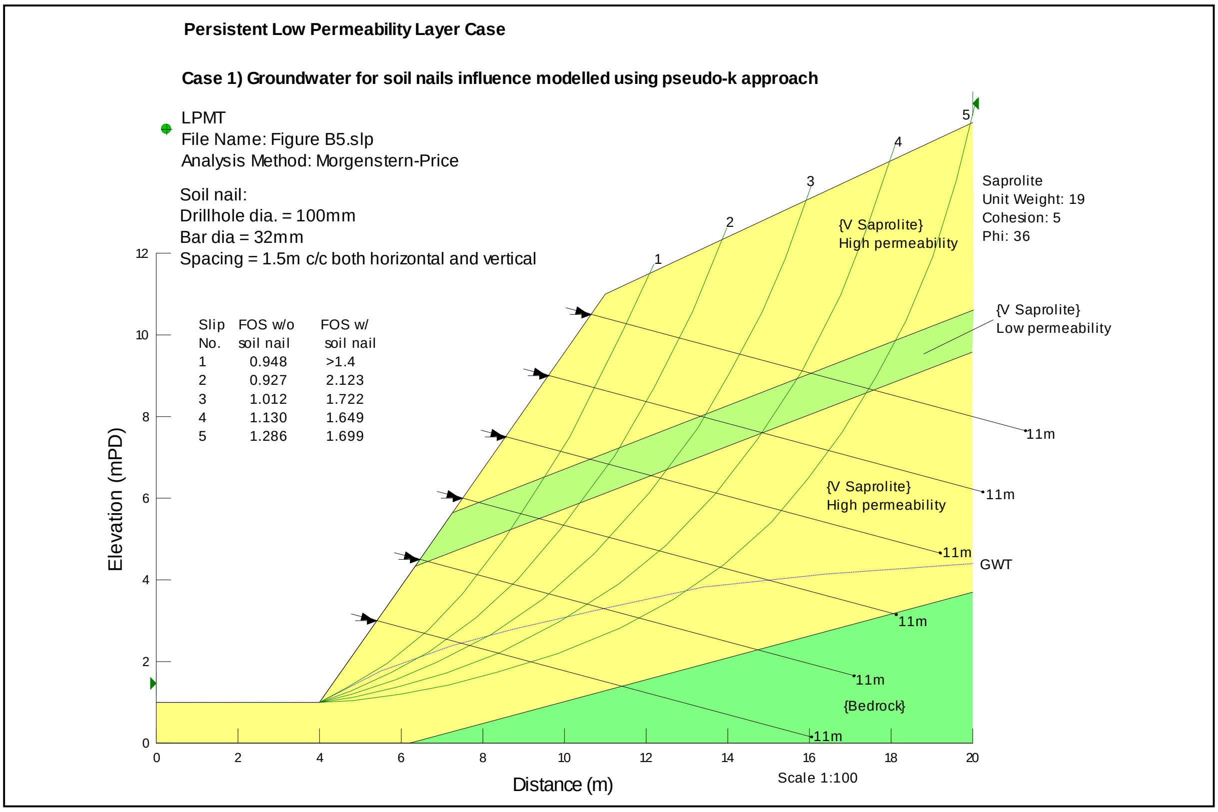

Figure B5 – Stability Analysis of Model 7 Before and After Soil Nailing

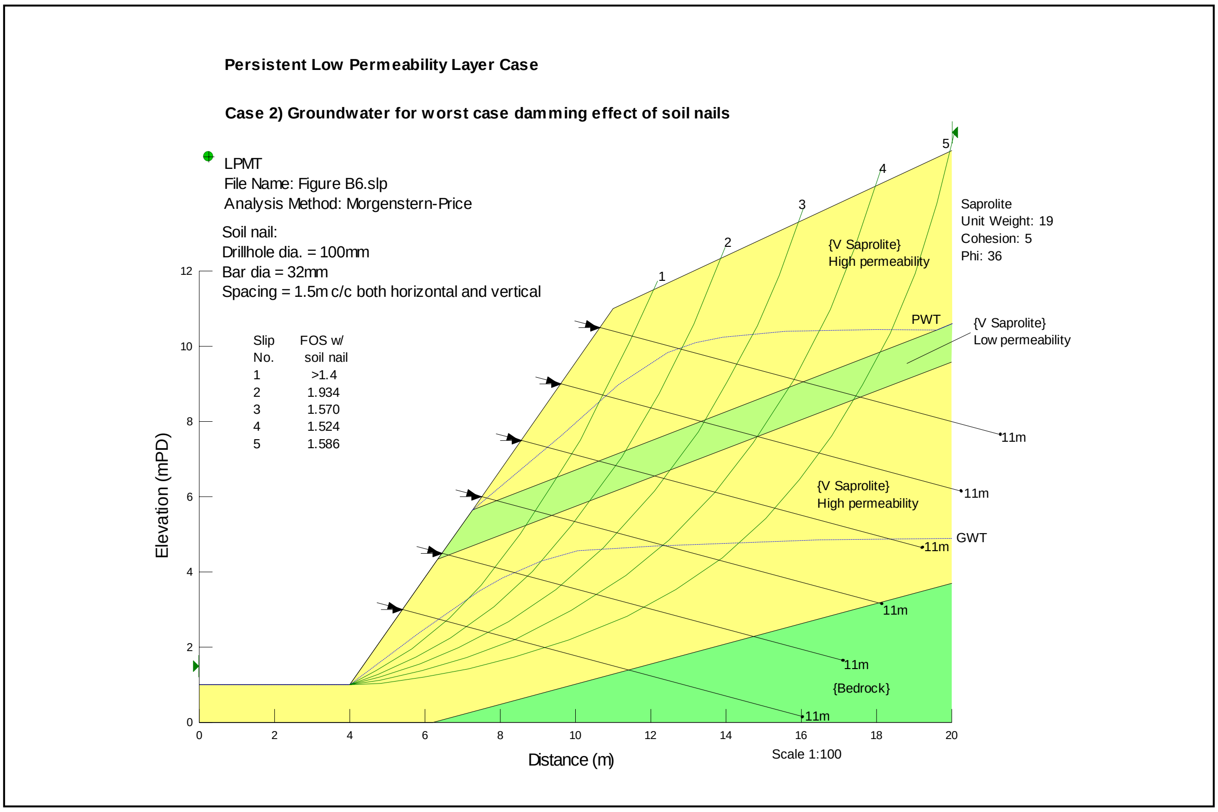

Figure B6 – Stability Analysis of Model 7B Assuming a Worst Cast Groundwater Due to Damming Effect of Soil Nails

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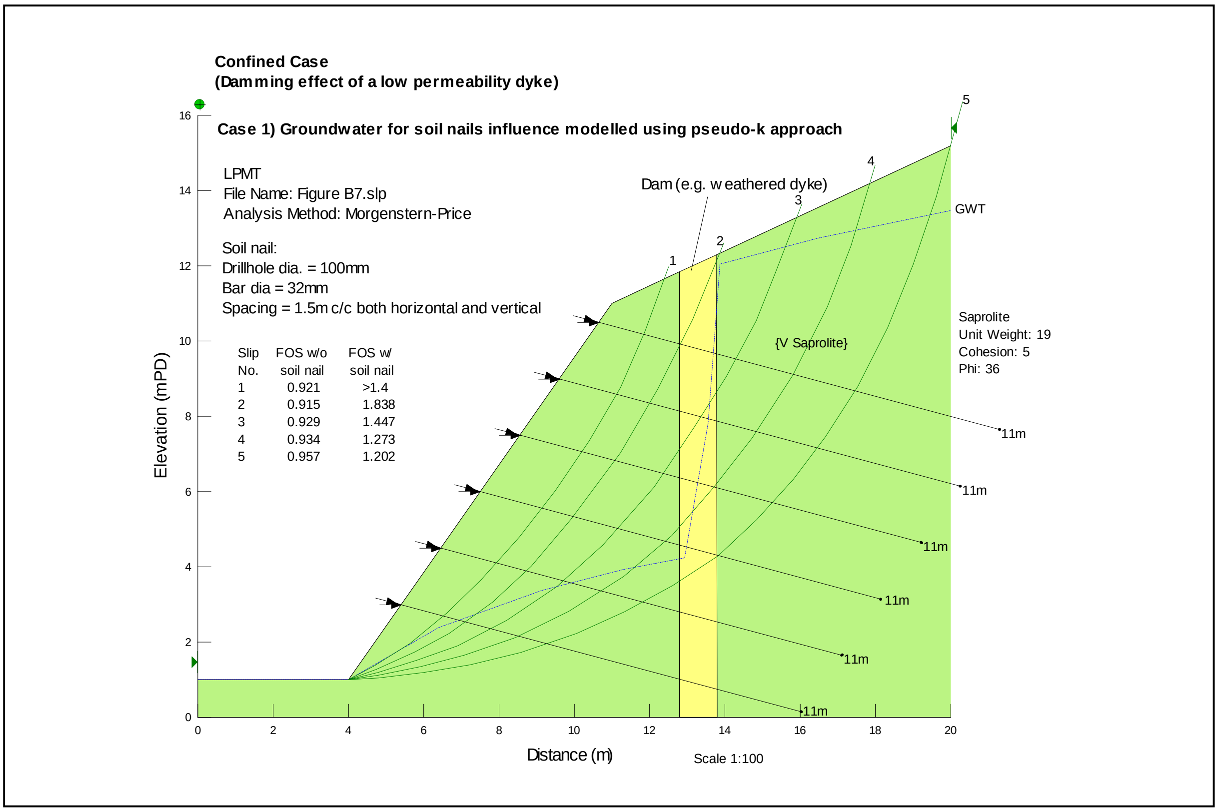

Figure B7 – Stability Analysis of Model 8 Before and After Soil Nailing

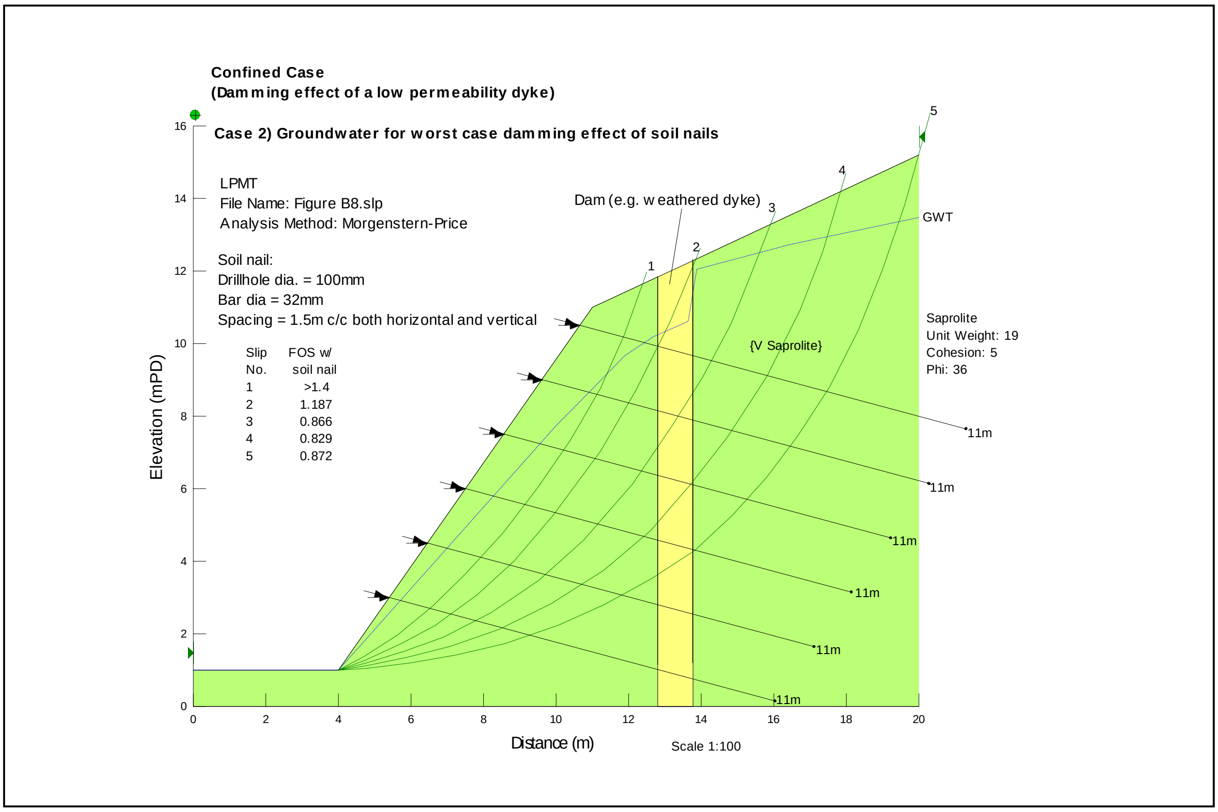

Figure B8 – Stability Analysis of Model 8B Assuming a Worst Cast Groundwater Due to Damming Effect of Soil Nails

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APPENDIX C

ADDITIONAL MODELLING FOR LARGE THROUGH-FLOW OF GROUNDWATER

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Additional Modelling for Large Through-flow of Groundwater

1. Introduction

Following completion of the draft Study Report, comments were received during the presentation of the findings of the study at the LPM Liaison Meeting in October 2005. As a result additional model has been run to study the case where a large through-flow of underground water affects the model.

2. Model 3-add: Soil Nails in Uniform Slope with a Fixed Head Upper Boundary

Model 3B (see Figure 8), a uniform slope with background K = 10^{-6} m/s, was selected to undertake this additional modelling. The following modifications were made to the original model:

(1) The upper vertical boundary is changed to a fixed boundary condition, with a head at 20 mPD, to model the situation where a large amount of underground water flows into the model from upslope.

(2) There is no infiltration from rainfall.

(3) Soil nails are modelled using a pseudo-K of 8 x 10^{-7} m/s

All other aspects of the model remain unchanged.

2. Comparison of Additional Modelling

The modified model has been run before and after soil nailing and the two cases have been compared with the detailed changes in head at Points A, B, C and D shown in attached Table 3b.

The simulation results show that there is very little change in total head as a result of the soil nailing. In addition, the flow patterns and water table in the slope are very similar before and after soil nail installation. It is noted that the fixed head boundary at 20 mPD results in higher groundwater levels in the slope than for the original Model 3, which adopted infiltration as the source of water in that model.

Thus despite the increased water levels, as a result of adopting a fixed head upper boundary, the simulation again demonstrates that the soil nails themselves have little or no affect on the relative groundwater levels in the slope, providing that there is no significant lateral migration of grout (ie the pseudo-K case).

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Table 3b – Detailed Changes of Total Head (m) after Soil Nailing a Uniform Slope with Fixed Head Upper Boundary (Model 3b)

Location	Head without Nail	Head with Nail	Change in Head	% Change in Head
A	14.103	14.072	-0.031	-0.22
B	15.571	15.563	-0.008	-0.05
C	17.177	17.186	0.009	0.05
D	17.208	17.230	0.022	0.13

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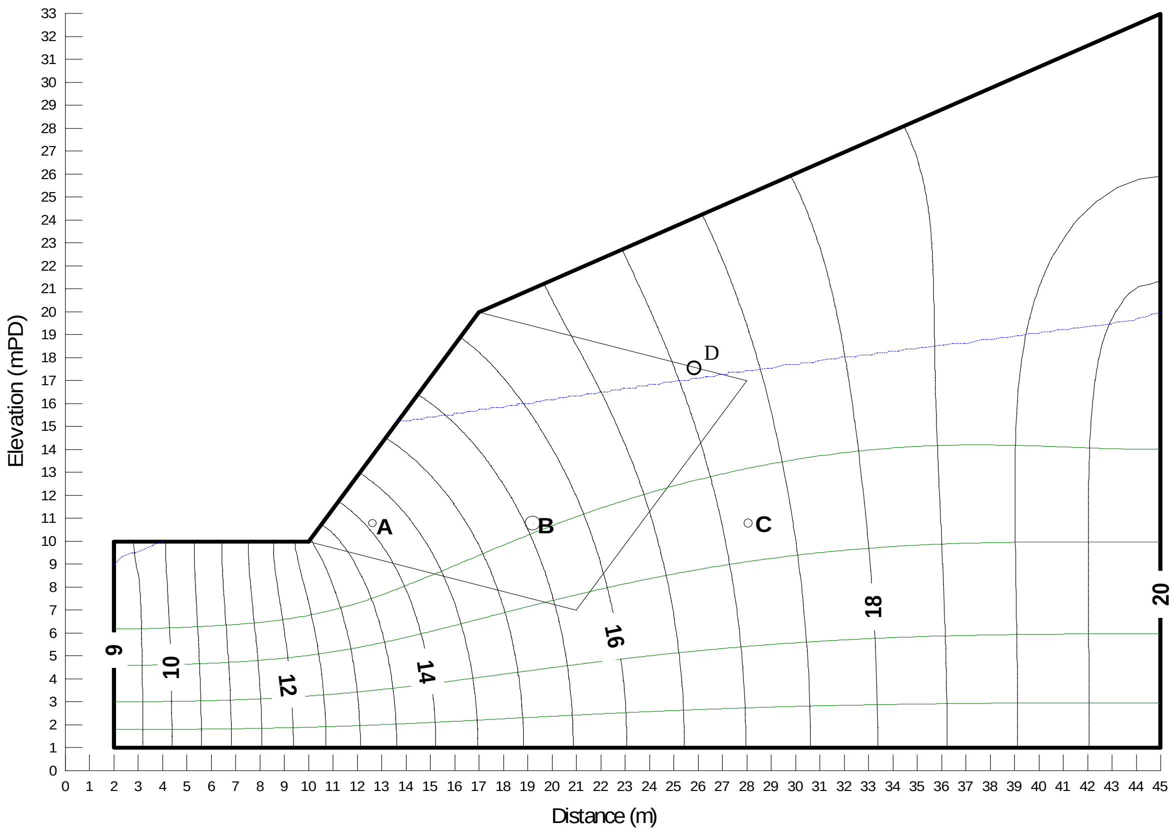

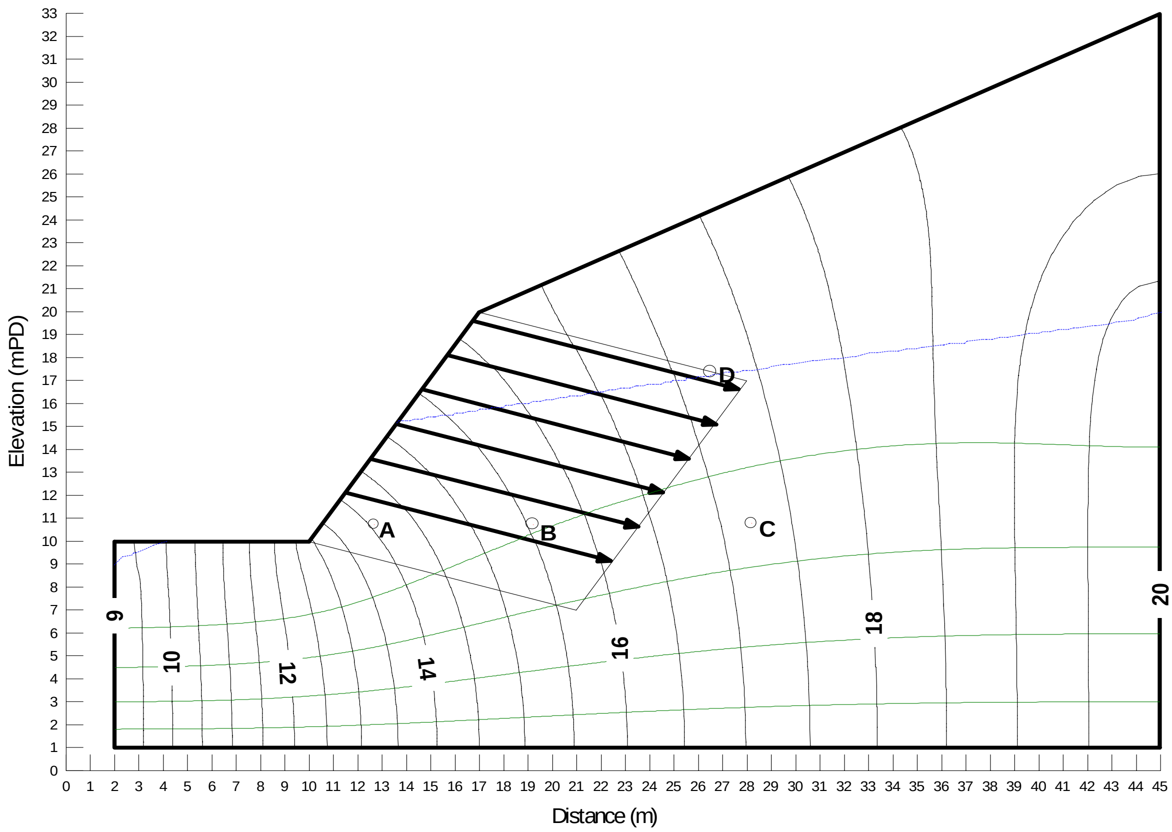

Model 3-add – Comparison of Flow Patterns and Water Tables before (top) and after (bottom) Soil Nailing a Uniform Slope with K = 10^{-6} m/s

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土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 300 p. (English Version), (Reprinted, 2000).

斜坡岩土工程手冊(1998)，308頁(1984年英文版的中文譯本)。

Highway Slope Manual (2000), 114 p.

GEOGUIDES

Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2007).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
Geoguide 3	Guide to Rock and Soil Descriptions (1988), 186 p. (Reprinted, 2000).
Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
Geoguide 5	Guide to Slope Maintenance, 3rd Edition (2003), 132 p. (English Version).
岩土指南第五冊	斜坡維修指南，第三版(2003)，120頁(中文版)。
Geoguide 6	Guide to Reinforced Fill Structure and Slope Design (2002), 236 p.

GEOSPECS

Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
Geospec 3	Model Specification for Soil Testing (2001), 340 p.

GEO PUBLICATIONS

GCO Publication No. 1/90	Review of Design Methods for Excavations (1990), 187 p. (Reprinted, 2002).
GEO Publication No. 1/93	Review of Granular and Geotextile Filters (1993), 141 p.
GEO Publication No. 1/2000	Technical Guidelines on Landscape Treatment and Bio-engineering for Man-made Slopes and Retaining Walls (2000), 146 p.
GEO Publication No. 1/2006	Foundation Design and Construction (2006), 376 p.
GEO Publication No. 1/2007	Engineering Geological Practice in Hong Kong (2007), 278 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

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