REVIEW OF SUB-SURFACE DRAINAGE PROVISIONS FOR RECOMPACTED FILL SLOPES

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GEO REPORT No. 225

Fugro Scott Wilson Joint Venture

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GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING AND DEVELOPMENT DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

REVIEW OF SUB-SURFACE DRAINAGE PROVISIONS FOR RECOMPACTED FILL SLOPES

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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.

The Geotechnical Engineering Office also produces documents specifically for publication. These include guidance documents and results of comprehensive reviews. These publications and the printed GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the second last page of this report.

R.K.S. Chan
Head, Geotechnical Engineering Office
May 2008

FOREWORD

This report presents a review of the sub-surface drainage provisions for recompacted fill slopes in Hong Kong. Recent observations have noted some distress on fill slopes upgraded by recompaction, which could have been a result of unusual transient groundwater movements. The key objective of this review was to look into feasible ways to enhance the robustness of the sub-surface drainage provisions to fill slopes to be upgraded by means of recompaction.

The report was prepared as part of the 2006 and 2007 Landslide Investigation Consultancy for Hong Kong Island and Outlying Islands, for the Geotechnical Engineering Office (GEO), Civil Engineering and Development Department (CEDD), under Agreement No. CE 49/2005 (GE). This is one of a series of reports produced during the consultancy by Fugro Scott Wilson Joint Venture (FSWJV).

Y C Koo
Project Director
Fugro Scott Wilson Joint Venture

Agreement No. CE 49/2005 (GE)
Study of Landslides Occurring in
Hong Kong Island and Outlying
Islands in 2006 and 2007 –
Feasibility Study

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1. INTRODUCTION

1.1 Scope

Distress has recently been observed on selected recompacted fill slopes treated following the recommendations made by the Independent Review Panel for Fill Slopes (Government of Hong Kong, 1976) and the Geotechnical Manual for Slopes (Geotechnical Control Office, 1984). The detailed investigation of the distress at the recompacted fill slope behind the Hong Kong Sanatorium and Hospital revealed that the distress might have been caused by unanticipated adverse transient groundwater conditions. Fugro Scott Wilson Joint Venture (FSWJV), the 2006 and 2007 Landslide Investigation Consultants, was subsequently tasked with carrying out a review of the practice of incorporating sub-surface drainage provisions for recompacted fill slopes in Hong Kong under Agreement No. CE 49/2005 (GE) for the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD).

This report presents the results of the review and proposes means to further enhance the robustness of the sub-surface drainage provisions to fill slopes to be upgraded by means of recompaction, over and above the prevailing standard practice, where this is judged to be warranted for the specific site setting by the designers.

1.2 Background

Fill slopes formed by end-tipping without proper compaction were common in Hong Kong prior to the establishment of the Geotechnical Control Office in 1977 (renamed GEO, in 1991), due to the need for rapid urban development and the lack of geotechnical control at the time.

The potential problem of loose fill slopes was highlighted when two fill slopes failed catastrophically in Sau Mau Ping in 1972 and 1976 with mobile debris, causing multiple fatalities. To investigate the 1976 incident, the Independent Review Panel for Fill Slopes, which was convened by the then Hong Kong Government to investigate the 1976 Sau Mau Ping landslide, considered that “the minimum treatment [to the potentially dangerous slopes] would consist of removing the loose surface soil to a vertical depth of not less than 3 meters, and re-compacting to an adequate standard [i.e. 95% maximum dry density]”. Since then, upgrading of loose fill slopes has generally followed this recommendation, until recently when soil nailing, together with prescriptive raking drains, is accepted as a technically feasible alternative provided certain qualifying criteria are met (Hong Kong Institution of Engineers, 2003).

Law et al (1998) carried out a review of 128 fill slopes upgraded by recompaction in Hong Kong for the GEO, and concluded that there was a general improvement in the performance of fill slopes after recompaction works, in that only one major distress occurred on one recompacted fill slope (see Section 2.3), which was caused by leakage from a water main. Despite the inherent limitations of the methodology used in the review (i.e. survey using questionnaire and file search), which precluded precise quantitative information being obtained on specific slope performance, Law et al (1998) noted the following post-construction problems:

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(a) cracks continued to develop especially in the transition zone between the uncompacted fill and recompacted fill;

(b) there was no improvement in the problem of blocked drainage; and

(c) there was no improvement in the problems of groundwater seepage and leakage from water-carrying services, which was suspected as being "an indication of the poor performance of the drainage layer behind the recompacted fill".

Bolton et al (2003) carried out a number of centrifuge tests to observe the behaviour of loose granular fill slopes of completely decomposed granite (CDG) subject to infiltration conditions. They concluded that:

(a) model slopes built of uniform CDG materials in a deep profile over bedrock, whether loose or dense, did not fail because the CDG was too permeable to achieve saturation and develop significant water pressure and turn into a flowslide as water can drain out from the soil pores;

(b) it was necessary to constrain the groundwater flow, either by raising the bedrock (case 3 reported in the paper), or by inserting a 'tongue of permeable material' (cases 4 and 5 reported in the paper, see also Figure 1) in order to promote a mobile failure caused by hydraulic blowout due to the elevated groundwater pressure; and

(c) for model slopes built of fine CDG over coarse CDG (which acts as the tongue of permeable material), densification of the fine CDG (to a relative compaction of 91%) was not of much benefit in preventing a failure.

Lee & Bolton (2006) described two further centrifuge tests, and noted that deep seated failure with significant distortion was induced when layered fill slopes were subjected to seepage flow from a more permeable layer. The results indicate that "shear failure can be developed when transient pore water pressure is allowed to build up in a blind layer underneath a fill slope, even though the top fill layer is compacted to a high degree of compaction".

It is noted that the heterogeneity of the in-situ condition of loose fill slopes may not have been adequately modelled in the above centrifuge tests and hence the observations made from the laboratory tests should be treated with caution. Notwithstanding this, the tests have re-affirmed the crucial importance of ensuring sufficient sub-surface drainage provisions.

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2. SOME EXAMPLES OF DISTRESS RECENTLY NOTED IN RECOMPACTED FILL SLOPES

2.1 General

Despite that there is only one major distress (caused by leakage from a water main) (see Section 2.3) having been observed on fill slopes upgraded by recompaction, some recompacted fill slopes have exhibited fairly extensive distress. In recent incidents that involved fill slope distress, there were indications that the distress was probably related to the adverse build-up of transient groundwater pressure at shallow depths. Three incidents recently observed are described below.

2.2 Slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital

Slope No. 11SW-D/FR1 is a fill slope with a toe retaining wall situated above Hong Kong Sanatorium and Hospital at Happy Valley. The slope has a total height of about 65 m and comprises eight batters inclined at around 32° separated by 1 m to 2 m wide berms (Figures 2a and 2b). The slope was upgraded under the Landslip Preventive Measures (LPM) Programme between 1977 and 1979 with the provision of at least 3 m thick soil fill compacted to a minimum 95% relative compaction.

Major distress of the slope was first observed in March 2004 (Plate 1) and subsequently mapped in detail by FSWJV. The distress observed included major cracking on berms and the lower two batters of the slope, displaced concrete cover beyond the edge of the berm drainage channels, crushed concrete drainage channels and blocked drainage outlet pipes.

The detailed study of the incident (FSWJV, 2005) concluded that the distress was mainly related to water ingress into the old loose fill body underlying the compacted fill cap within the upper half of the slope, and the build-up of groundwater pressure in the compacted fill within the lower half of the slope.

Piezometers installed within the compacted fill in the lower half of the slope indicated a piezometric head at between 1 m and 2 m below the ground surface, and some piezometers exhibited storm responses of 0.5 m rise with a time lag of 3 to 6 hours. Tensiometers installed within the compacted fill in the lower slope also indicated positive groundwater pressure during rainstorms.

The main source of water ingress was probably from the catchment in the upslope areas (leakage from stormwater drains within private lots cannot be precluded), although direct surface infiltration through the vegetated areas and leakage from a sewer beneath Stubbs Road might also have played a contributory role. The setting of the site (within a buried valley) could lead to concentrated sub-surface groundwater flow along preferential paths.

2.3 Slope No. 11NE-D/F10 at Hiu Kwong Street, Sau Mau Ping

Slope No. 11NE-D/F10 is located on the south-western side of Hiu Kwong Street at Sau Mau Ping. The feature is a fill slope approximately 70 m in length and 25 m to 30 m in height, with three batters inclined at about 33° and separated by 1.5 m to 2.5 m wide berms

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(Figures 3a and 3b). The slope was upgraded under the LPM Programme in 1977 and the works involved placement of at least 3 m thick compacted fill over the original slope profile.

Major distress to the slope was observed in April 1998, which was largely confined to the upper batter of the slope (Plate 2). The distress comprised bulging and lifting of the shotcrete surfacing and downward movement of the shotcrete surfacing, which extended beyond the lip of the berm U-channel to a maximum of about 50 mm. Subsidence of up to 200 mm was also observed at the crest of the slope. Prior to the reporting of the distress, heavy seepage from the weepholes installed in the U-channels located along the toe of the slope was observed, which had continued since February 1998.

A detailed study of the incident was undertaken by FSWJV (1999). The probable causes of the ground movements were postulated as being the presence of disturbed material in the compacted cap, the wetting up of the pre-1977 fill and the shear deformation in the fill body. The source of the prolonged seepage was determined to be leakage from a 400 mm diameter pressurised saltwater main located at the crest of the slope. The slope was formed over an old valley, which is prone to promoting concentrated sub-surface groundwater flow.

The study noted that a major failure of the slope, involving a failure volume between 50 m^3 and 160 m^3, also occurred in 1984 (Incident No. K 4/1), reportedly as a result of leakage from a water main. Since then, the slope apparently started to suffer from distress and progressive deterioration in its condition.

2.4 Slope No. 11SE-A/FR11 at Lai Tak Tsuen Road

Slope No. 11SE-A/FR11 is a fill slope with a toe wall, located below Lai Tak Tsuen Road. The slope comprises a 5 m high cantilever concrete toe retaining wall supporting a 17 m high fill slope with two batters inclined at about 30° and separated by a 1 m wide berm between the lower two batters (Figures 4a and 4b). The slope was upgraded under the LPM Programme between 1977 and 1978 by recompacting the top 3 m of fill materials.

In August 2004, distress to the slope was observed by FSWJV (2004), see Plate 3. The distress comprised extensive cracking and crushing of the U-channel at the crest of the toe retaining wall, the dilapidated condition of the shotcrete cover at the lowest batter (with overhang up to 130 mm), and the presence of a sub-vertical crack on the face of the toe retaining wall, which also showed notable differential movement at an expansion joint.

3. SUB-SURFACE DRAINAGE PROVISIONS FOR FILL SLOPES IN HONG KONG

3.1 General

The 1976 Independent Review Panel for Fill Slopes (see Section 2.1), in relation to the recommendation to recompact the top 3 m of the loose fill materials, stated that "drainage of the fill behind the recompacted surface layer must also be provided at the toe of the slope". Since then, sub-surface drainage blankets have been provided to the fill slopes upgraded by the above treatment.

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3.2 Previous Practice in Sub-surface Drainage Provisions

The fill slopes described in Section 2 were three of the early slopes upgraded by the above recommended recompaction treatment in Hong Kong. The sub-surface drainage provisions to these slopes are probably representative of the practice adopted in the late 1970s.

In the case of slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital, drainage blankets were provided at the base of each batter of the compacted fill slope (Figures 2 and 5). Only 'Filter A' (i.e. fine granular filter) of 750 mm thick was provided to the upper batters, whereas a sandwich-type 'Filter A/B/A' (i.e. fine/coarse/fine granular filter) with a total thickness of 1,000 mm (500 mm being 'Filter B') was provided to the lower two batters. The grading ranges specified for 'Filter A' and 'Filter B' materials are shown in Figure 6. A reinforced concrete cover was provided at the slope surface where the drainage blankets daylight. Discharge from drainage blankets was through a row of drainage outlet pipes of 75 mm diameter and 750 mm long, provided at 1.5 m horizontal spacing.

In the case of slope No. 11NE-D/F10 at Hiu Kwong Street, 'Filter A' of 500 mm thick was provided at the base of the upper two batters, whereas a 1,500 mm thick sandwich type 'Filter A/B/A' (each filter layer being 500 mm thick) was provided at the base of the lowest batter (Figure 3). A 150 mm thick mortared stone pitching was provided at the slope surface where the drainage blankets daylight. Discharge from drainage blankets was through drainage outlet pipes of 50 mm diameter and 750 mm long, provided at 1.5 m horizontal spacing.

In the case of slope No. 11SE-A/FR11 at Lai Tak Tsuen Road, a 500 mm thick 'Filter A' layer was provided at the base of the slope, whereas a sandwich type 1,000 mm thick 'Filter A/B/A' layer (500 mm thick being 'Filter B') was provided behind the toe retaining wall (Figure 4). A reinforced sprayed concrete cover was provided at the slope surface where the drainage blanket daylights.

It would appear that the practice in the late 1970s involved the provision of the 'Filter A' layers to the upper slope batters, whereas a sandwich type 'Filter A/B/A' drainage blankets was incorporated at the lowest slope batter (or at the lowest two slope batters in the case of slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital).

3.3 Current Practice in Sub-surface Drainage Provisions

CEDD Standard Drawing No. C2302 (Rev. F) dated January 2005 gives details of the current recommended practice in respect of sub-surface drainage provisions to fill slopes upgraded by recompaction (Figure 7).

A notable difference with the practice adopted for the three slopes upgraded in the late 1970s as mentioned in Section 3.2 is that the current practice requires a sandwich-type fine/coarse/fine granular filter to be provided to each batter of the compacted slope. The thickness of the sandwich-type filter is reduced to 900 mm (300 mm being coarse granular filter), as compared to the earlier practice of 1,000 mm or 1,500 mm.

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The drainage blankets do not daylight but stop short at about 500 mm from the slope surface. Discharge from the drainage blanket is through a row of drainage outlet pipes of 50 mm diameter at 1.5 m horizontal spacing with the perforated section penetrating to a length of 800 mm into the coarse granular filter. It is noteworthy that the size of the outlet pipe has been reduced to 50 mm in diameter, as compared to the earlier practice of 75 mm in diameter. The intercepting length has been marginally increased to 800 mm, as compared to the earlier practice of 750 mm.

CEDD Standard Drawing No. C2302 (Rev. F) does not provide clear guidance on the longitudinal gradients (out of the slope) of the sub-horizontal drainage blankets, but some might interpret the gradients as being equal to those of the outlet pipes at 1 in 10 (maximum) to 1 in 30 (minimum) (see Figure 7). CEDD Standard Drawing No. C2302 (Rev. F) also does not provide guidance on the lateral gradients (across the slope) of the sub-horizontal drainage blankets and these gradients may vary from site to site to suit the actual conditions.

4. REVIEW OF SUB-SURFACE DRAINAGE PROVISIONS FOR RECOMPACTED FILL SLOPES IN OTHER COUNTRIES

4.1 General

There is limited information presented in the literature on the detailing of sub-surface drainage provisions for recompacted fill slopes formed against a sloping ground, a site setting that is common in Hong Kong. Two relevant publications have been identified and the salient aspects are discussed below. It is noteworthy that both publications indicate the general practice of providing perforated pipes within the drainage layer to discharge groundwater, instead of relying solely on outlet pipes as is the practice in Hong Kong.

4.2 Seattle Landslide Study

In the Seattle Landslide Study Project (Seattle Department of Planning and Development, 2000), some typical details of the drainage blanket for the construction of ‘compacted earth buttress fill’ were proposed, which are reproduced in Figure 8. The ‘compacted earth buttress fill’ and the drainage blanket were proposed to be constructed against a sloping ground.

A drainage blanket of minimum 18 inches (approximately 450 mm) thick was proposed at the base of the ‘compacted earth buttress fill’, which did not daylight at the slope surface. Discharge from drainage blanket would be from ‘subdrains’. The main ‘subdrain’ was placed at the toe of the slope and the intermediate ‘subdrains’ were at higher levels.

4.3 Department of Transportation, State of New York

In 2002, the Department of Transportation of the State of New York issued its Standard Drawing No. M203-3R1, which depicts the details of granular fill slope protection installation (reproduced as Figure 9).

According to the above drawing, where the granular fill is to be constructed against a

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sloping ground, no drainage blanket provisions would be required at the base of the granular fill. Instead, at the locations of "seepage planes", "pipe drains" (surrounded with filter) are to be provided to convey sub-surface water issuing from the slope. These "pipe drains" are to be designed to ensure that the intercepted water is carried to a drainage system.

5. POTENTIAL SCOPE FOR ENHANCING ROBUSTNESS OF SUB-SURFACE DRAINAGE PROVISIONS FOR RECOMPACTED FILL SLOPES

Four plausible measures that may enhance the robustness of conventional sub-surface drainage provisions in current local practice for loose fill slopes subjected to recompaction treatment are identified as follows:

(a) lengthening the slotted section of outlet pipes;

(b) increasing the diameter of outlet pipes;

(c) increasing the permeability and/or the thickness of the filter materials; and

(d) providing sub-soil pipes (viz. filter pipes) across the slope at the up-stream end of the sub-horizontal drainage blanket (see Figures 11 and 12).

Lengthening the slotted section of the outlet pipes will permit transient groundwater to be tapped earlier to permit earlier release of hydraulic pressure. It also has an added advantage of increasing the intercepting capacity of the outlet pipes as well as reducing the likelihood of pipe clogging, although the latter is difficult to quantify.

Increasing the diameter of the outlet pipes would increase the intercepting and discharge capacity of the outlet pipes. This would be an effective measure if the outlet pipe is the 'bottle-neck' in the drainage system but would have little effect if the 'bottle-neck' is in the drainage blankets.

Increasing the permeability of the filter materials would increase the discharge capacity of the drainage blankets. However, since filters are designed to satisfy the requirements of stability, permeability and segregation (GEO, 1993b), there appears to be little room in readily increasing the permeability of the filter materials unless a very permeable material (such as rock fill) is entrapped within 'Filter B'. However, such provision can be complicated and costly. On the other hand, increasing the thickness of the filter materials (in particular the coarse filter) could be a more credible option in increasing the discharge capacity of the drainage blankets.

The purpose of providing laterally persistent filter pipes across the slope at the up-stream end of the sub-horizontal drainage blankets is to intercept the transient groundwater earlier, thus releasing any build-up of hydraulic pressure sooner. An added advantage of filter pipes is that they would avoid over-reliance on the effectiveness of the drainage blankets (which are difficult to construct, especially the sloping portion of the sandwich type drainage blankets) and the outlet pipes for discharging any transient groundwater, which could be

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prone to blockages (Law & Thorn, 2001). These filter pipes need to be fabricated from relatively flexible material in order to cater for any potential small differential settlement that might occur in the long run arising from the variable loose fill below.

6. THEORETICAL ANALYSES

The effects of the four plausible enhancement measures identified in Section 5 have been examined by reference to theoretical analyses, including hand calculations as well as finite element seepage analyses using the computer program 'SEEP/W' (see Appendices A and B).

It is worth mentioning that the seepage analyses carried out were not aimed at giving a definitive assessment of what might happen on site. On the contrary, the seepage analyses were intended to provide a sensitivity analysis of the differing behaviour of the sub-surface drainage provisions upon implementation of the various enhancement measures, i.e. to examine the potential changes in the behaviour of the drainage provisions.

In this review, slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital has been chosen for the seepage analyses, since major distress has been observed at this site and comparatively more information, in terms of material properties and groundwater conditions, is available. The specific site setting comprises a fill slope formed over a well-defined old drainage line, with concentrated sub-surface groundwater flow, and the compacted fill at the lower half of the slope probably underlain by a tongue of fairly permeable loose fill (see Appendix B1.5).

The results of the seepage analyses prior to the provision of enhancement measures (Appendix B2) indicate that drainage blanket with the provision of 'Filter A' alone would not be effective in discharging the build-up of transient groundwater pressure. The drainage blanket with the provision of 'Filter A/B/A' proves to be more effective, but it would still take a fairly long time to release any build-up of water pressure. The potential 'bottle-neck' in terms of discharge of transient groundwater discharge appears to be with the drainage blankets.

6.1 Lengthening the Slotted Section of Outlet Pipes

In slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital, the outlet pipes provided were 750 mm long. In this review, the effect of lengthening the slotted section of the outlet pipes at the horizontal drainage blankets was examined.

The results of seepage analyses (Appendix B2) indicate that the benefit is not very obvious in the release of transient groundwater given an increased length of 3 m for the slotted section of the outlet pipes. It still takes a fairly long time for the transient groundwater to reach this extended portion of the outlet pipes, prior to releasing the hydraulic pressure. With an increased length of 12 m for the outlet pipes, the benefit becomes more obvious.

The results of simplified theoretical hydraulic analyses given in Appendix A3 indicate

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a similar conclusion that there is only a marginal (about 10%) increase in the discharge capacity of the outlet pipe when it is extended by 3 m into the drainage blanket.

6.2 Increasing the Diameter of Outlet Pipes

The results of theoretical hydraulic analyses (Appendix A2) indicate that there is little merit in increasing the diameter of the outlet pipes since their current capacity (with a diameter of 50 mm as shown in CEDD Standard Drawing No. C2302 (Rev. F) dated January 2005) is generally sufficient to discharge the transient groundwater collected in the drainage blankets comprising a fine/coarse/fine granular filter. The slow response in releasing transient groundwater pressure was primarily a result of the insufficient transmissivity (i.e. permeability x thickness) of the drainage blankets. Increasing the diameter of the outlet pipes alone will not help in relieving the transient groundwater pressure. However, in the case of discharging groundwater collected by the filter pipes (see Section 6.4), increasing the diameter of the outlet pipes (such as from 50 mm to 75 mm) will have a direct benefit in the release of transient groundwater flow.

6.3 Increasing the Thickness of 'Filter B'

The results of theoretical hydraulic analyses (Appendix B2.3) indicate that there is little merit in increasing the thickness of the 'Filter B' layer from 0.5 m to 2 m. The 2 m thick 'Filter B' layer is still insufficient to quickly dissipate the hydraulic pressure built up at the far end of the 'tongue of permeable material'.

6.4 Providing Filter Pipes at the Up-stream End of Sub-horizontal Drainage Blankets

The provision of lateral filter pipes in the drainage blankets has been promulgated in some other countries (see Section 4), but this practice has not been commonly adopted in Hong Kong for upgrading loose fill slopes by means by surface recompaction.

In this review, a 75 mm diameter flexible slotted plastic pipe was assumed to have been placed laterally across the slope at the intersection of the inclined and sub-horizontal drainage blankets. To model the effect of this filter pipe, a 75 mm diameter hole was assumed to be open at that location, which permitted water to enter from its circumference and be drained away immediately (see Appendix B2).

Figure 10 presents a comparison of the transient groundwater condition of the slope before and after provision of the filter pipes. As can be seen from Figure 10, the highest hydraulic pressure was noted to be 20 kPa at the far end of the tongue of permeable loose fill after 36 hours since the start of the heavy rainfall when a 75 mm diameter filter pipe was provided within the drainage blanket, whereas a hydraulic pressure of 60 kPa was noted at the same location after 36 hours when no filter pipe was provided. The results indicate the effectiveness of the filter pipes in enhancing the robustness of sub-surface drainage provisions for fill slopes upgraded by recompaction.

The results of simplified theoretical hydraulic analyses (Appendix A4) indicate an

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improvement of 58% in the discharge capacity of the system when a filter pipe is provided at the up-stream end of the sub-horizontal drainage blanket.

7. DISCUSSIONS

Whilst the performance review by Law et al (1988) indicates a marked improvement in the performance of loose fill slopes upgraded by recompaction in that no liquefaction failure has occurred, slope distress and signs of inadequate drainage provisions have been observed in certain site settings and slope detailing (e.g. the fill slope above Hong Kong Sanatorium and Hospital). The present review has examined various means of further enhancing the robustness of sub-surface drainage provisions which may be considered for the more vulnerable site setting, e.g. a deep layer of loose fill over a natural drainage line with a fairly large catchment.

The results of theoretical analyses suggest that a drainage blanket with only fine granular filter may be limited in its effectiveness in discharging significant transient groundwater flow. The current practice in Hong Kong, as shown in CEDD Standard Drawing No. C2302 (Rev. F) dated January 2005, requires the installation of a drainage blanket of sandwich-type comprising fine/coarse/fine granular filter to each of the slope batters, which is an improvement in this regard, provided they are constructed properly.

Theoretical analyses suggest that the drainage blanket itself, even with a fine/coarse/fine granular filter, might be a 'bottle-neck' in the sub-surface drainage provisions during heavy rainfall and rapid sub-surface seepage from the catchment. At times of significant inflow of transient groundwater, the prescriptive drainage blanket alone may not be sufficient in quickly dissipating the build-up of water pressure within it.

The diameter of the outlet pipes plays a relatively minor role in improving the effectiveness of the sub-surface drainage provisions if the outlet pipes are short. The provision of very long outlet pipes (of the order of 12 m) is more effective in intercepting the transient groundwater table at the up-stream end of the sub-horizontal drainage blankets. The installation of such drains is relatively cheap and simple.

An even more effective way to enhance the effectiveness and robustness of the sub-surface drainage system is to provide continuous flexible filter pipes at the up-stream end of the sub-horizontal drainage blankets across the slope. The installation of such filter pipes is relatively simple and cheap for slopes to be upgraded by recompaction. Any water collected in these filter pipes can be discharged to the berm U-channels. A possible arrangement is presented in Figures 11 and 12, and a suggested specification is given in Appendix C for general reference.

It should be noted that the fill around the filter pipes could settle unevenly and compaction of fill above the pipes may affect their vertical/horizontal alignment. In the event of highly distorted pipes, they are liable to locally form a concentrated source of water infiltrating into the loose fill behind/below the pipes. In view of this potential concern, the suggested arrangement in Figures 11 and 12 has incorporated a steeper fall for the drainage blankets as well as the filter pipes than the common practice. Should there be considered an undue risk of major uneven settlement occurring around the pipes, designers should carefully

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review whether the provision of prescriptive filter pipes is warranted.

It should also be noted that the sub-horizontal drainage blankets, as well as the filter pipes, might sometimes be designed to fall laterally across a slope in order to suit the actual site conditions. Designers should exercise discretion in considering whether there is a need to provide outlet pipes with a larger diameter or outlet pipes at a closer spacing at the location of the lowest point with a view to helping the release of any potential concentration of groundwater flow.

8. RECOMMENDATIONS

For loose fill slopes that are to be upgraded by recompaction, one effective means to enhance the robustness of the sub-surface drainage detailing is the provision of prescriptive filter pipes at the up-stream end of the sub-horizontal drainage blankets (see Figures 11 and 12). Designers may exercise discretion on a case-by-case basis as to whether such prescriptive filter pipes are warranted.

For recompacted fill slopes underlain by a significant thickness of untreated old fill, especially where there is a large catchment, designers should consider carefully the adequacy of sub-surface drainage provisions. Prescriptive raking drains may be called for in controlling the possible build-up of groundwater pressures at depth during intense rainfall. The need of these should be assessed on a site-specific basis.

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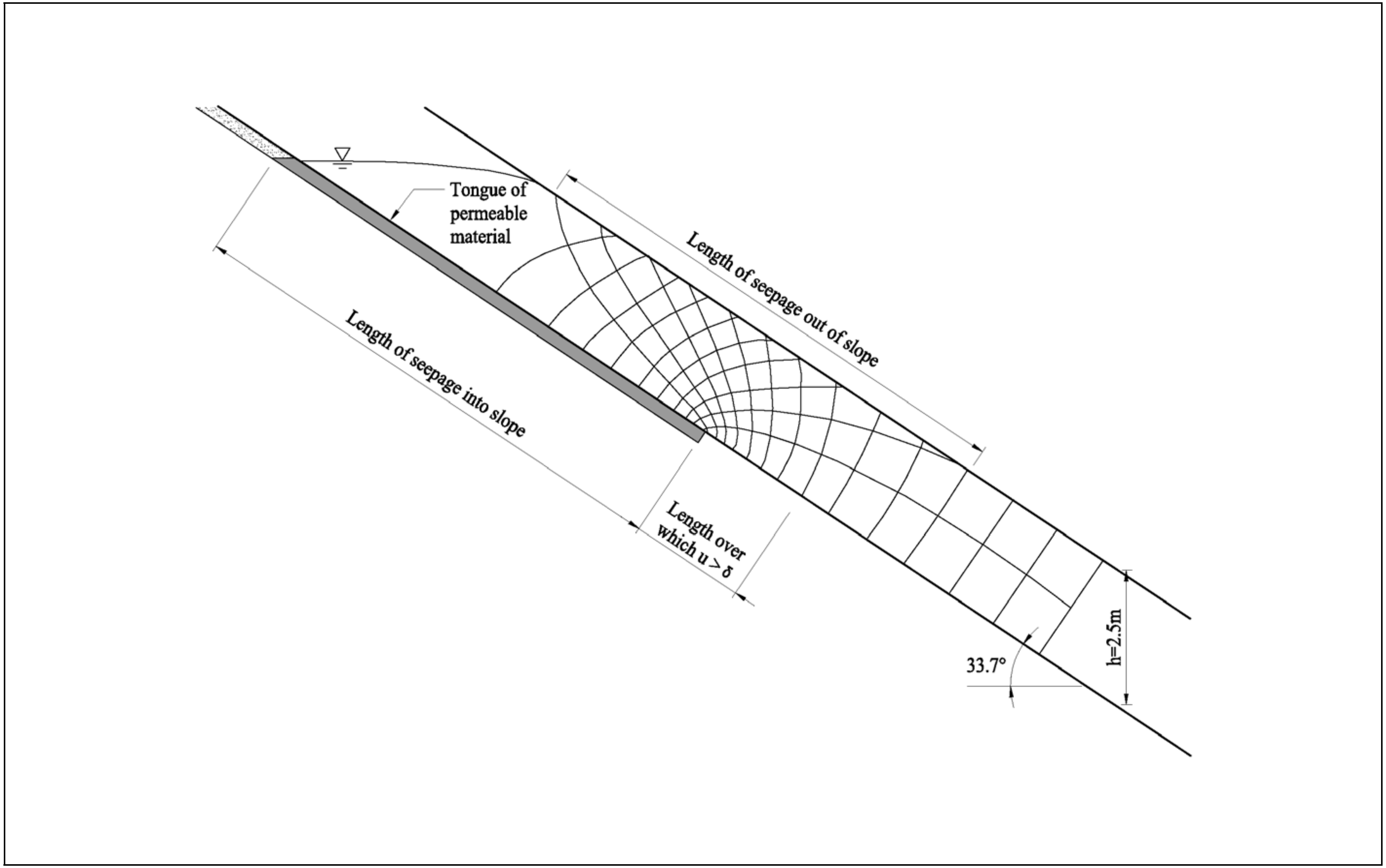

Figure 1 - Hydrological Considerations of a Layered Slope by Bolton et al (2003)

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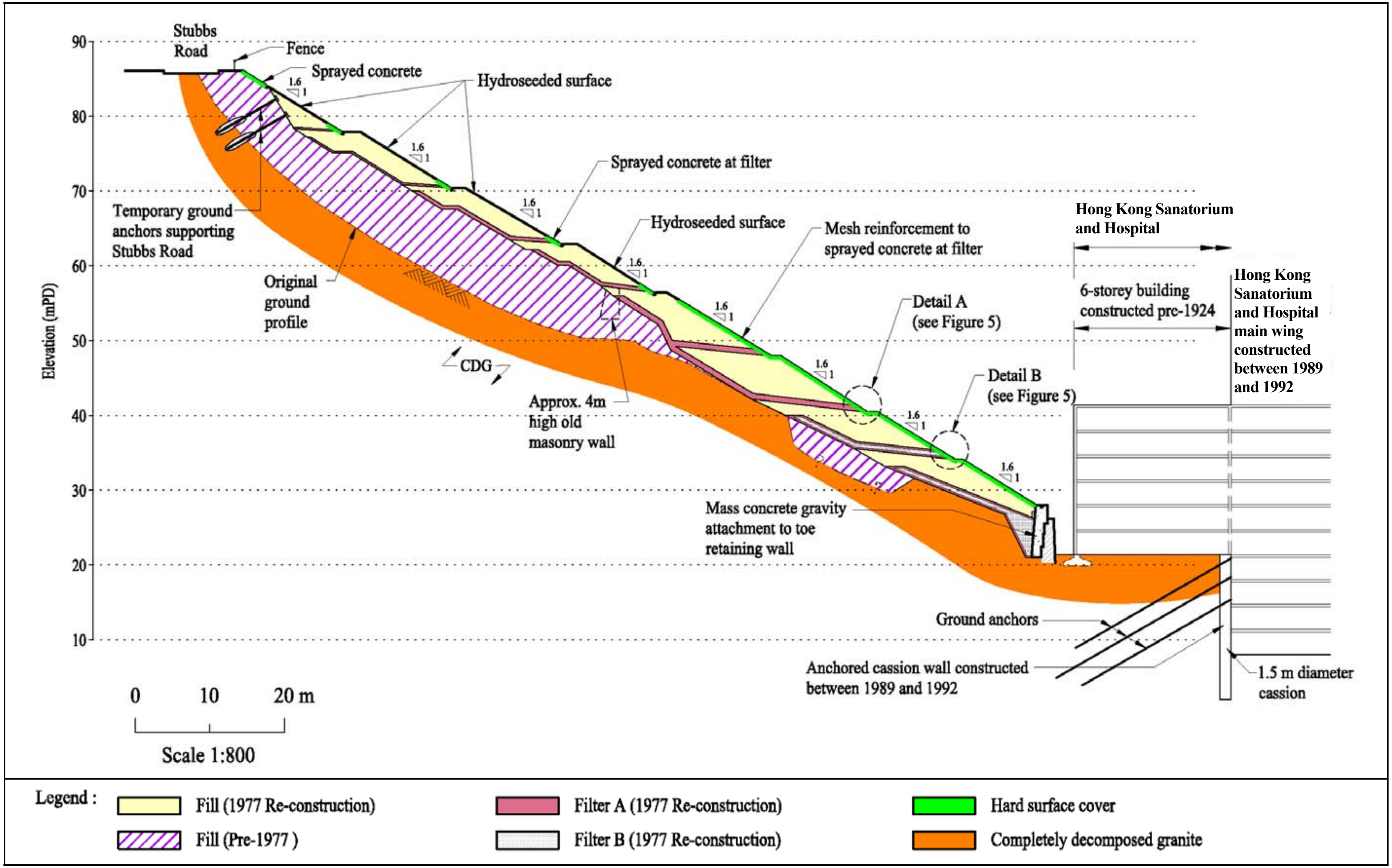

Figure 2a - Typical Section of Slope No. 11SW-D/FR1 at Hong Kong Sanatorium and Hospital

Notes: (1) Base Map is extracted from survey sheet No. 11SW-15C, scale 1:1000.
(2) General arrangement of the subject slope based on detailed topographic survey by CED Survey Division in May 2004.
(3) Cracking on third and fourth batters above toe unable to be mapped in detail due to heavy growth of unplanned vegetation.

Figure 2b - Distress of Slope No. 11SW-D/FR1 at Hong Kong Sanatorium and Hospital

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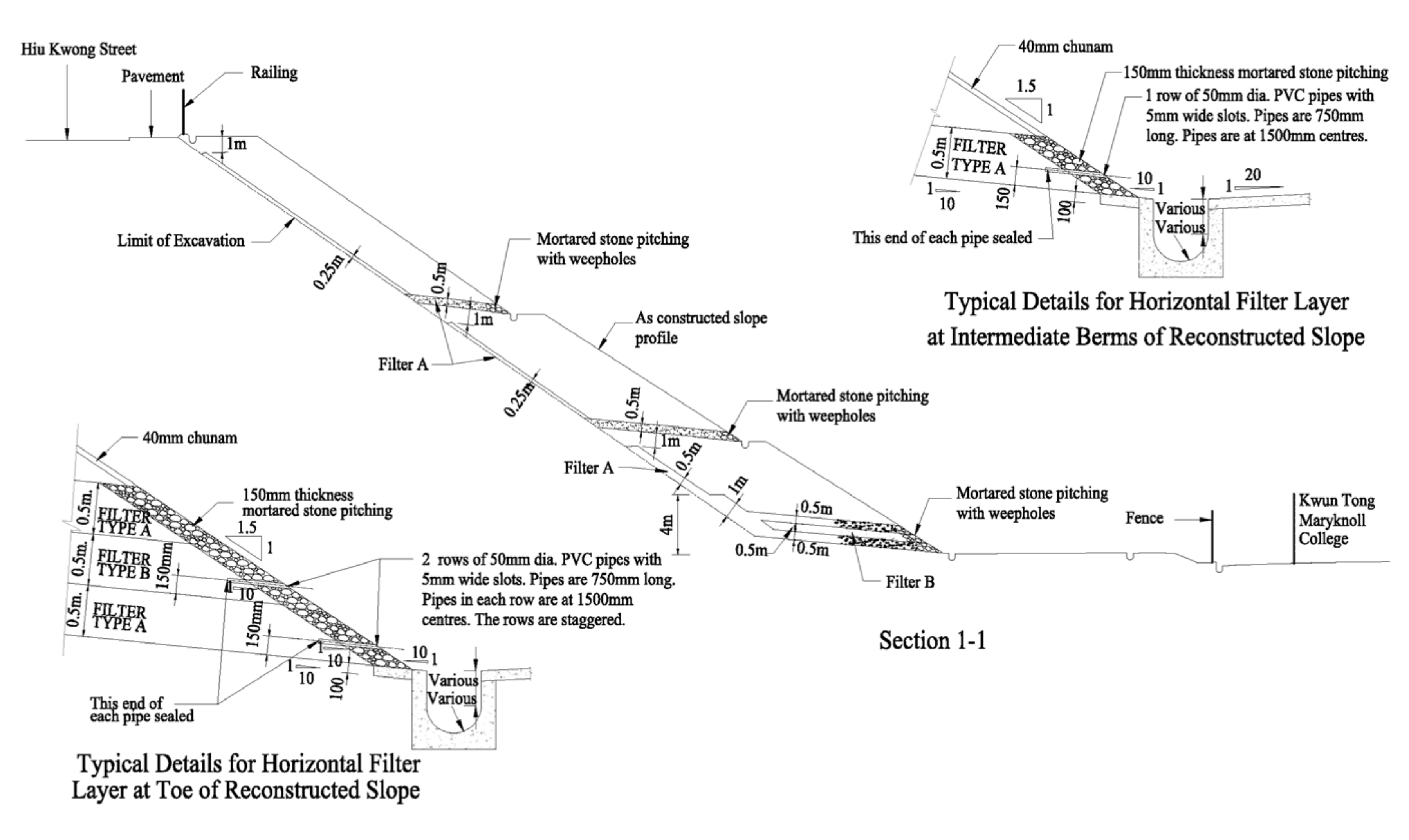

Note: Re-producted from Figure 6 of GEO (1999).

Figure 3a - Typical Section of Slope No. 11NE-D/F10 at Hiu Kwong Street

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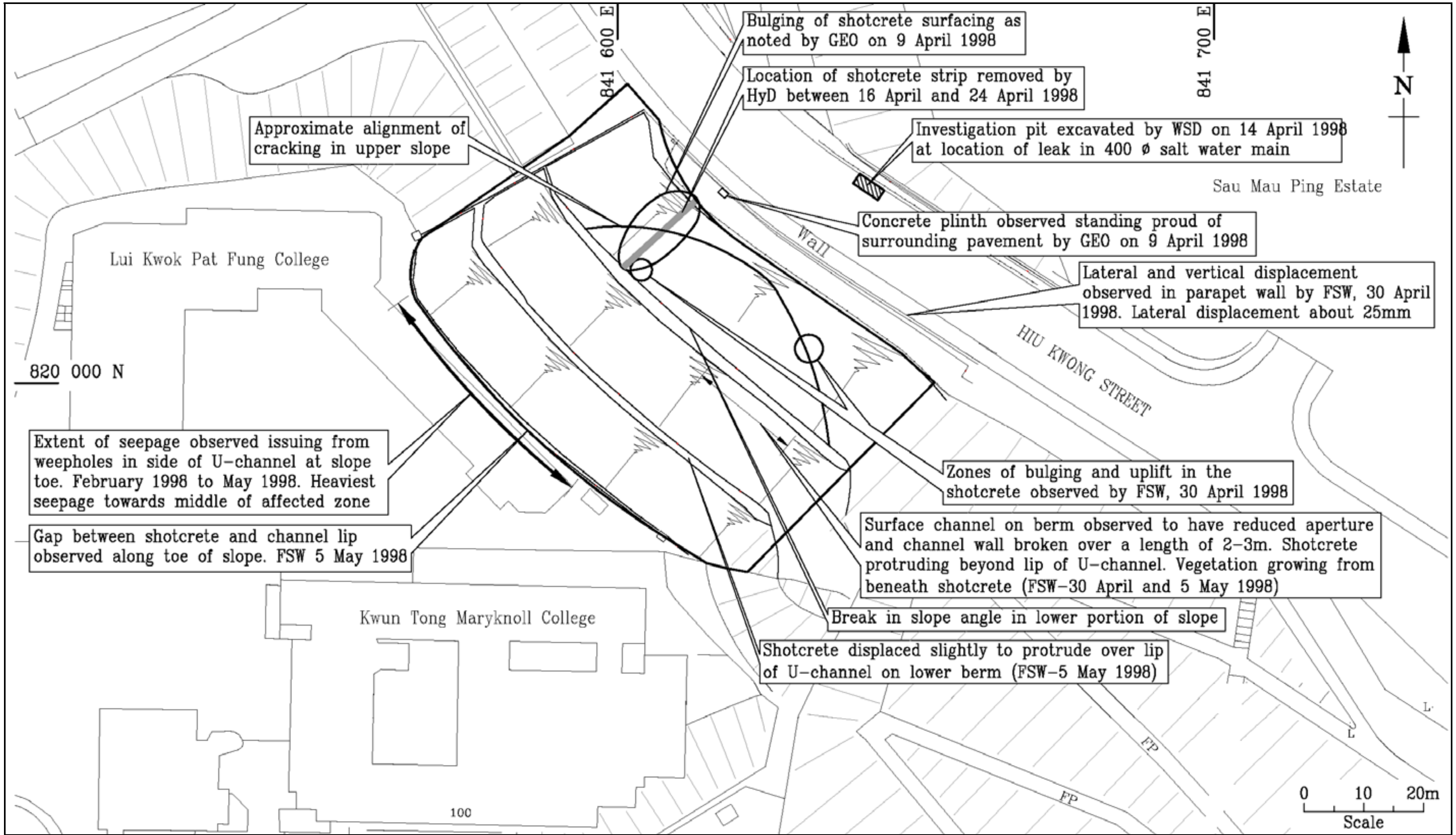
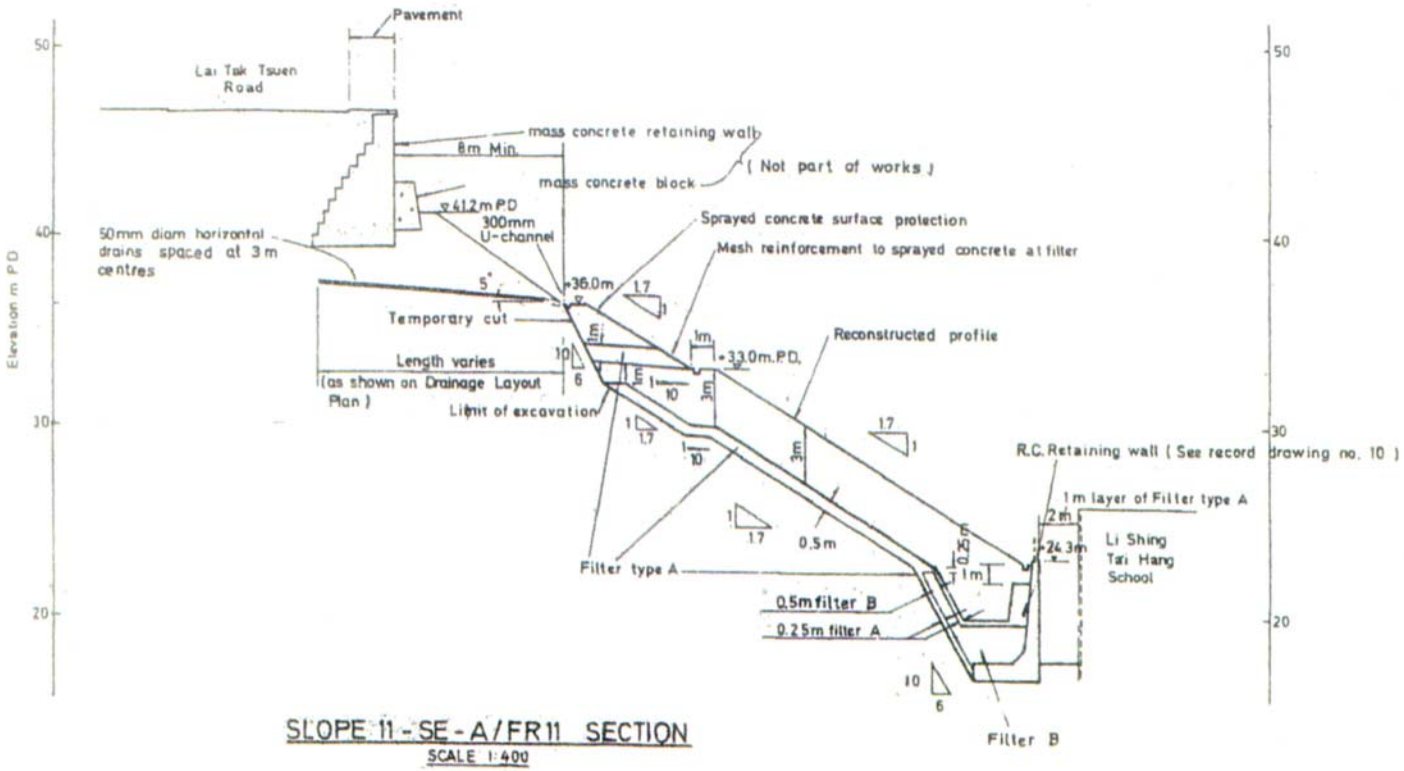


Note: Base Map is extracted from Survey Sheet No. 11NE-18B, scale 1:1000.

Figure 3b - Distress of Slope No. 11NE-D/F10 at Hiu Kwong Street



Note:	Plan extracted from Drawing No. 8 prepared by Binnie's Partners (Hong Kong) Consulting Engineers for Feature No. 11SE-A/FR11.

Figure 4a - Typical Section of Slope No. 11SE-A/FR11 at Lai Tak Tsuen Road

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Note: Base Map is extracted from Survey Sheet No. 11SE-11A, scale 1:1000 dated 1996.

Figure 4b - Distress of Slope No. 11SE-A/FR11 at Lai Tak Tsuen Road

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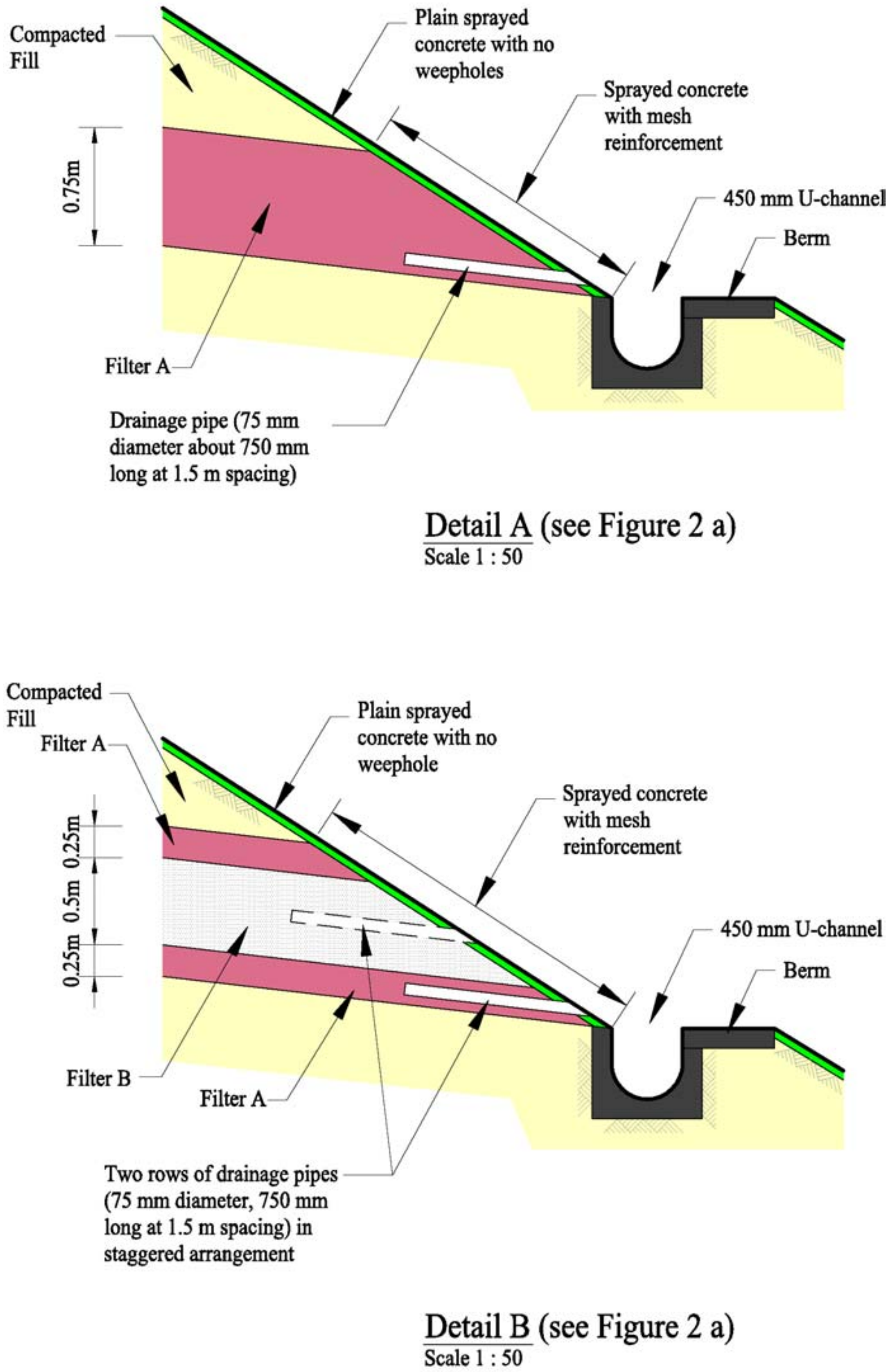

Note: Re-producted from Figure 11 of FSWJV (2005).

Figure 5 - Sub-surface Drainage Provisions of Slope No. 11SW-D/FR1 at Hong Kong Sanatorium and Hospital

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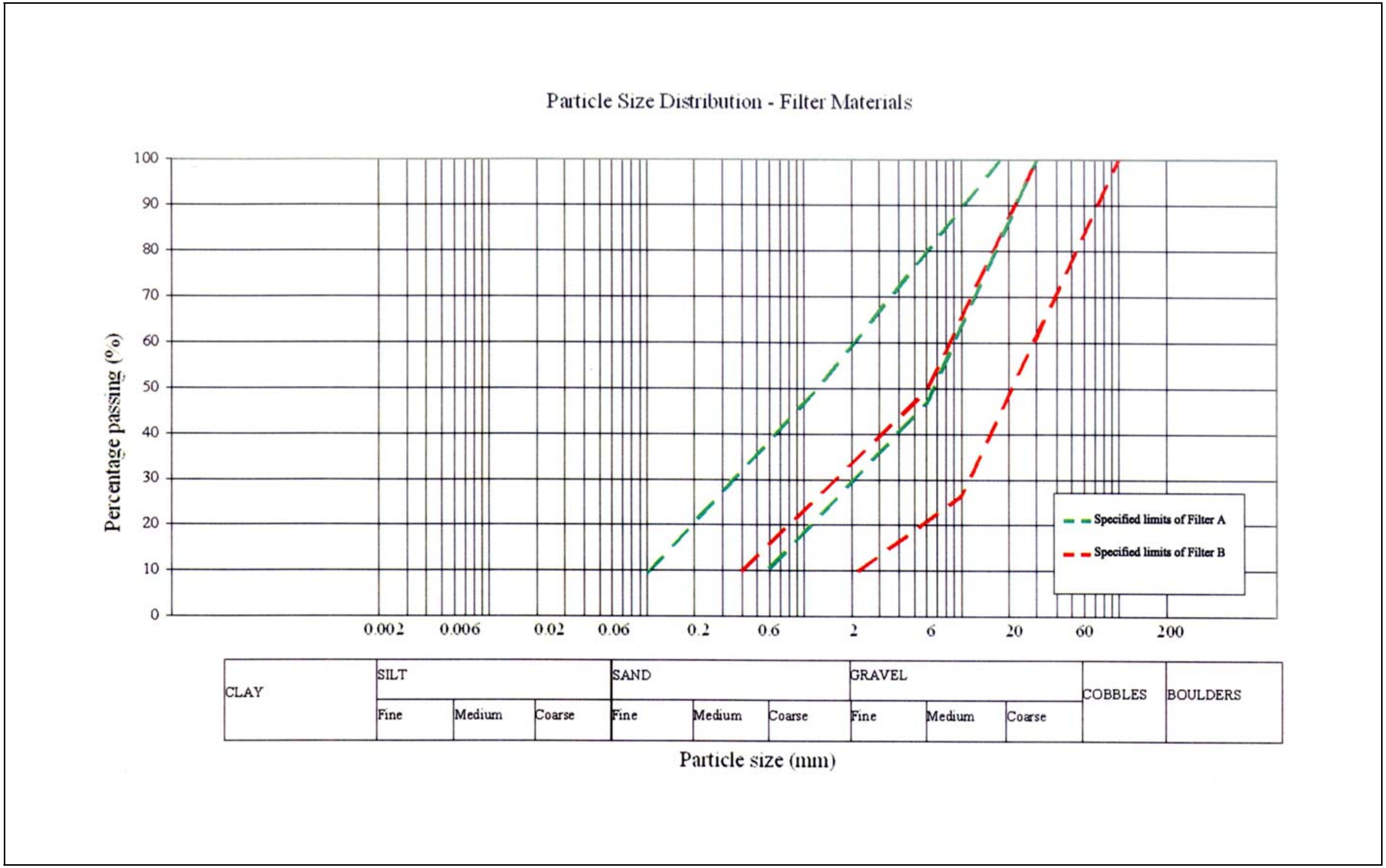

Figure 6 - Grading Ranges Specified for Filter A and Filter B Materials (Bowler & Phillipson, 1982)

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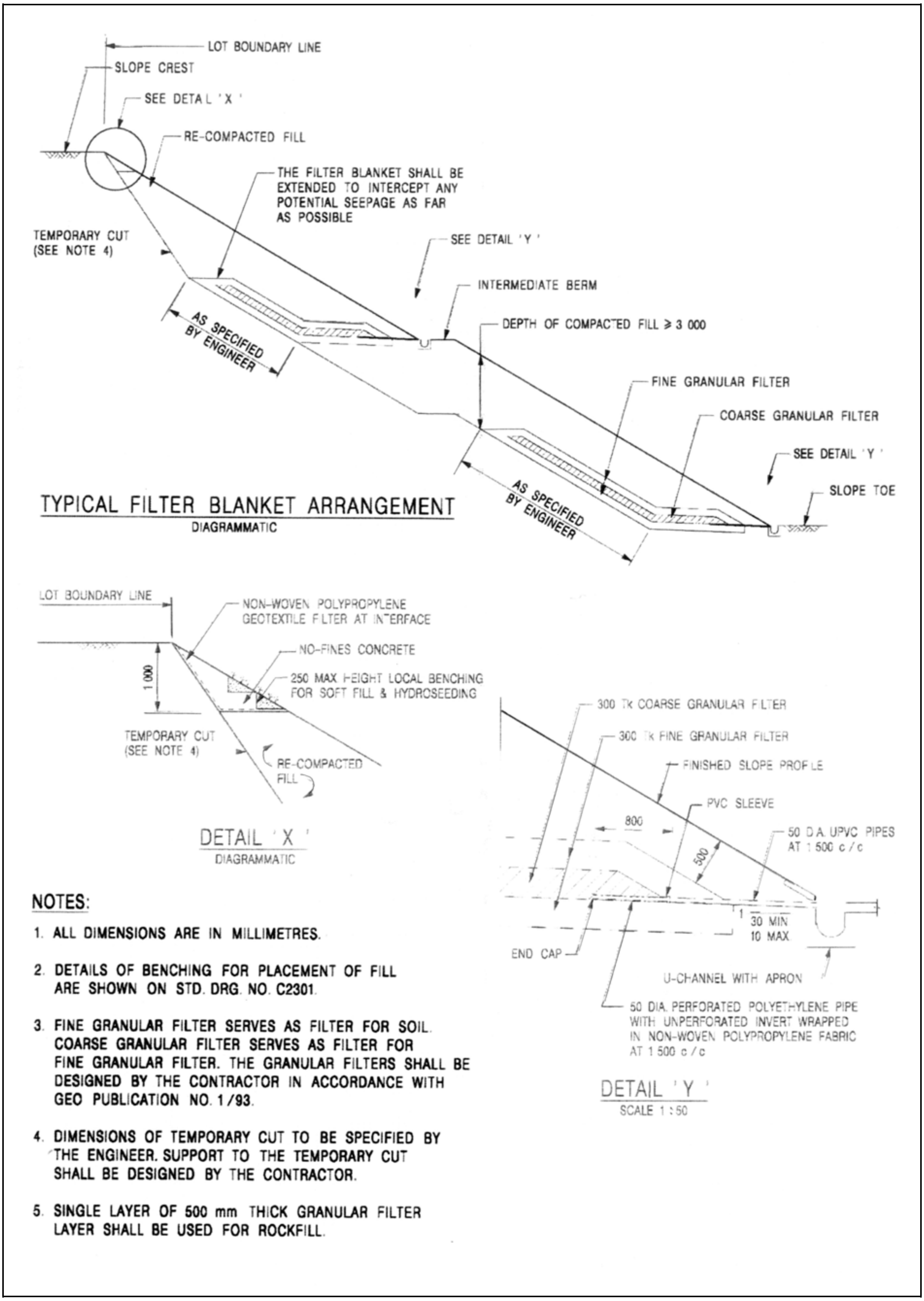

Figure 7 - Current Practice on Sub-surface Drainage Provisions for Fill Slopes in Hong Kong (reproduced from CEDD Standard Drawing C2302 (Rev. F))

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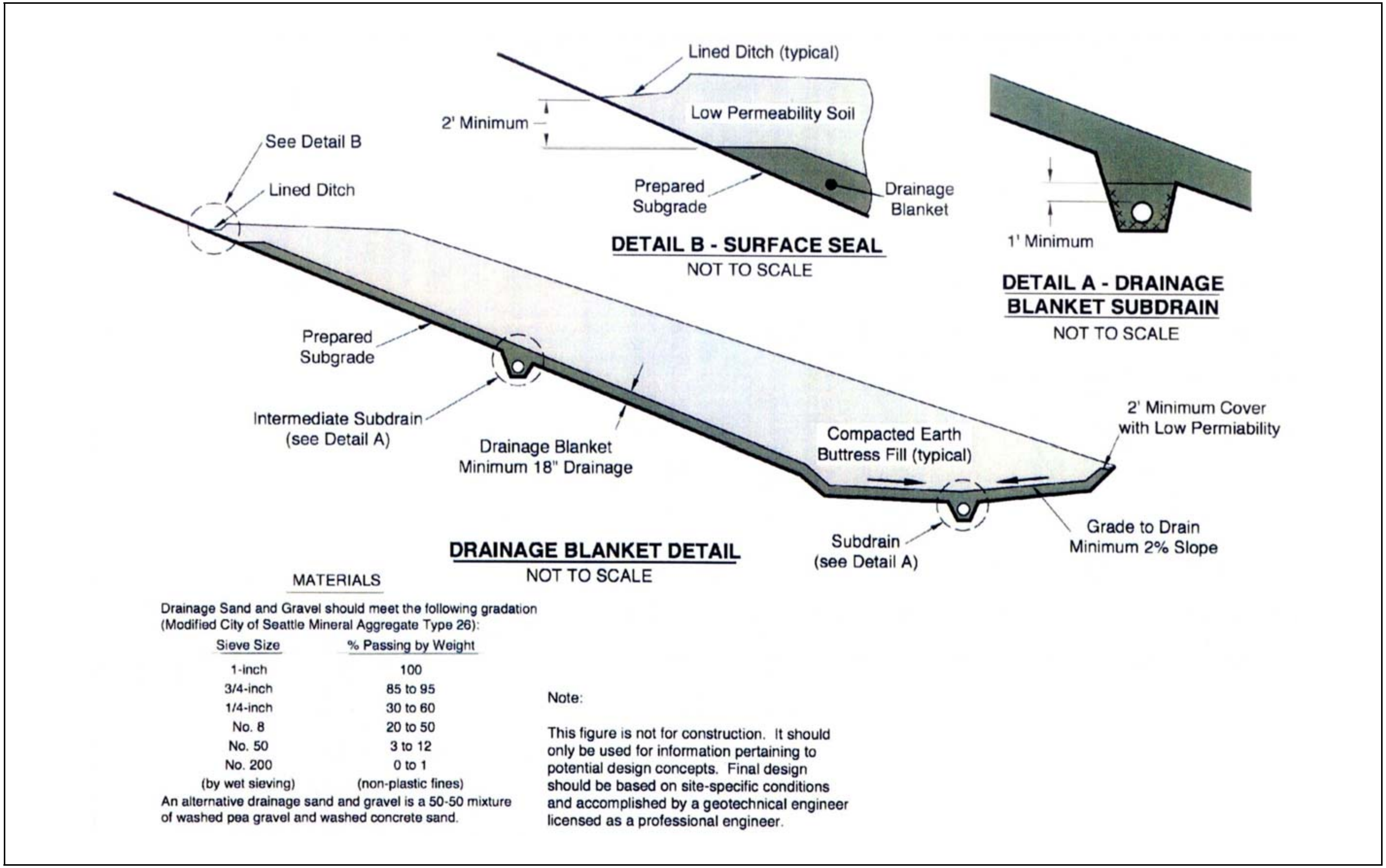

Figure 8 - Typical Drainage Blanket Details (reproduced from Figures 2-10 of the Seattle Landslide Study)

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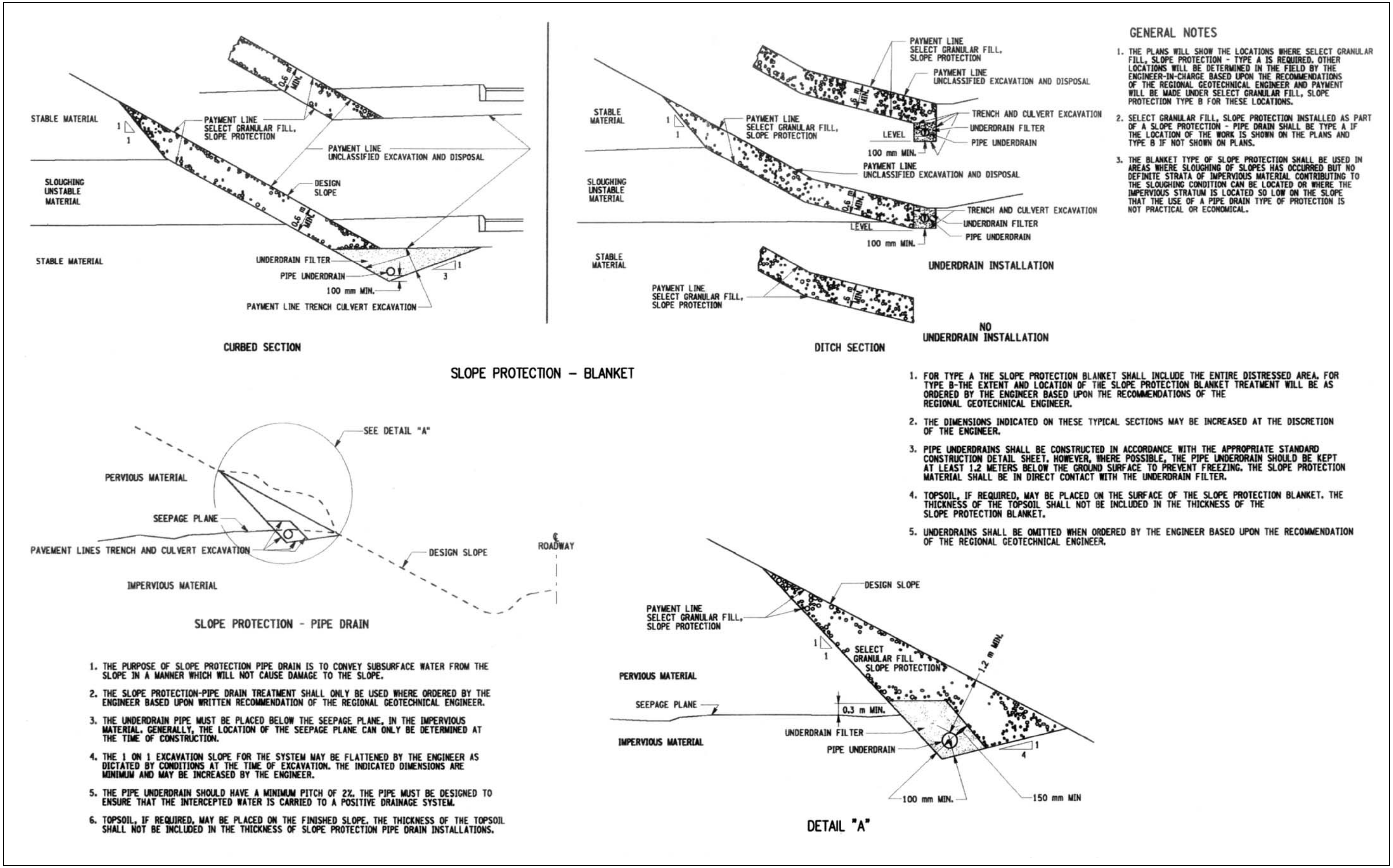

Figure 9 - Granular Fill Slope Protection Details of Department of Transportation, State of New York (reproduced from Standard Drawing M203-3R1)

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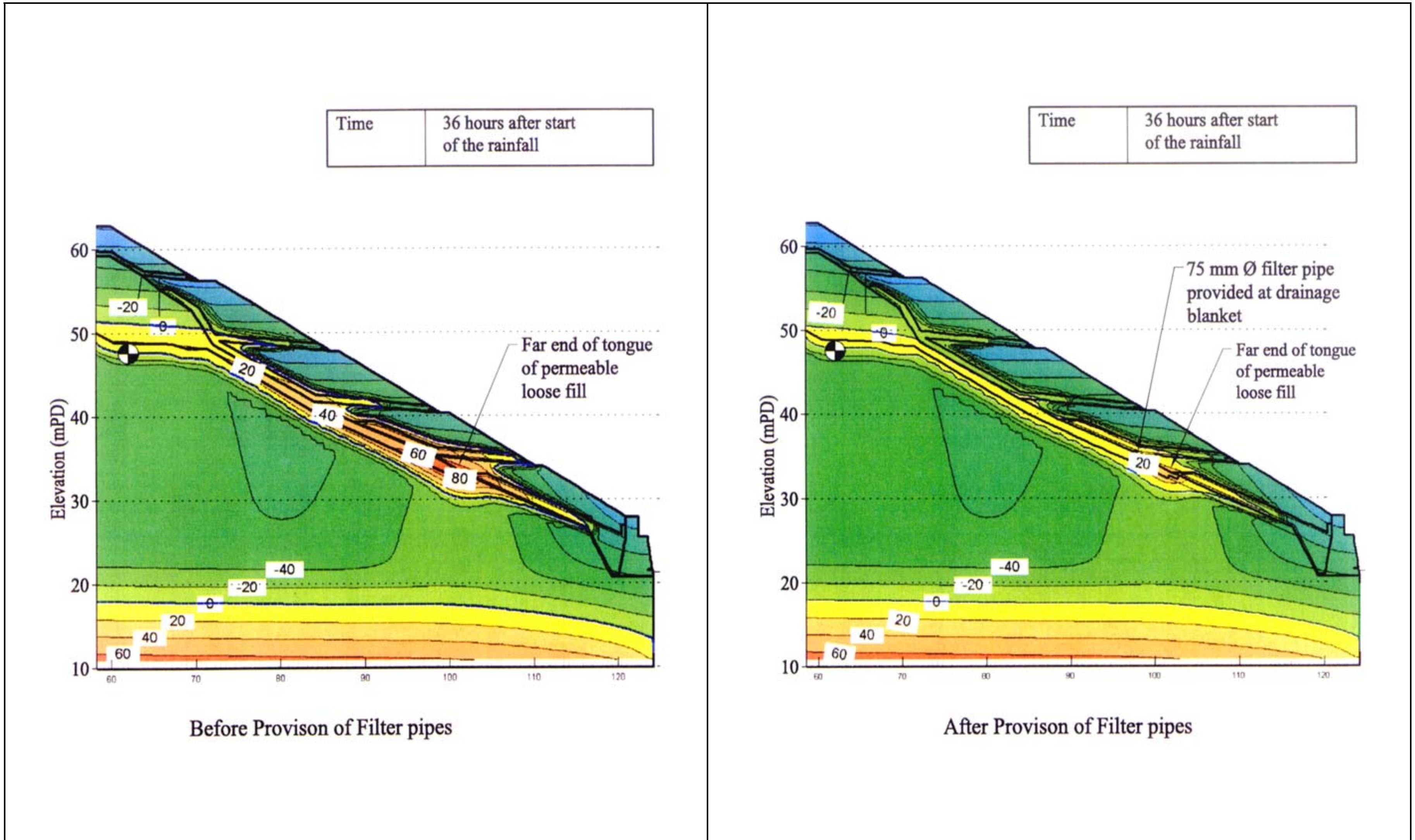

Note: 40 Transient groundwater pressure in kPa.

Figure 10 - Transient Groundwater Pressures before and after Provision of Filter Pipes

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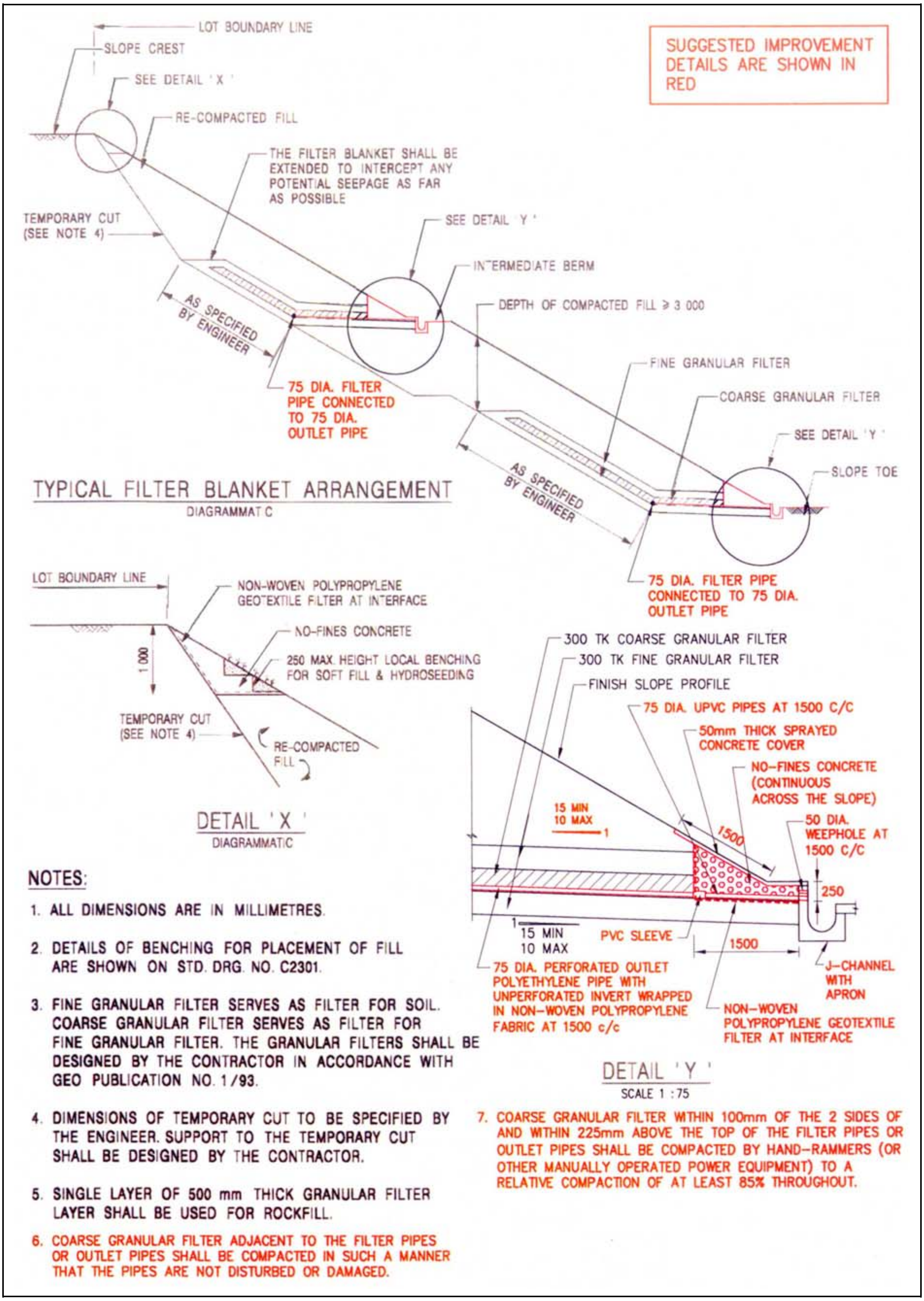

Figure 11 - Suggested Improvement to the Sub-surface Drainage Provisions for Compacted Soil Fill Slopes (Sheet 1 of 2)

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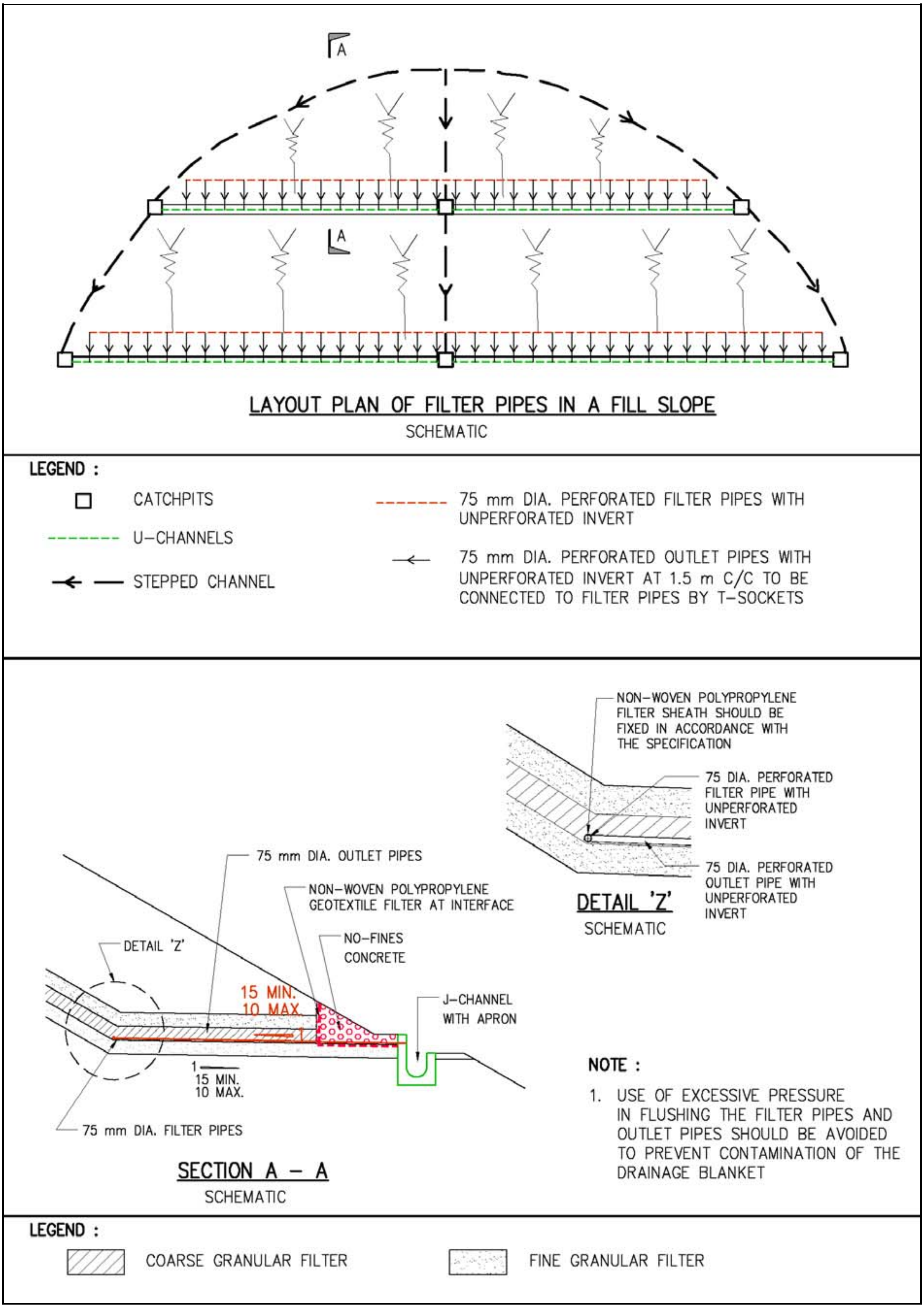

Figure 12 - Suggested Improvement to the Sub-surface Drainage Provisions for Compacted Soil Fill Slopes (Sheet 2 of 2)

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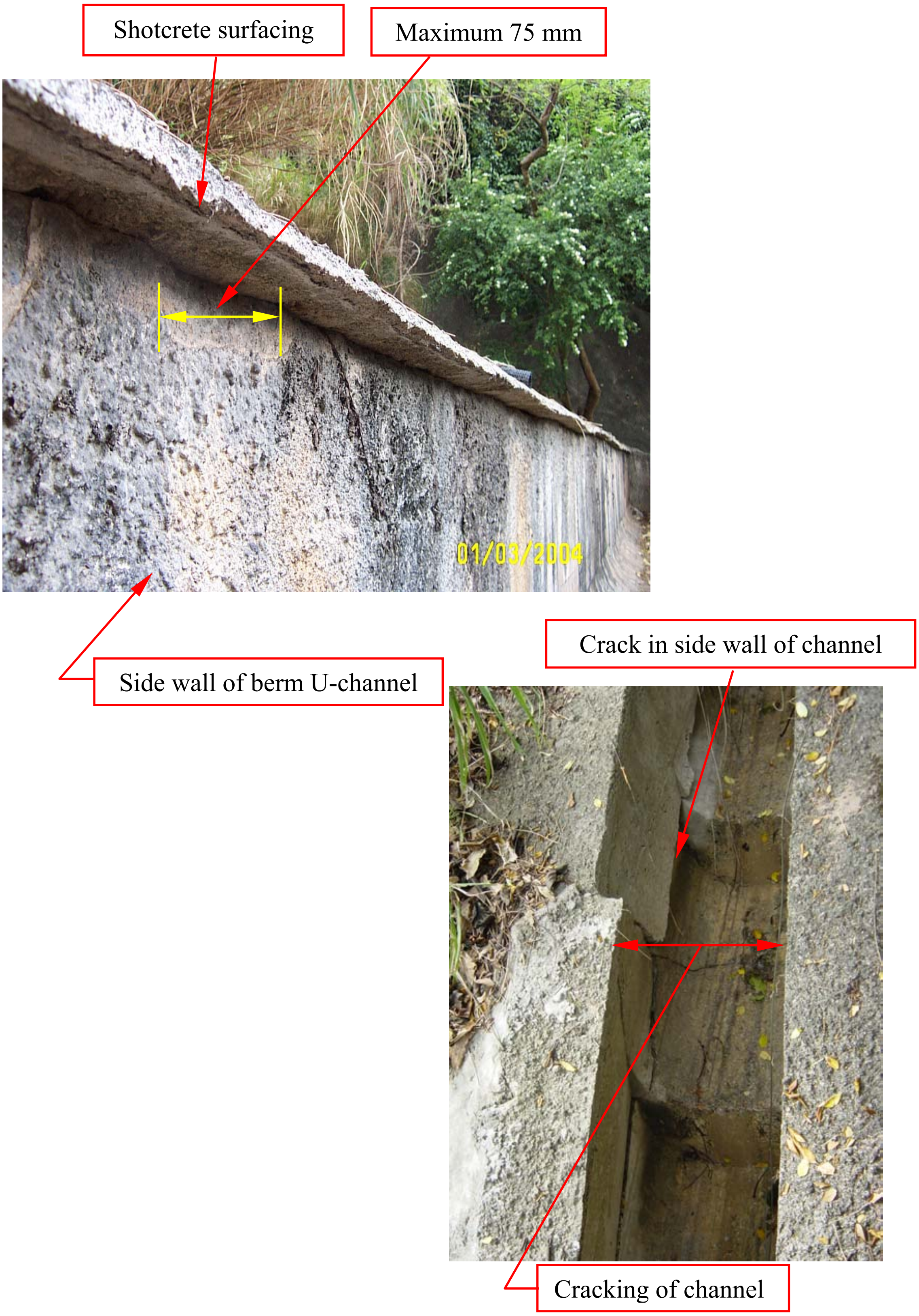

Plate 1 - Distress of Slope No. 11SW-D/FR1 at Hong Kong Sanatorium and Hospital

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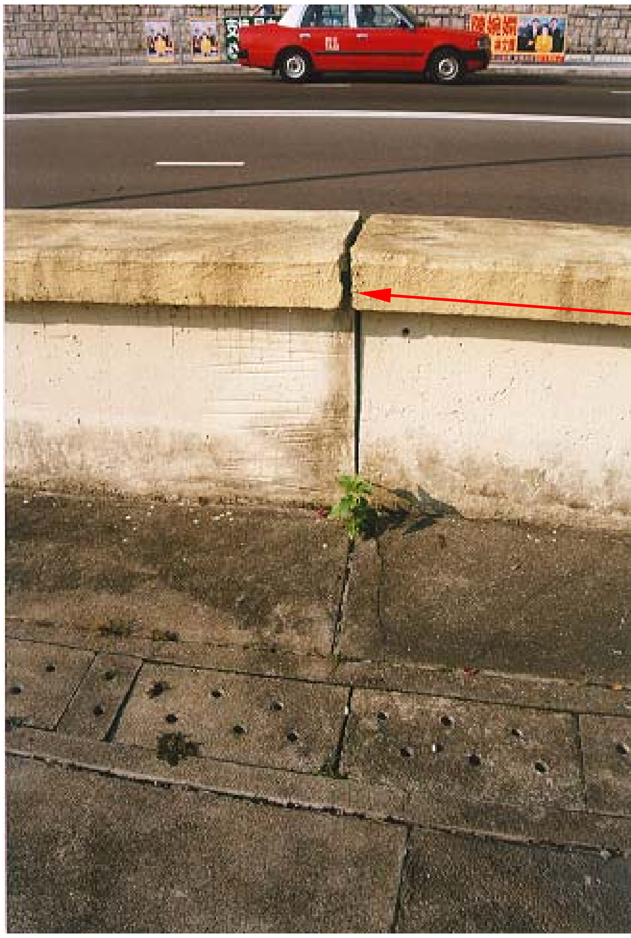

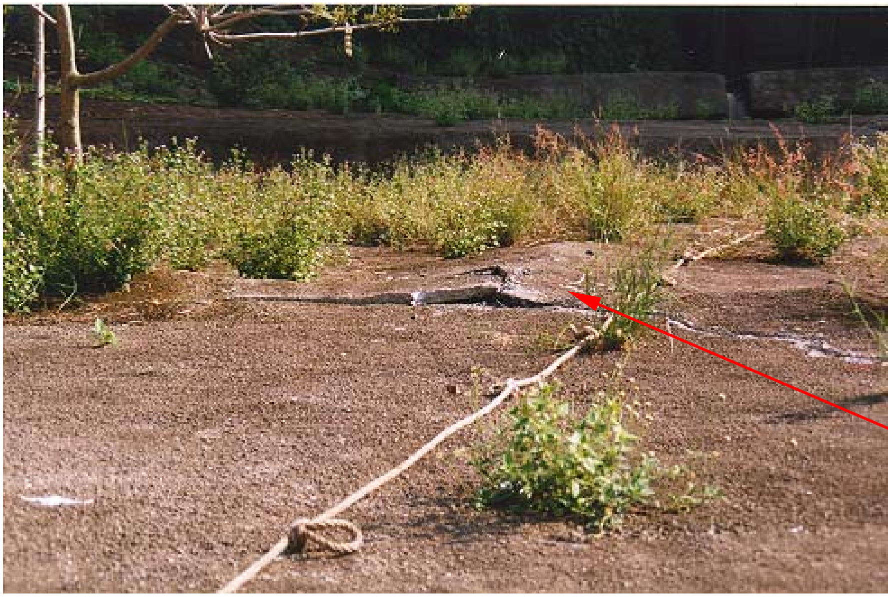

Plate 2 - Distress of Slope No. 11NE-D/F10 at Hiu Kwong Street

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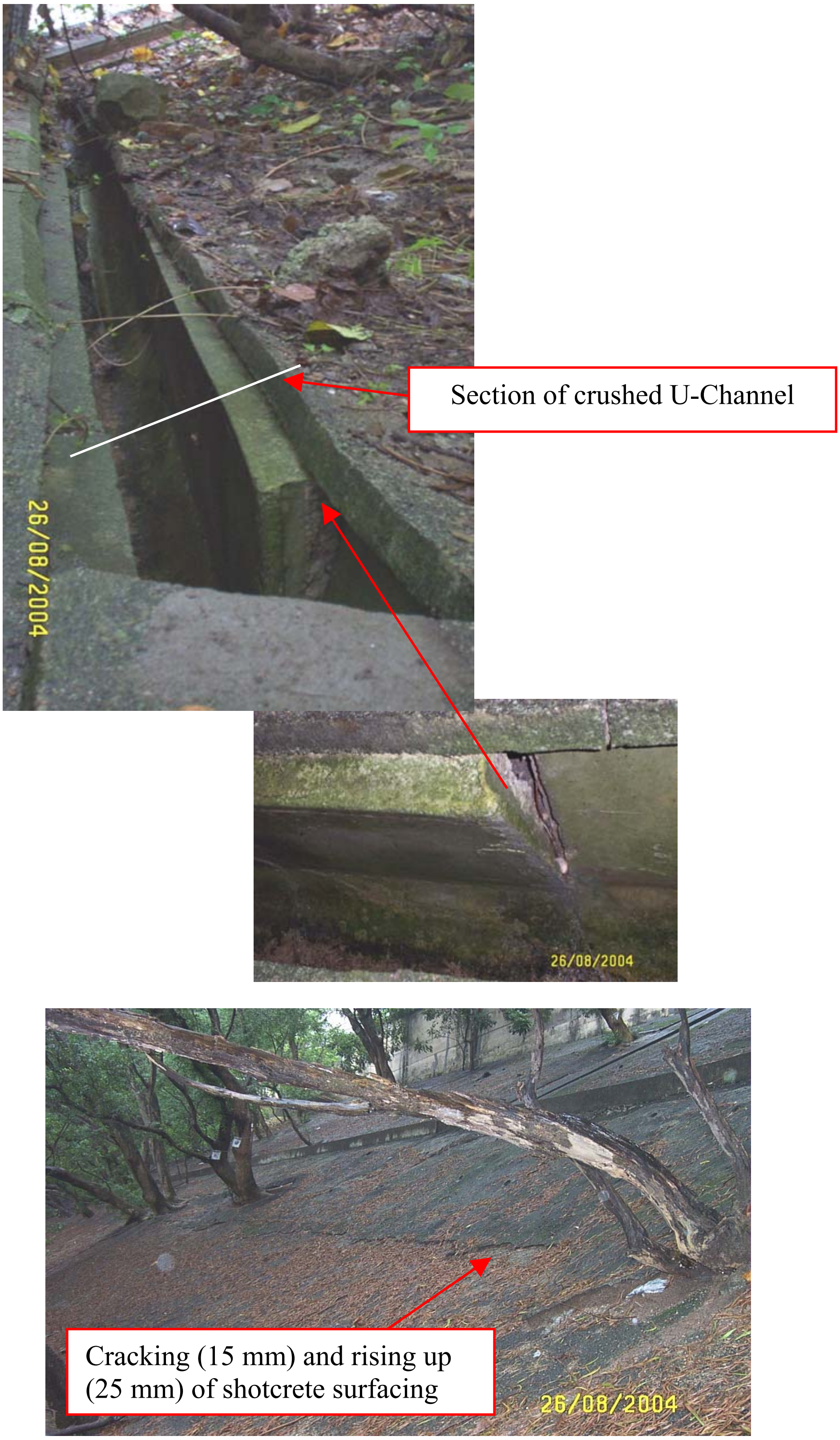

Plate 3 - Distress of Slope No. 11SE-A/FR11 at Lai Tak Tsuen Road

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APPENDIX A

THEORETICAL HYDRAULIC ANALYSES OF SUB-SURFACE DRAINAGE PROVISIONS FOR FILL SLOPES

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A1 DISCHARGE AND INTERCEPTING FUNCTIONS OF DRAIN PIPES

A1.1 General

The function of the outlet pipe is to provide an exit for the water collected in the drainage blankets. Two hydraulic properties of the drainage pipe are of relevance, viz. discharge capacity and intercepting capacity.

A1.2 Discharge Capacity

Flow in pipes and open channels are usually described by the Manning formula, which is based on experimental observations and is semi-empirical in nature. It relates the velocity of flow, v, to the hydraulic mean depth, R (defined as the cross-sectional area over the wetted perimeter), using the formula: $v = (R^{2/3} i^{1/2})/n$, where 'i' is the hydraulic gradient and 'n' is the coefficient of roughness of the surface. It should be noted that 'n' in fact is a dimensional parameter and has dimensions of $L^{-1/3}T$, and the various coefficients of roughness published are in units of $m^{-1/3}s$ (though sometimes not stated explicitly).

For a circular pipe with a given roughness and at a given hydraulic gradient, maximum flow occurs when the pipe is nearly full. In design, it is normally assumed that the pipe would be running full. In this case the discharge Q can be expressed as $Q = (0.312D^{8/3} i^{1/2})/n$ (the coefficient becomes 0.335 for maximum capacity). Assuming i = 0.1 and n = 0.015, the discharge capacity of various sizes of pipes are as follows:

Pipe Diameter (mm)	50	75	100	150	200
Discharge capacity (ml/s)	223	658	1417	4178	8997

In the drainage blanket, for a uniform soil of permeability k and hydraulic gradient i, the discharge capacity is given by Q = A.k.i, where A is the cross-sectional area of the drainage blanket. For a filter layer with $k = 10^{-4}$ m/s at the same hydraulic gradient of 0.1 as above, the discharge capacity of 1 m^2 section becomes 10^{-5} m^3/s or 10 ml/s. A 50 mm diameter pipe can therefore handle seepage from 2.23 m^2 of drainage blanket. With a blanket thickness of 0.3 m and a pipe centre-to-centre spacing of 1.5 m as shown in the present standard detail (Figure 7 of the report), each pipe has to handle the discharge from 0.3 m x 1.5 m or 0.45 m^2 of the drainage blanket. The safety margin is therefore 2.23/0.45 = 50, which is 5 times the requirement of Geoguide 1 (GEO, 1993) for permeability.

A1.3 Intercepting Capacity

Drainage pipes collect water from the openings at its sides. If the drainage pipe has sufficient openings (most of them do), they can be regarded as perfect drains. Data from Netlon Drains confirm this, and they provide a standard test for it. The arrangement is shown in Figure A1. The pipe specimen under test is buried in a rectangular box of standard sand. A constant head apparatus keeps the water level at the top of the sand, and the intercepting capacity of the pipe is reflected from the flow in the pipe, which is measured. This flow is basically a function of the permeability of the standard sand, and the size and efficiency (mainly a function of the opening ratio) of the pipe. The sides of the box are

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impermeable boundaries, while the top of sand is an equal-potential boundary. An approximate formula (indicated below) based on the equations of source and sink can be derived to evaluate the quantity of seepage into the ideal pipe for given values of the dimensions H, h, r, L, *l* and d, and permeability K of the uniform soil (see Figure A1 for definition of terms).

$$Q = 2\pi K\ell(r-h)\ell n \frac{(2H-r)\{L^2+(2H-r)^2\}(2H+2d+r)\{L^2+(2H+2d+r)^2\}(2H+2d-r)\{L^2+(2H+2d-r)^2\}}{r(L^2+r^2)(r+2d)\{L^2+(r+2d)^2\}(4H+2d-r)\{L^2+(4H+2d-r)^2\}}$$

From this formula, one can calculate the minimum penetration of the outlet pipe into the drainage blanket in order to intercept the entire flow from it, assuming it to be waterlogged. This penetration is independent of the permeability K, which cancels out each other in the formula. The following table shows the results of the calculation with a drainage blanket of cross section 300 mm x 1,500 mm with the outlet pipe placed at the bottom centre of the layer.

Pipe Diameter (mm)	50	75	100	150
Minimum Penetration (mm)	64	53	48	46

It would be prudent to provide extra length to allow for possible clogging of the holes on the surface of the outlet pipe in the long term, although the effect would be difficult to quantify. However, as little extra cost is involved, it is suggested that ample extra length be included (say, a factor of 10 or more), so that some area may remain unclogged to serve as intake.

A1.4 Comments

Results of this analysis show that if clogging is not considered, the capacity of subsoil drains in the present standard drawing is sufficient to provide outlet for the water from the drainage blanket. However, this would not solve the problem if the drainage blanket itself is the bottle-neck in the drainage path.

To account for the effect of clogging, it is recommended that a factor of at least 10 should be provided for the penetration distance of the pipe. This implied that even if 90% of the length is clogged, the drain can still function properly. This is considered worthwhile as very little extra cost is involved, and it may reduce long term maintenance costs, such as longer interval for flush cleaning.

A2 EFFECT OF INCREASING OUTLET PIPE DIAMETER

As mentioned in Section 5 of the report, increasing the pipe diameter would have little effect on the drainage system if the existing arrangement is already adequate. It could not solve the problem of a potential ‘bottle-neck’ in the drainage blanket. The table in Section A1.2 shows that a 50 mm outlet pipe has adequate discharge capacity, and increasing the diameter of the pipe would only reduce the required penetration (already small) slightly, and would not help to improve the hydraulic effectiveness of the system.

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A3 EFFECT OF LENGTHENING THE SLOTTED SECTION OF THE OUTLET PIPE

Lengthening the slotted section of the outlet pipe has the effect of intercepting the water earlier, and should have some effect on the drainage system. With reference to the filter layer arrangement as shown in Figure A2, it is assumed that the drainage blanket is of uniform material obeying Darcy's law and is of constant thickness, t, perpendicular to its length. If water is injected into the drainage blanket such that the water level remains at the top of the blanket, the piezometric level along the blanket will be as shown in Figure A2. The head, h, will be governed by the requirement of uniform flow, i.e. the hydraulic gradient of the inclined section and the sub-horizontal section would be the same since the cross-sectional area is constant. Thus, we have:

$$i = (H_1 - h) / \sqrt{(H_1^2 + L_1^2)} = (H_2 - h) / \sqrt{(H_2^2 + L_2^2)}$$

Typical values in metres for slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital are 10, 10, 5 and 1 for L1, L2, H1 and H2 respectively. These would give a value of 1.84 m for h, and 0.28 for i.

If the outlet pipe is extended 3 m into the filter layer as assumed in Section 6.1 of the report, it has the effect of reducing the length L2 from 10 m to 7 m, and H2 from 1 m to 0.7 m. This would give a value of 1.50 m for h (instead of 1.84 m) and 0.31 for i (instead of 0.28). This implies an increase in discharge capacity of merely 10%, confirming the results of analyses by SEEP/W as discussed in Section 6.1 of the report, which show the effect of increasing the outlet pipe to 3 m.

A4 EFFECT OF PROVIDING FILTER PIPES AT THE UP-STREAM END OF THE SUB-HORIZONTAL DRAINAGE BLANKET

If an additional sub-soil drain is placed at the up-stream end of the sub-horizontal drainage blanket, it would completely remove the piezometric head in the compacted fill above, and the hydraulic gradient in the sub-horizontal drainage blanket becomes 0.45, a 58% increase in discharge capacity. Again this confirms the results of analysis by SEEP/W as discussed in Section 6.3 of the report. Adding a sub-soil drain is certainly more cost effective than increasing the thickness of the filter layer by 58%. An alternative would be to extend the outlet pipes right into the up-stream end of the sub-horizontal drainage blanket, which should produce a similar effect, as demonstrated by SEEP/W analyses as discussed in Section 6.3 of the report.

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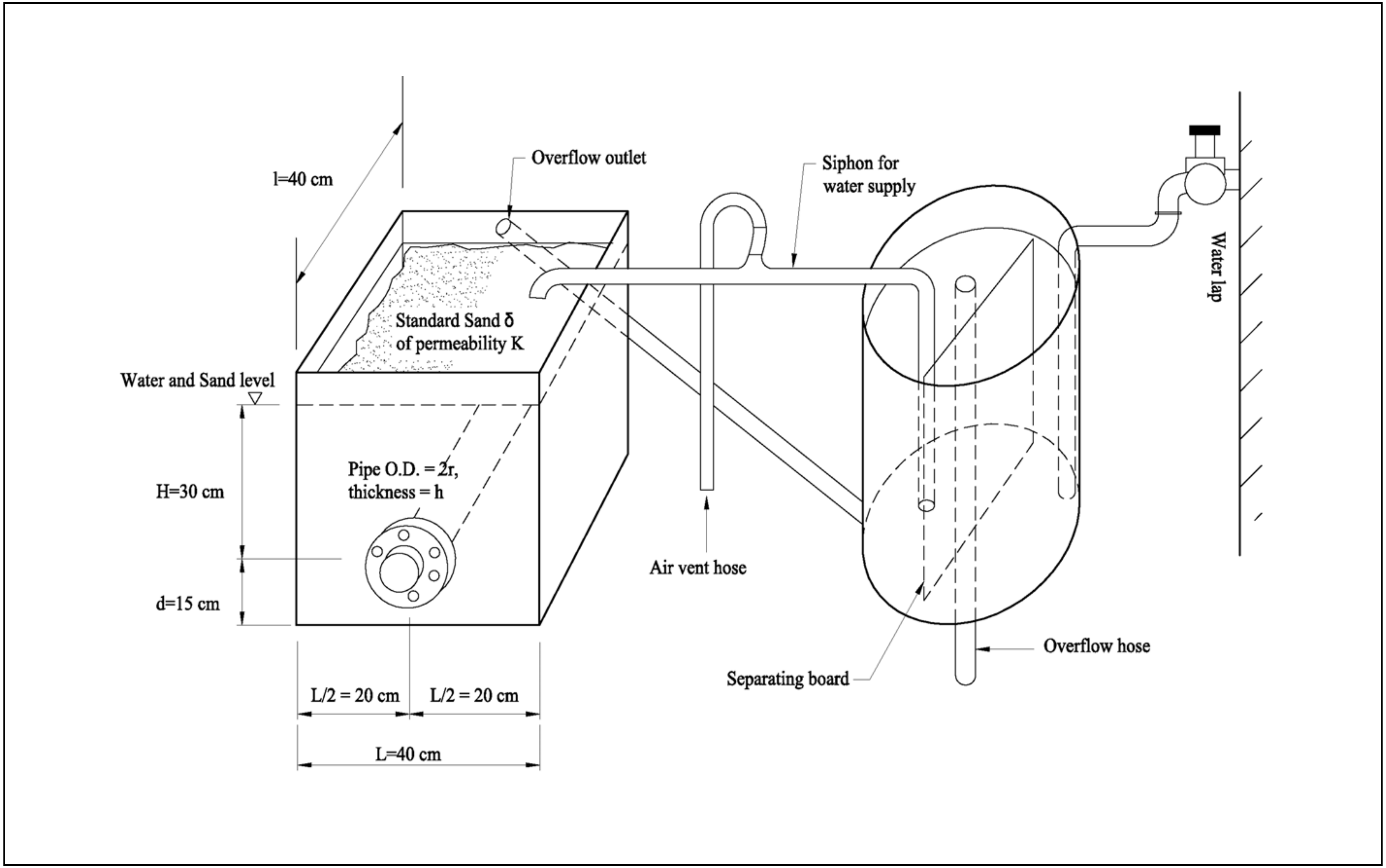

Figure A1 - Infiltration Test Arrangement (reproduced from Netlon Manual)

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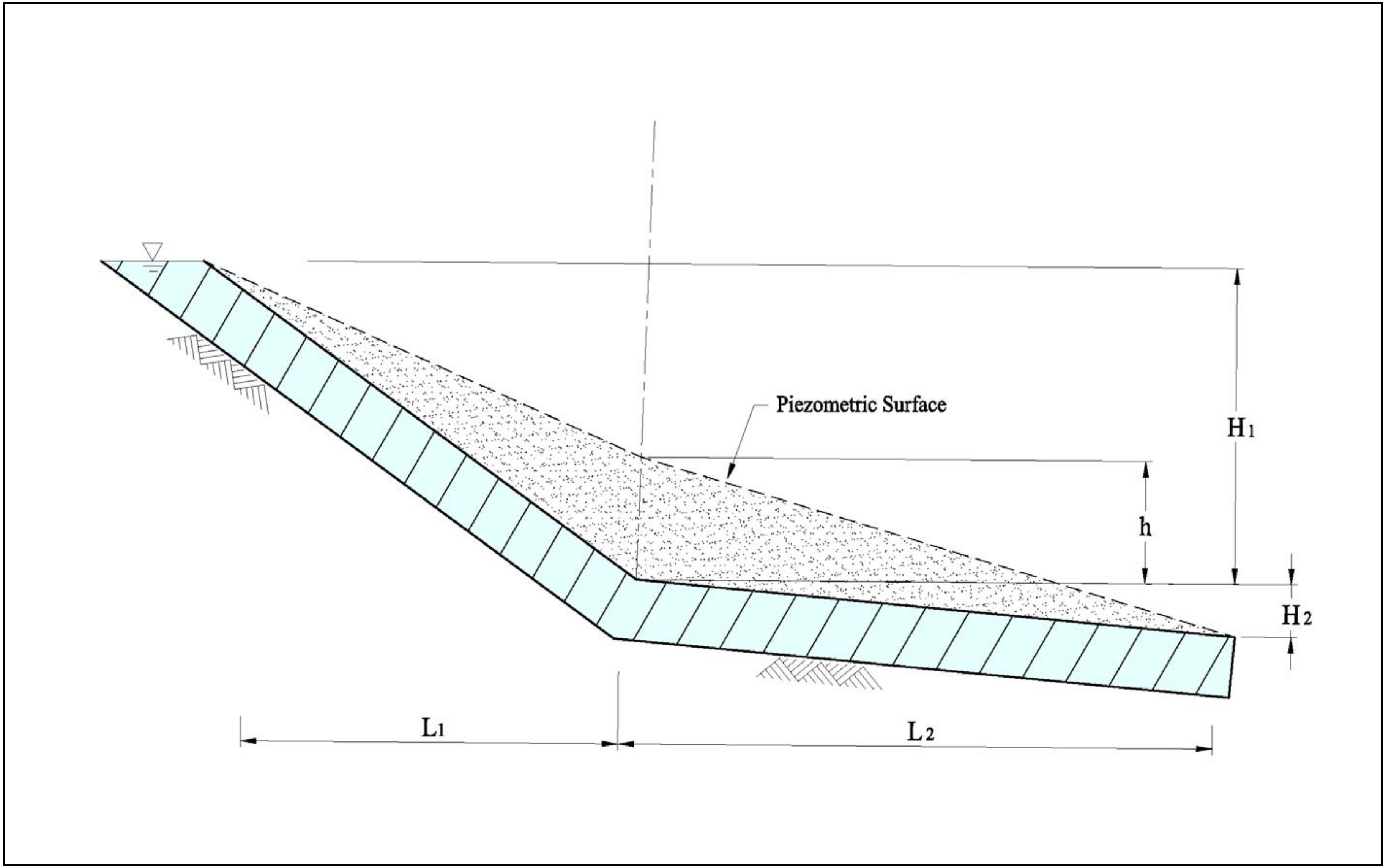

Figure A2 - Analysis of Effectiveness of Drainage Blanket

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APPENDIX B

SEEPAGE ANALYSES OF
SUB-SURFACE DRAINAGE PROVISIONS
FOR RECOMPACTED FILL SLOPES

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B1 SEEPAGE ANALYSES MODELLING

B1.1 Site Setting for Analyses

A common site setting of the three fill slopes discussed in Section 2 of the main report is that they are located within a well-defined old valley, which concentrated surface runoff from the natural hillside prior to the formation of the fill slopes. This kind of site setting is particularly prone to promoting an adverse hydrogeological condition involving concentrated transient groundwater flows along the old buried natural drainage line within the old, loose fill body, still existing underneath the minimum of 3 m thick recompacted fill cap.

In this review, slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital has been chosen for the seepage analyses, since comparatively more information on this site in terms of material properties and groundwater conditions, is available.

B1.2 Permeability of Saturated Materials

The following saturated permeability values have been adopted for the seepage analyses, which generally fall within the range of results obtained by FSWJV (2005).

Materials	**Order of Saturated Permeability, k (m/s)**
Compacted Fill	10^{-7}
Filter A	10^{-5}
Filter B	10^{-4}
Old Fill	10^{-3}
Granitic Saprolite	10^{-6}

For the uncompacted old fill, a higher order of saturated permeability has been adopted (i.e. 10^{-3} m/s), since this material is probably much more permeable than that indicated by the permeability test results (i.e. 10^{-4} m/s to 10^{-6} m/s) due to the presence of locally very loose fill (possibly small voids) in some drillholes sunk at the upper half of the slope. Conventional field permeability tests could not be performed in these kinds of loose materials because of the high permeability.

B1.3 Permeability Functions and Soil-water Characteristic Curves of Partially Saturated Materials

For the analysis of unsaturated flow (which has little effect on the results of the present analysis, which deals mainly with saturated flow), the soil-water characteristic curves and the permeability functions of the involved materials are required. The former gives the relationship between suction and moisture content, whilst the latter gives the relationship between suction and (unsaturated) permeability. Normally the former is obtained from experimental determination whilst the latter is calculated from the former based on theoretical models. However, if the soil properties are known, the soil-water characteristic curves can be estimated.

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The soil-water characteristic curves and the permeability functions of various materials adopted for the present analyses are shown in Figures B2a to B2c, which are typical curves recommended by computer program SEEP/W.

B1.4 Equivalent Permeability of Outlet Pipes

To model the outlet pipes in a 2-D computer program such as SEEP/W, a suitable approach is to find the equivalent permeability based on the discharge capacity of the outlet pipe by treating it as a continuous drainage blanket of 1 m thick.

From Appendix A, the discharge capacity of 75 mm diameter pipe (Q) is 658 ml/s when the hydraulic gradient (i) = 0.1 and the coefficient of roughness, (n) = 0.015.

Since $Q = k.i.A$

where k is permeability in m/s and
A is the cross-sectional area of the drainage blanket in m^2

Therefore $0.658 \times 10^{-3}\ m^3/s = k \times 0.1 \times 1.5 \times 1\ m^2$
$k = 4.39 \times 10^{-3}$ m/s

A material with an equivalent permeability of 4.39×10^{-3} m/s and a thickness of 1 m was adopted for the outlet drainage pipes.

B1.5 Groundwater Modelling in Seepage Analyses

The base groundwater table at slope No. 11SW-D/FR1 is located within the granitic saprolite at a depth of around 10 m below the slope toe, while piezometers installed within the compacted fill in the lower batters indicated a piezometric head at between 1 m and 2 m below ground surface.

Water ingress into the old loose fill body probably occurred within the upper half of the slope resulting in transient groundwater flow to the lower half of the slope leading to the build-up of water pressure.

In the seepage analyses using computer program SEEP/W, the site for modelling was assumed to be bounded by a vertical line some 20 m beyond the crest of the fill slope and a vertical line just beyond the toe of the slope. The initial condition of the site was established by allowing a small amount of rainfall to infiltrate into the crest of the slope at a rate of 1 mm per day until steady state was reached (see Figure B3). However, this initial condition is found to be not critical to affect the result of the subsequent seepage analyses.

In this review, various rates of water ingress into the upper half of the slope were modelled. The rate of water ingress arising from a 1-in-10 year return period rainstorm with a duration of 4 hours and with 5% of the water collected by the upslope catchment area leaking into the old loose fill body was chosen for the seepage analyses. The rainstorm profile used in the seepage analyses is shown in Figure B4. This rate of water ingress was

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chosen to permit a reasonable depth of transient groundwater flow to occur within the loose fill body in the upper half of the slope.

B1.6 Presence of a Tongue of Permeable Materials below the Compacted Fill in the Lower Half of Slope

The finite element mesh used in the seepage analysis was initially developed based on a typical cross-section of slope No. 11SW-D/FR1 above Hong Kong Sanatorium and Hospital as shown in Figure 2 of the report. With this model, it was noted early in the seepage analyses that it was not possible to simulate a situation to permit transient groundwater formed within the upper half of the slope to flow to the lower half of the slope, since there was no direct drainage linkage between the upper and lower halves of the slope. This observation is contrary to what was observed by FSWJV (2005).

With a view to permitting transient groundwater to reach the lower half of the slope, a thin layer of old fill was assumed to exist underneath the compacted fill at the lower half of the slope, yet this layer of old fill was not to extend to the toe retaining wall. The possible existence of such a thin layer of old fill at this location is, to some extent, reflected by the observed 2 m thick disturbed material underlying the compacted fill in some drillholes sunk at this part of the slope (FSWJV, 2005).

This thin layer of fill (with a high permeability) has served, to a certain extent, as the 'tongue of permeable material' described by Bolton et al (2003) and Lee & Bolton (2006). The finite element mesh thus used in the seepage analysis is given in Figure B1.

B2 RESULTS OF SEEPAGE ANALYSES

B2.1 Initial Condition Prior to Provision of Drainage Enhancement Measures

The results of the seepage analyses showing the transient groundwater pressure within the slope, prior to the provision of drainage enhancement measures, are given in Figure B5.

As can be seen from Figure B5, by 12 hours after the start of the rainstorm, a confined aquifer was developed in the old fill at the location where it converges to the 'tongue of permeable material'. Transient groundwater had not yet entered into the sub-horizontal drainage blankets.

By 24 hours, a maximum positive water pressure of 60 kPa had been established at the far end of the 'tongue of permeable material' just below the lowest sub-horizontal drainage blanket. Some of the transient groundwater had advanced into the sub-horizontal drainage blankets, but none had reached the drainage outlets.

By 36 hours, the positive water pressure at the far end of the 'tongue of permeable material' remained as 80 kPa. Notably, the transient groundwater at the lowest sub-horizontal drainage blanket (with 'Filter A/B/A') had advanced to the outlet, but this was not the case at the upper sub-horizontal drainage blankets (with 'Filter A' only).

By 48 hours, more transient groundwater had discharged through the outlets of the

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lowest sub-horizontal drainage blanket (with 'Filter A/B/A') and some transient groundwater might have been discharged through the toe retaining wall. The hydraulic pressure at the far end of 'tongue of permeable material' still remained high at 60 kPa. Transient groundwater at the upper sub-horizontal drainage blankets (with 'Filter A' only) had still not yet reached their outlets.

An obvious observation from these results is that drainage blanket with the provision of 'Filter A' alone would not be effective in discharging transient groundwater. Drainage blanket with the provision of 'Filter A/B/A' will be more effective, but it still took a long time prior to the release of any build-up of positive water pressure. The potential bottle-neck of transient groundwater discharge appears to be with the drainage blankets.

B2.2 Effect of Lengthening Slotted Section of Outlet Pipes

The effect of lengthening the slotted section of the outlet pipes was examined in the seepage analyses by extending the length from 750 mm to 3 m and 12 m long respectively. The results of the analyses are given in Figures B6 and B7.

For an increased length of 3 m of the slotted section of the outlet pipes, the results indicate that there was little benefit in terms of release of transient groundwater (comparing Figure B5 with Figure B6). The hydraulic pressure at the far end of the 'tongue of permeable material' remained at 60 kPa after 48 hours since the start of the heavy rainfall with the lengthened outlet pipes.

For an increased length of 12 m of the slotted section of the outlet pipes, the benefit in terms of the release of transient groundwater became more obvious (comparing Figure B5 with Figure B7). The hydraulic pressure at the far end of the 'tongue of permeable material' never exceeded 40 kPa, whereas a hydraulic pressure as high as 60 kPa was noted at the same location before lengthening of the outlet pipes.

B2.3 Effect of Increasing the Thickness of 'Filter B'

The effect of increasing the thickness of 'Filter B' was examined in the seepage analyses. The results of the analyses are given in Figures B8.

For an increased thickness of 2 m for 'Filter B', the results indicate that there was little benefit in terms of the release of transient groundwater (comparing Figure B5 with Figure B8). The hydraulic pressure at the far end of the 'tongue of permeable material' still remained at 60 kPa after 48 hours since the start of the heavy rainfall. This suggests that the discharge capacity of a 2 m thick 'Filter B' is still insufficient to quickly dissipate the hydraulic pressure built up at the far end of the 'tongue of permeable material'.

B2.4 Effect of Providing Filter Pipes at the Up-stream End of Sub-horizontal Drainage Blankets

The effect of placing a 75 mm diameter flexible slotted plastic pipe (as filter pipes)

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laterally across the slope at the intersection of the inclined and sub-horizontal drainage blankets was examined in the seepage analyses. To model the effect of this filter pipe, a 75 mm diameter hole was assumed to be open at that location, which permitted water to enter from its circumference and be drained away immediately. The results of analyses are given in Figure B9.

As indicated by the results of the analyses, the benefit of providing filter pipes in enhancing the effectiveness of the sub-surface drainage provisions was very obvious (comparing with Figure B5 and Figure B8). The hydraulic pressure at the far end of the 'tongue' of permeable loose fill never exceeded 20 kPa, whereas a hydraulic pressure as high as 80 kPa was noted at the same location before provision of filter pipes.

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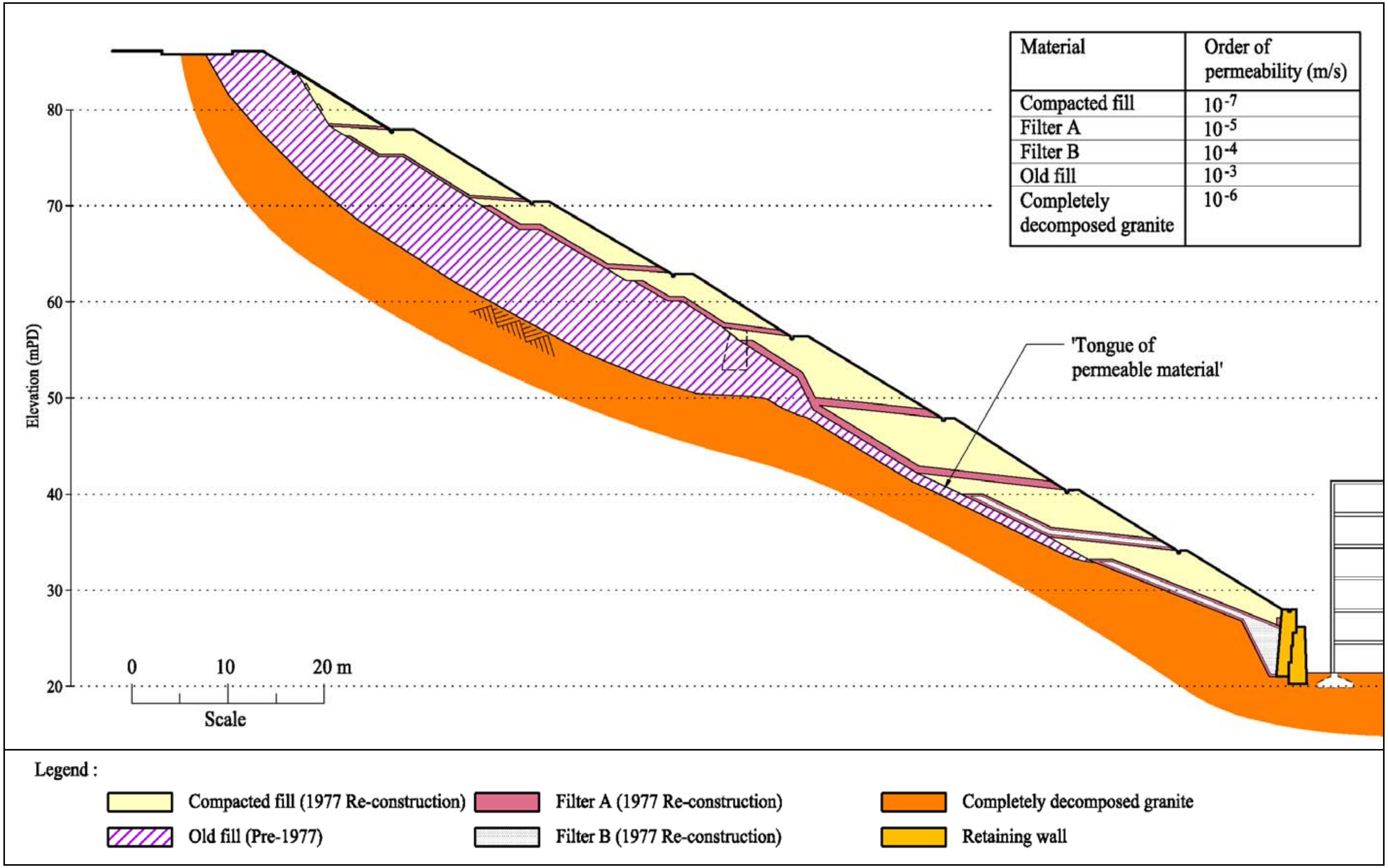

Figure B1 - Section of Slope No. 11SW-D/FR1 at Hong Kong Sanatorium and Hospital used for SEEP/W Analyses

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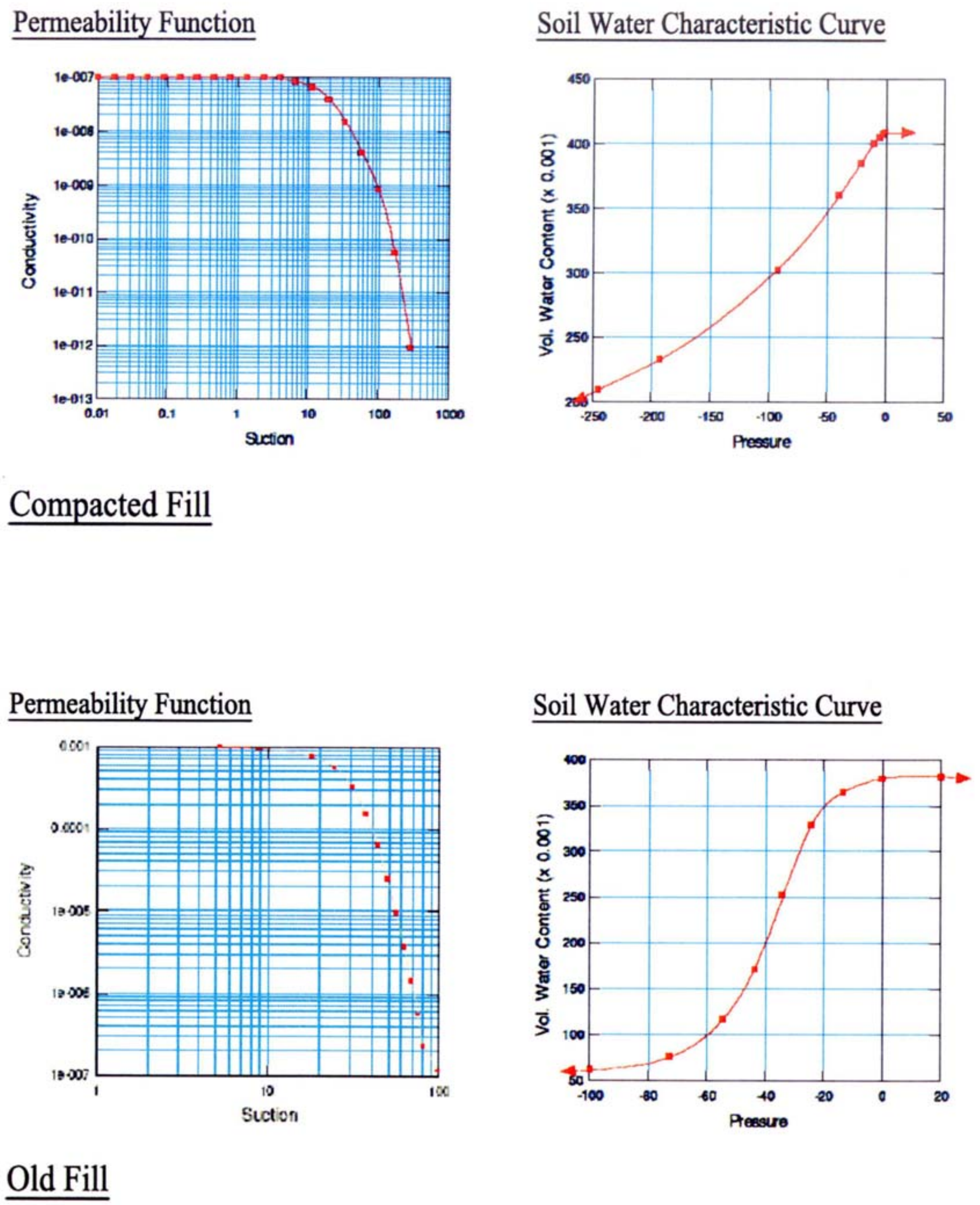

Figure B2a - Permeability Function and Soil Water Characteristic Curve of Compacted Fill and Old Fill Adopted in Seepage Analyses (reproduced from SEEP/W Users' Guide)

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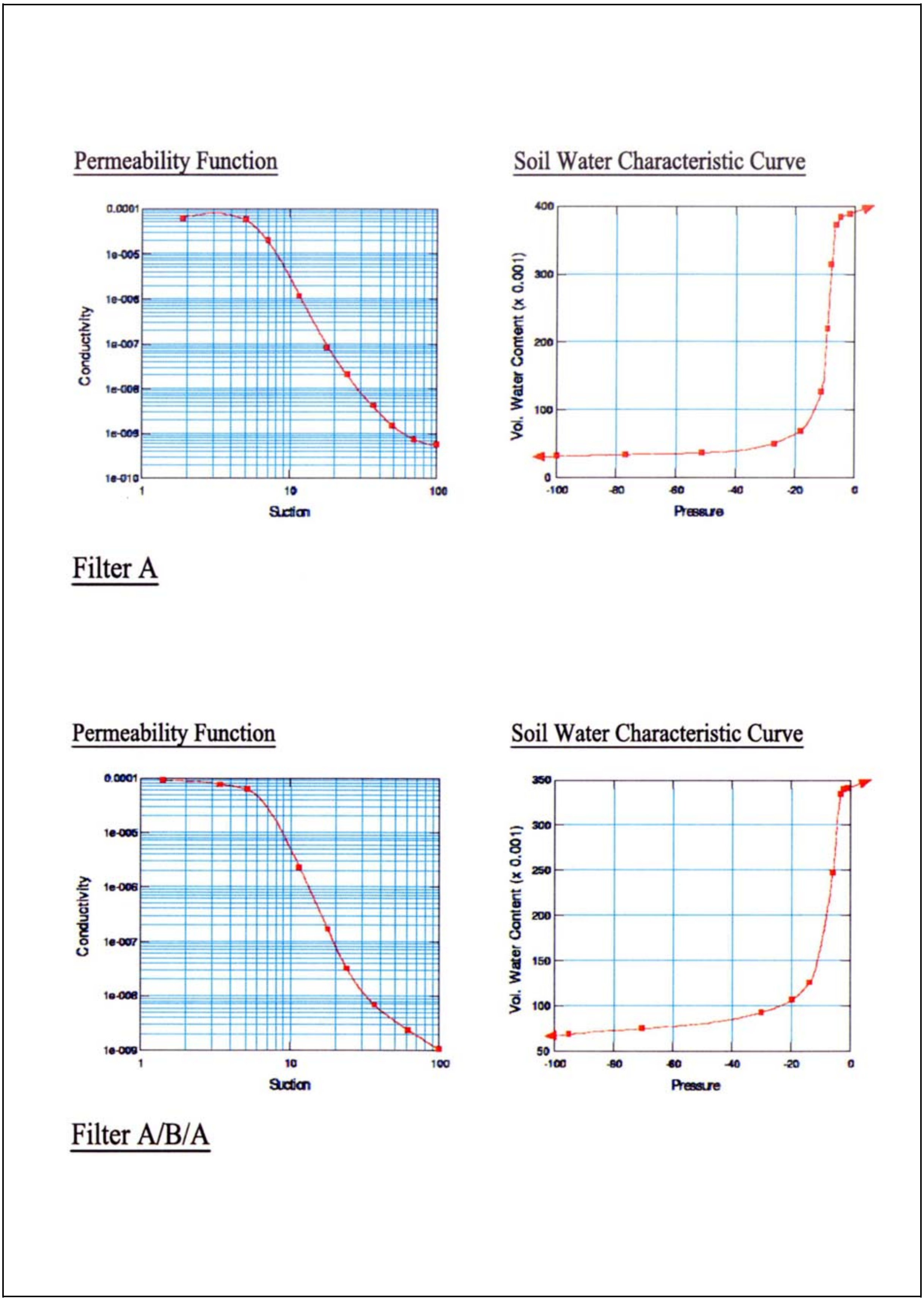

Figure B2b - Permeability Function and Soil Water Characteristic Curve of Filter A and Filter A/B/A Adopted in Seepage Analyses (reproduced from SEEP/W Users' Guide)

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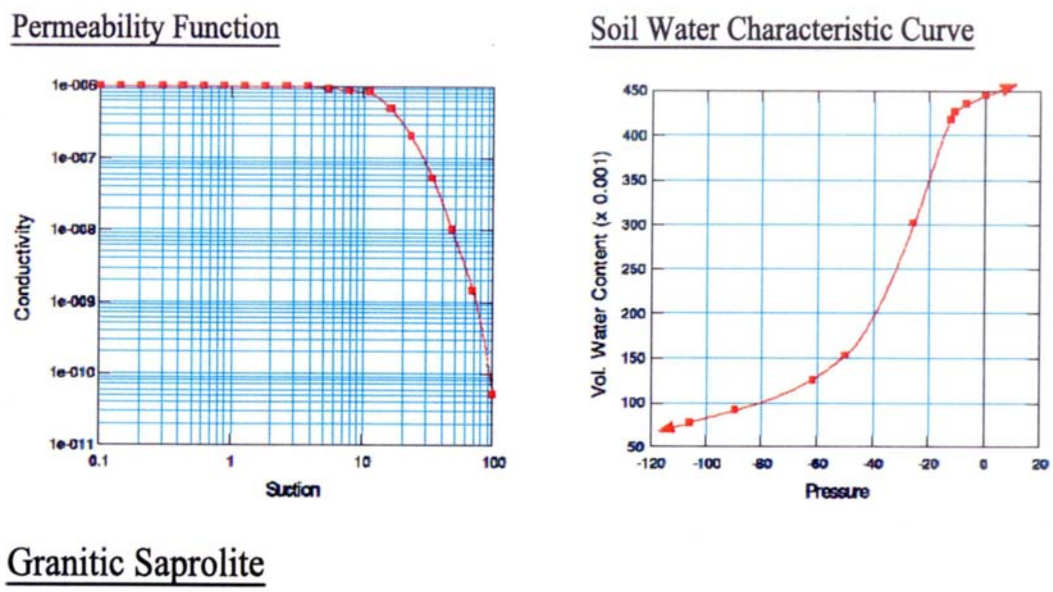

Figure B2c - Permeability Function and Soil Water Characteristic Curve of Granitic Saprolite Adopted in Seepage Analyses (reproduced from SEEP/W Users' Guide)

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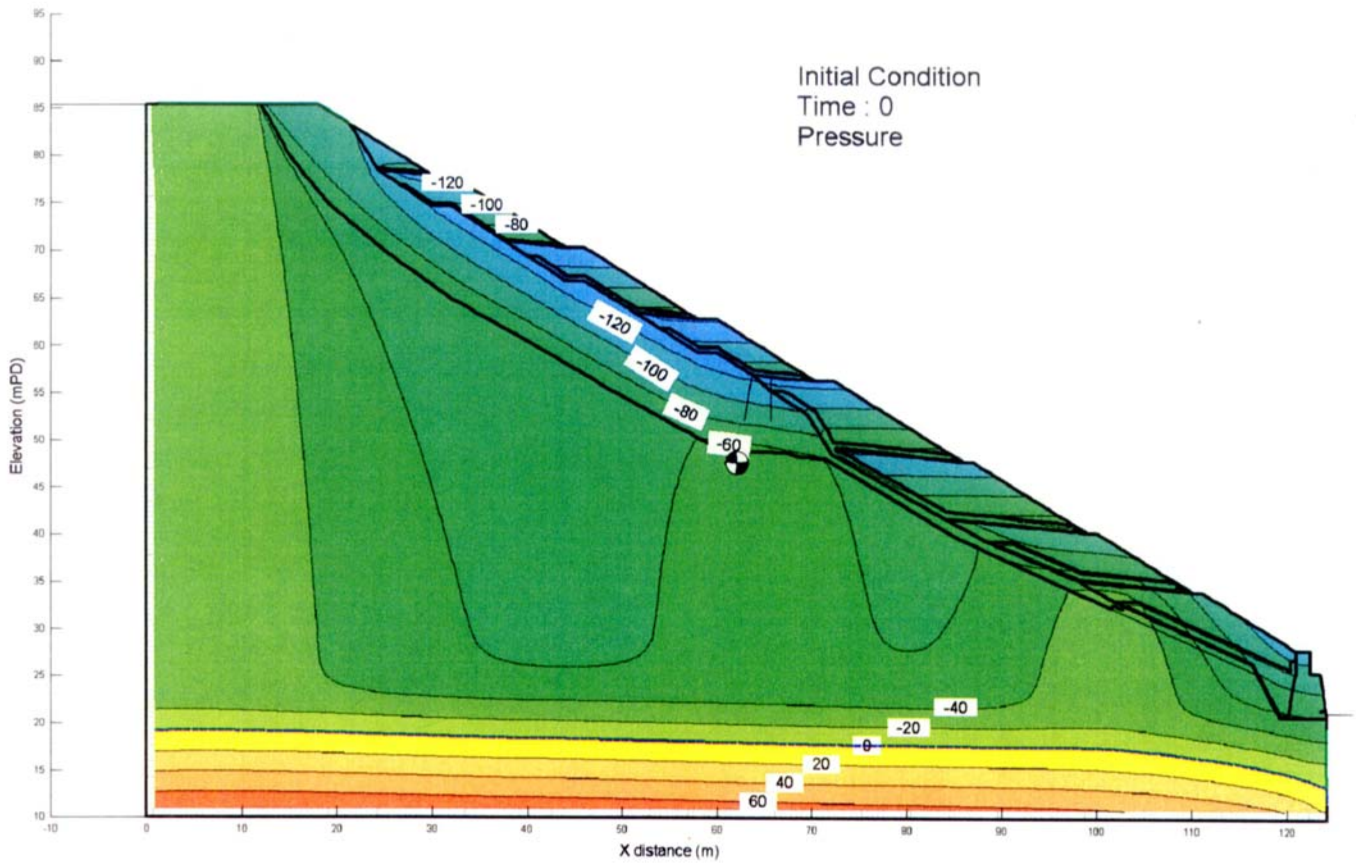

Note:	40	Transient groundwater pressure in kPa.

Figure B3 - Initial Condition in Slope No. 11SW-D/FR1 Prior to Ingress of Storm Water

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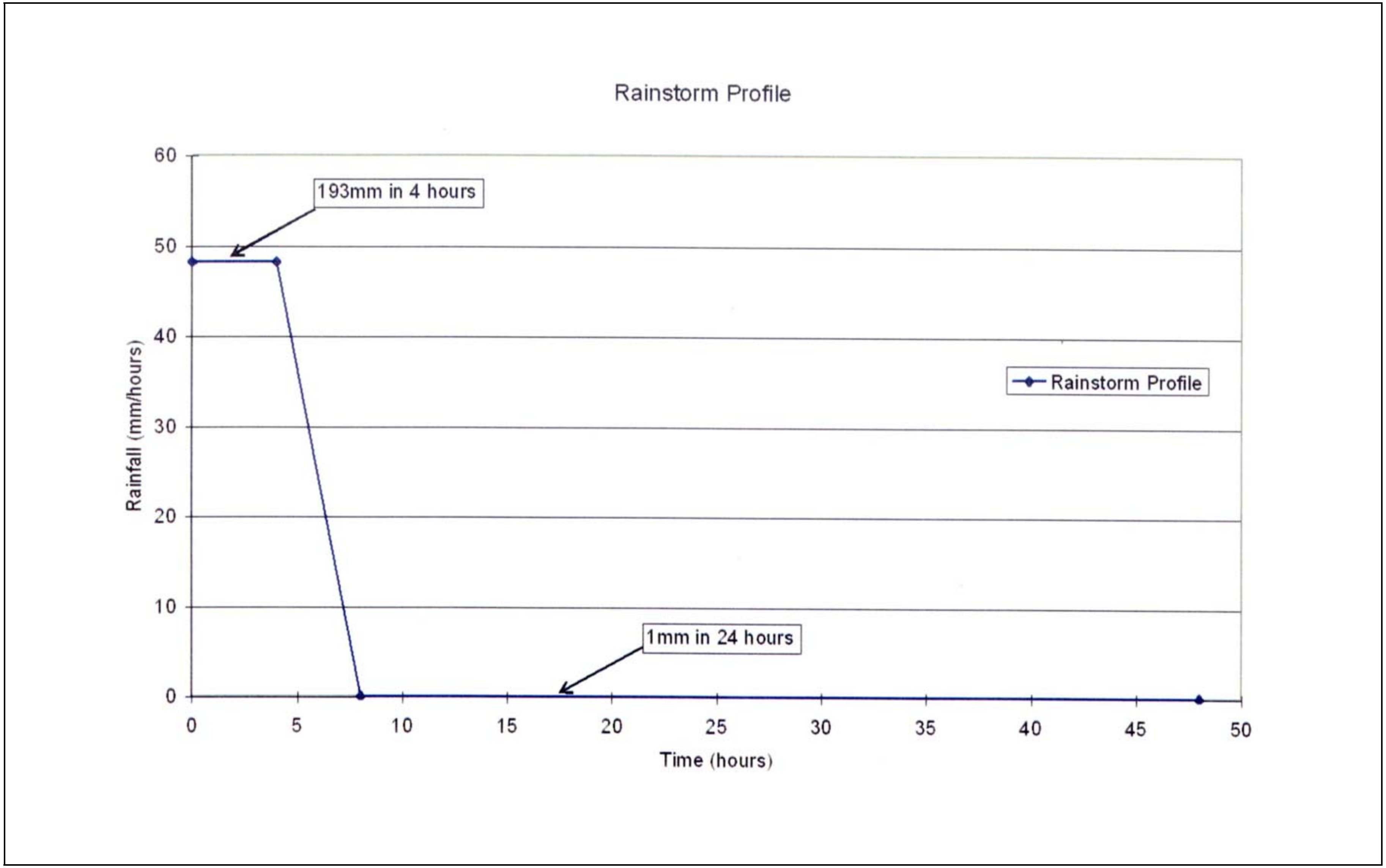

Figure B4 - Rainstorm Profile used in Seepage Analyses

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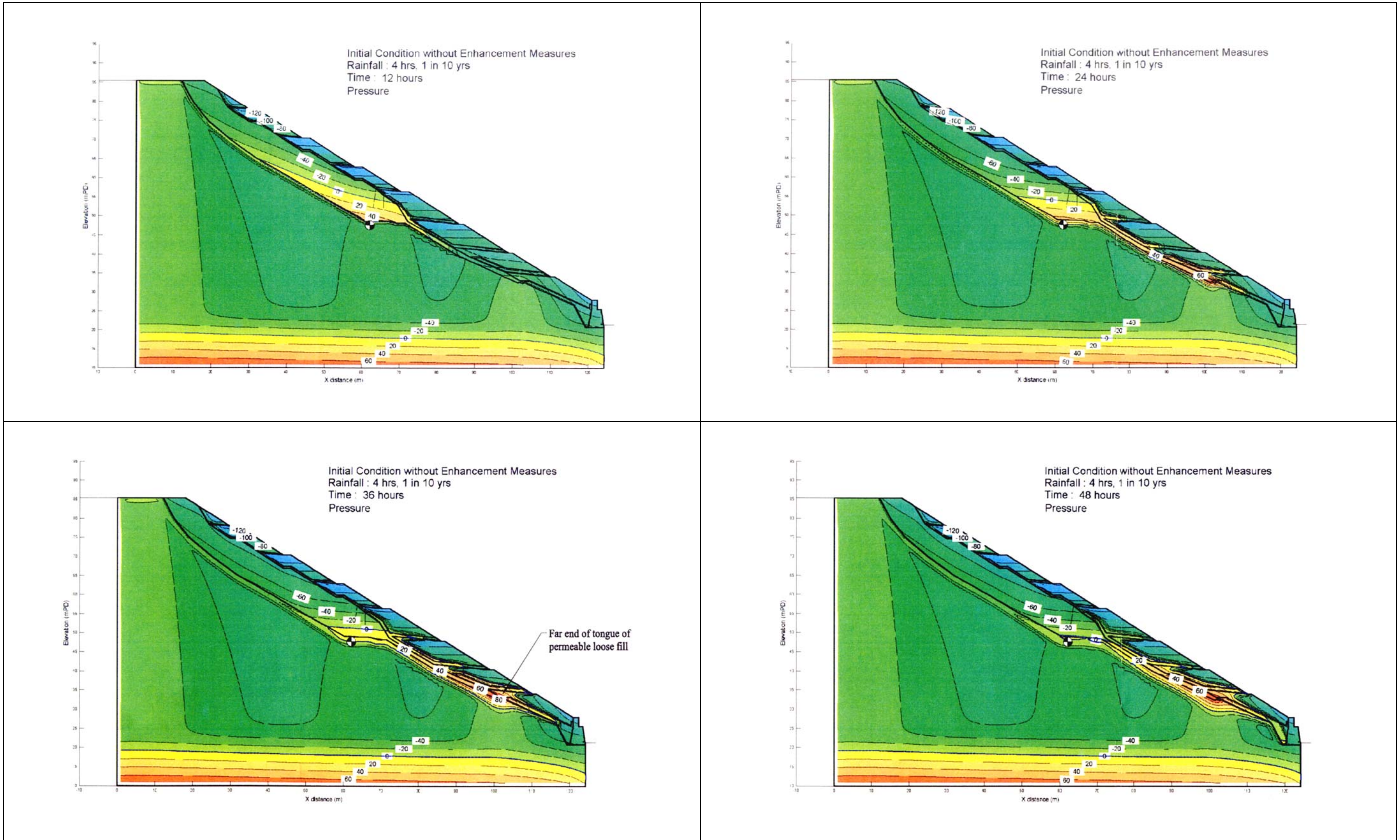

Note: 40 Transient groundwater pressure in kPa.

Figure B5 - Transient Groundwater Pressures in Slope No. 11SW-D/FR1 Prior to Provision of Drainage Enhancement Measures

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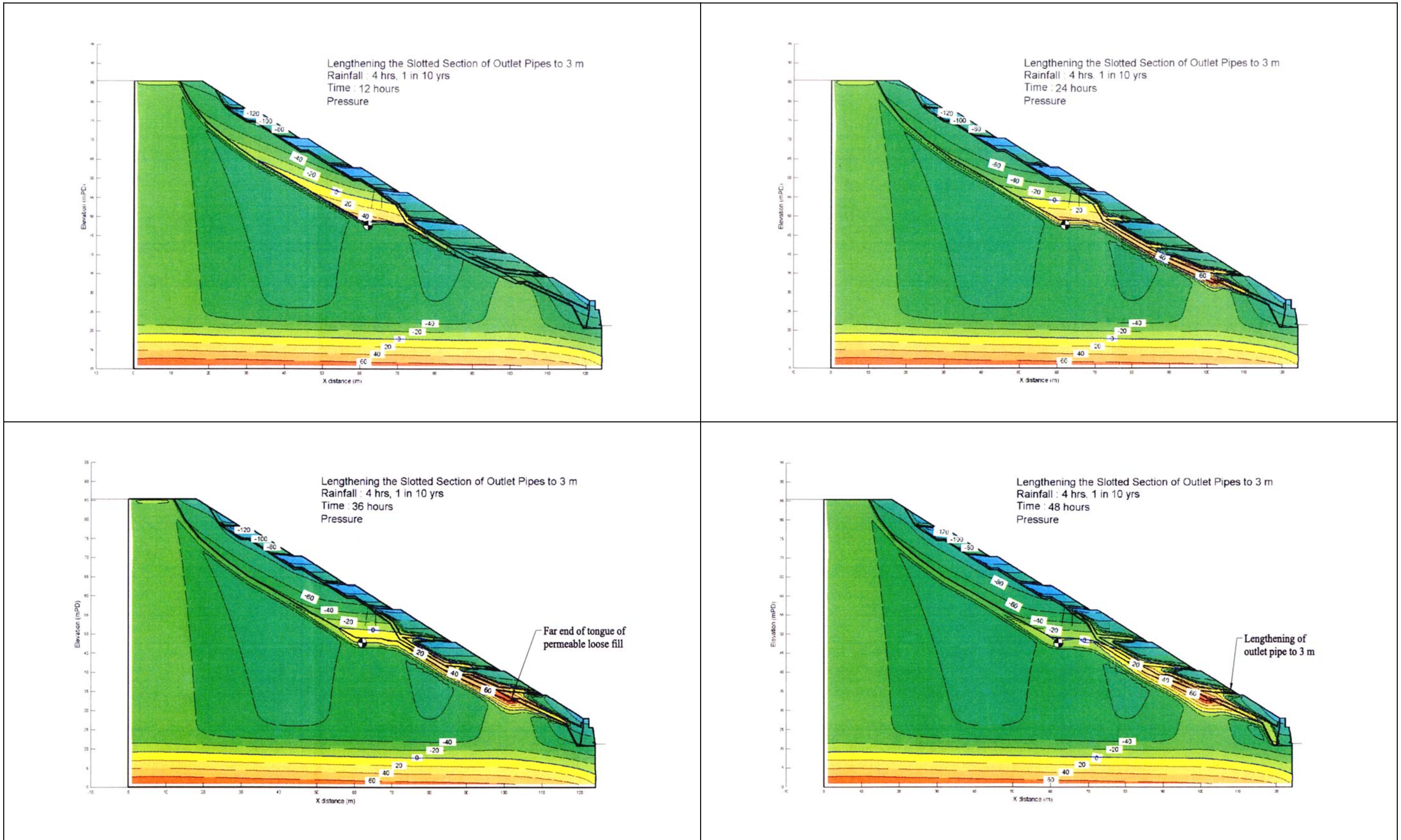

Note: 40 Transient groundwater pressure in kPa.

Figure B6 - Transient Groundwater Pressures in Slope No. 11SW-D/FR1 after Lengthening the Slotted Section of the Outlet Pipes to 3 m

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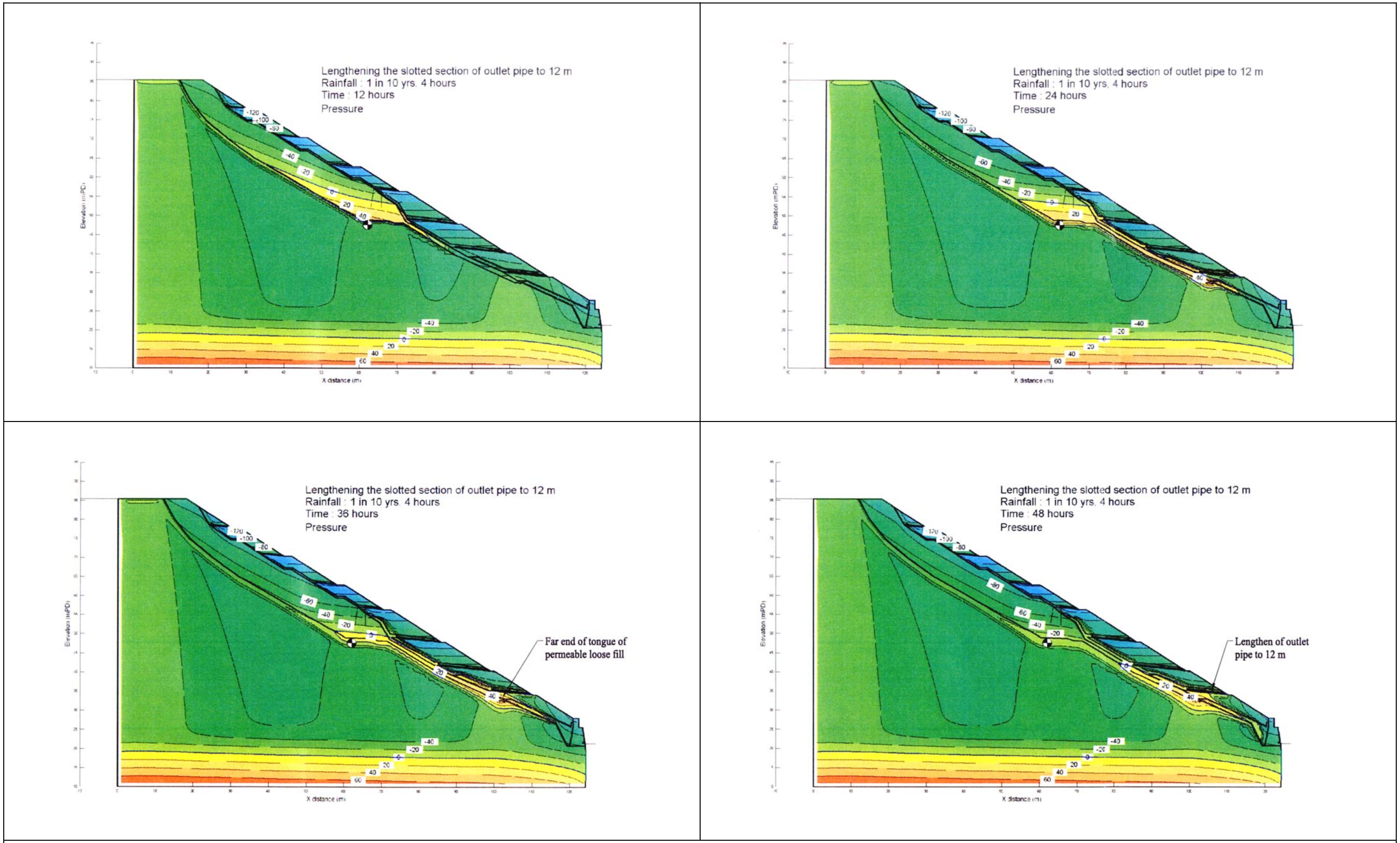

Note: 20 Transient groundwater pressure in kPa.

Figure B7 - Transient Groundwater Pressures in Slope No. 11SW-D/FR1 after Lengthening the Slotted Section of the Outlet Pipes to 12 m

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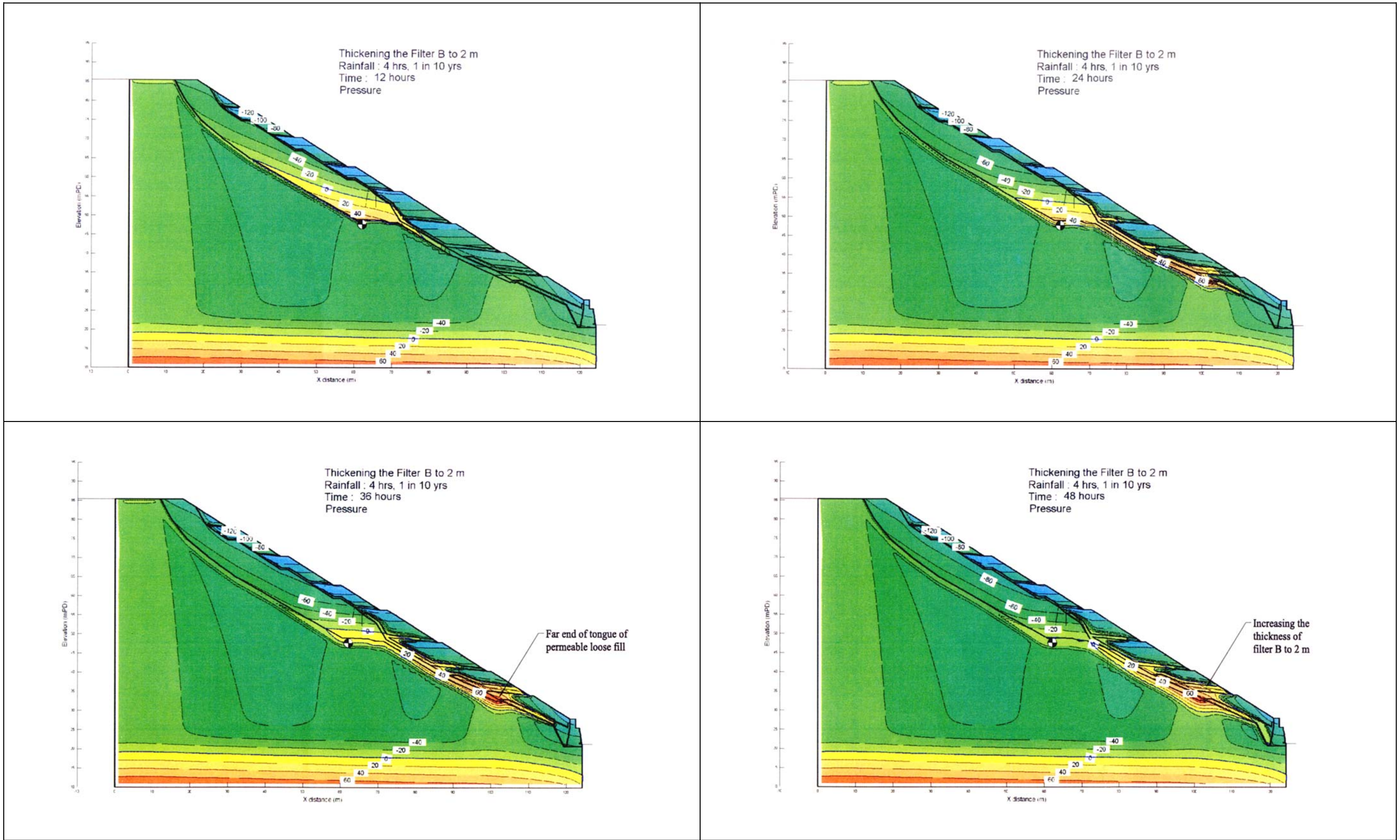

Note: 40 Transient groundwater pressure in kPa.

Figure B8 - Transient Groundwater Pressures in Slope No. 11SW-D/FR1 after Increasing the Thickness of the ‘Filter B’ to 2 m

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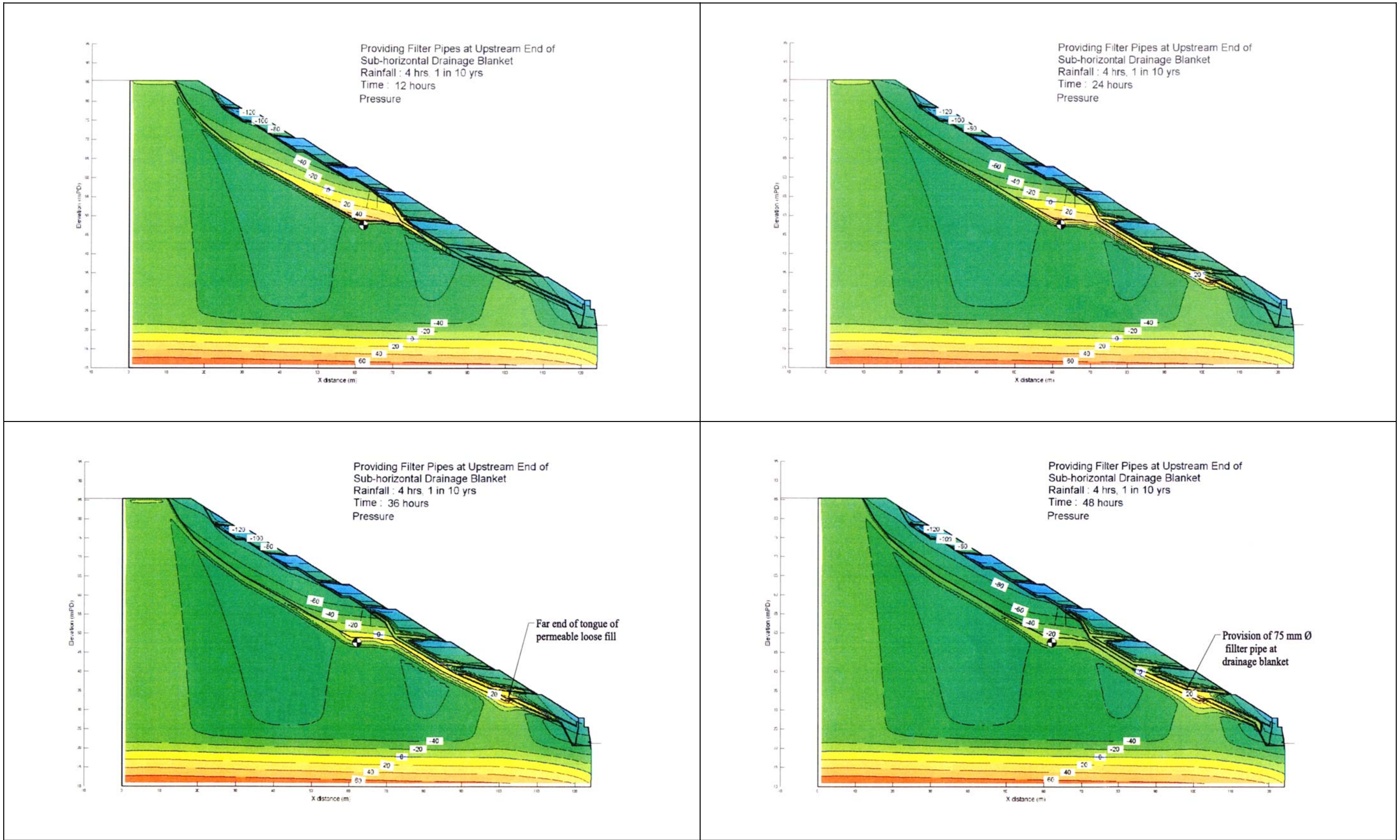

Note: 40 Transient groundwater pressure in kPa.

Figure B9 - Transient Groundwater Pressures in Slope No. 11SW-D/FR1 after the Provision of a Filter Pipe at the Up-stream End of the Sub-horizontal Drainage Blanket

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APPENDIX C

SUGGESTED PARTICULAR SPECIFICATION OF DRAINAGE PIPES

Suggested Particular Specification of Drainage Pipes

Add the following to GS Clause 7.163

7.163A1 (1) Drainage pipes shall be perforated with non-perforated inverts as approved by the Engineer. The portion of openings in the perforated pipes shall cover between 50% and 70% of the circumference of the pipe. The percentage of opening areas to overall surface area of the pipe shall not be less than 8%. The pipe material shall have the following physical properties or equivalent functions:

(a) Material: High-density Polyethylene

(b) Minimum tensile strength: 21,300 kN/m^2

(c) Minimum compressive strength: 22,000 kN/m^2

(d) Minimum flexural strength: 6,800 kN/m^2

(2) Couplers and T-sockets for drainage pipes shall have non-perforated invert and shall be of similar strength and durability of the pipe material. The lapped length of coupler (and the lapped length of the T-socket) and each end of the drainage pipes shall be at least 100 mm. The elongation at the pipe connection shall be less than 5 mm under a 45 kg pulling force.

(3) Geotextile filter sheaths for drainage pipes shall be formed of non-woven geotextile filter robust enough to prevent tearing and shall have the following physical properties or materials having equivalent functions or performance as approved by the Engineer:

(a) Material: Polypropylene

(b) Minimum tensile strength: 17 kN/m

(c) Apparent opening size: 140 μm

(d) Coefficient of permeability under 2 kN/m^2: 5×10^{-3} m/s

(e) Flow rate at 100 mm head under 2 kN/m^2: 195 ℓ/m^2s

(4) Ties for jointing pipes and stitching filter sheath shall be non-metallic wires of a minimum breaking load of 400 N or equivalent as approved by the Engineer.

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(5) Drainage pipes are to be wrapped in geotextile filter sheath in the following manner prior to installation to ensure that the overlap and stitching would be against the non-perforated invert of the pipe. The pipe shall be placed onto and along the centre of a strip of geotextile filter with the non-perforated invert uppermost. The strip of geotextile filter, which shall be of a sufficient width to allow an overlap of at least 50 mm, shall be drawn around the pipe and stitched together tightly with non-metallic wires. The stitching should be tied off onto the pipe and the fabric bound every 300 mm to prevent dislocation during installation. The filter sheath shall be marked to ensure that the non-perforated invert is correctly positioned during installation.

(6) During delivery and installation of drainage pipes, care must be taken to ensure that the pipe and the geotextile filter sheath are not damaged. The method of installing the drainage pipes should be submitted to the Engineer for approval prior to installation.

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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.

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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.
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Geospec 3	Model Specification for Soil Testing (2001), 340 p.

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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.
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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.

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