FACTORS AFFECTING SINKHOLE FORMATION

GEO REPORT No. 28

Y.C. Chan

GEOTECHNICAL ENGINEERING OFFICE
CIVIL ENGINEERING DEPARTMENT
HONG KONG

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This report was originally produced in July 1988
as GCO Technical Note No. TN 4/88

First published, January 1994
First Reprint, April 1995

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PREFACE

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A. W. Malone
Principal Government Geotechnical Engineer
April 1995

FOREWORD

This Note reviews the mechanisms of sinkhole formation and the likely seepage forces involved. It considers those factors in relation to the geological history of Yuen Long and attempts to assess the potential problems.

The Note has been prepared by Mr Y.C. Chan in response to comments received on the conditions for sinkhole formation mentioned in TN 1/88. It should form a useful basis for further work on the risk of sinkhole formation in the Yuen Long area.

The draft of this Note was reviewed by GCO's specialist consultants.

M.C. Tang
Chief Geotechnical Engineer/Mainland West (Atg)

CONTENTS

1. INTRODUCTION

In September 1987, the Mainland West Division of the Geotechnical Control Office carried out a search for groundwater information in the Yuen Long area. A preliminary assessment of the risk of sinkhole formation in the area was also made. Very limited time was however available for this exercise as the information was required urgently.

The exercise was described in a draft report which was sent to the GCO's specialist consultant, Dr A.C. Meigh as part of the background information for his February 1988 visit to Hong Kong. In his preliminary "situation assessment" to GCO, Dr Meigh supported the general conclusions in the draft report regarding sinkhole risk, namely, that the short term risk for wide-spread sinkhole formation in the Yuen Long area is small, but isolated sinkholes may still be possible in the vicinity of particular pumps sunk into unfavourable ground. Groundwater monitoring was suggested for surveillance of long term sinkhole risk.

The final report was issued in March 88 as TN 1/88. Comments were received from GGE/D, CGE/SP and GCO's engineering consultant Messrs Dames and Moore (HK). The comments were centered around two points :-

(a) The amount of groundwater information was regarded as limited.

(b) The drawdown of groundwater to below rockhead as the condition for sinkhole formation was challenged.

The limited nature of groundwater information noted in (a) is accepted. There is simply not much groundwater data in the area that could be obtained.

However, point (b) requires further consideration since the relationship between the groundwater table below rockhead and sinkhole formation is quite often mentioned in papers by authors from different countries and with widely different backgrounds.

As a result, the author has reviewed most available papers on the subject of sinkhole formation. He has attempted to quantify forces induced on soil above karst limestone by groundwater lowering and examined mechanisms of sinkhole formation. This report records the outcome of the exercise.

2. MECHANISM OF SINKHOLE FORMATION

This Note considers the formation of "subsidence sinkholes" or "ravelling sinkholes" as defined by Beck (1984). These are bowl-shaped ground depressions formed by piping and ravelling of soil into wide joints, slots or caves in the bedrock. A subsidence sinkhole is formed by progressive failure in which the part of soil nearest to a slot ravels or is eroded, exposing a new soil surface which then become unstable in time (Figure 1) In cohesive soil, the gradual loss of soil into the slot leads to the formation of an expanding soil cavity. A sinkhole forms when the crown of the soil cavity is too thin to support the forces on it. In cohesionless soil, materials just settle to replace those eroded near the slot, leading to the gradual formation of a ground depression (Culshaw & Waltham, 1987).

In both cases, the sinkhole will not form if the soil next to the slot does not slip into the slot. Hence, to evaluate the potential for sinkhole formation, the first step is to examine the stability of the layer of soil immediately above rockhead. From theories of arching, the thickness of this layer is very approximately the width of the slot (Figure 2). This is referred to as the critical layer in the subsequent sections.

3. EFFECT OF GROUNDWATER LOWERING

3.1 General

Lowering of groundwater may induce a downward hydraulic gradient on the soil. This is accompanied by a body force (Terzaghi & Peck,1967) given by

$$P_s = \gamma_W \cdot i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where γ_W = unit weight of water

i = downward hydraulic gradient

The downward hydraulic gradient induced by a lowered groundwater table is demonstrated in Figure 3. Figure 3(a) represents the situation around a dewatering well for which the hydraulic gradient is given by

$$i = \Delta h/L$$

$$\simeq (L - L\cos^2\alpha)/L = \sin^2\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

For the very steep drawdown surface gradient of $\alpha = 45°$, $i = \sin^2 45° = 0.5$ and $P_s = 0.5\,\gamma_W$

Figure 3(b) shows the case of the superficial deposit being much less permeable than the bedrock. In this case, the groundwater in the superficial deposit may remain unchanged despite drawdown in the bedrock. For the case of the limestone remaining as a confined aquifer, the hydraulic gradient i will still be less than 1. The corresponding seepage force at the critical layer would be $P_s < \gamma_W$. If the drawdown in the limestone is such that the phreatic surface falls below rockhead. $\Delta h = L$ and $i = 1$. The corresponding seepage force at the critical layer would be $P_s = \gamma_W$.

3.2 Groundwater Lowered to Below Rockhead - Loss of Bouyance

When the critical layer is submerged the unit weight of the soil is given by the submerged unit weight (γ'). When groundwater is lowered below rockhead, the unit weight is given by the saturated unit weight (γ_s). This implies an increase in body force on the soil particles immediately above the rock slot of

$$P_a = \gamma_s - \gamma' = \gamma_W$$

3.3 Groundwater Lowered to Below Rockhead - Other Effects

Shi (1984) discussed three mechanisms by which soil is eroded into cavities as a result of lowering of groundwater table to below rockhead (Figure 4). These are :-

(a) Surface Tension Effect - When the water level drops below the underside of soil in or above a slot in the bedrock, the surface tension between water and soil particles will create a tension force that pulls the soil with it into cavities below.

(b) Suction Effect - As the water surface continues to drop, a partial vacuum may develop in the enclosed space in the cavity between the water surface and the overburden. This will suck soil into the slots and cavities.

(c) Vortex Effect - After formation of a through pipe from the ground surface to the slots/ cavities in the bedrock, a vortex may form in the water flow in the soil pipe. The vortex will create local low pressure zones into which soil particles are drawn.

Mechanism (a) operates every time the groundwater table drops below the unsupported soil surface, and is most evident when there is a frequent fluctuation of the groundwater level at rockhead. Mechanism (b) is important if the groundwater table drops rapidly in an enclosed cavity system. Mechanism (c) operates only to enlarge soil pipes and thereby transports soil into the cavity system.

4. EFFECT OF WATER RECHARGE

4.1 Underground Recharge

Figure 5 shows the effect of a water source above groundwater table. If the water source exists for long enough, the soil below the source will be saturated and a downward flow will occur. The hydraulic gradient at the critical layer will be given approximately by

$$i = (h_s - h_w)/h_s = 1 - h_w/h_s < 1$$

The associated seepage force is

$$P_s = (1 - h_w/h_s)\gamma_w < \gamma_w$$

For the case of groundwater table below rockhead, $h_w = 0$ and $P_s = \gamma_w$.

If the water source is not located immediately above the immediate vicinity of a slot, the seepage force P_s would not apply. Figure 6 depicts the situation for the cases of groundwater table above and below rockhead. When the water table is above rockhead, the water from the source will infiltrate down until it meets the water table and then spread in all directions. The flow that reaches any slot would be a minor fraction of the original flow and the seepage force that can be induced on the critical layer above any slot would be small.

If however, the water table is below rockhead, the downward flow from the source would finally flow along rockhead towards a local trough which may contain a cavity or a slot. Depending on the flow volume, materials may be transported into the slot and initiate soil cavity formation in the manner described in Hodek et al (1984). This is also the mechanism implied by Brink (1984).

4.2 Recharge by Surface Ponding

Figure 7 shows the effect of surface ponding on superficial deposits above karst limestone. The hydraulic gradient at the critical layer is approximated by $i = (h_p - h_w)/L$.

For a thin soil cover and low original groundwater table, the resulting hydraulic gradient can be much higher than 1. The extreme case is when the groundwater table is below rockhead in which case $i = h_p/L$. The corresponding seepage force at the critical layer is in multiples of γ_w. This is very favourable to the formation of sinkholes as reflected in the cases described by Wegrzyn et al (1984), Soto & Morales (1984), Beggs & Ruth (1984), White et al (1984) and Crawford (1984).

5. EFFECT OF SOIL STRUCTURES

Figure 8 shows the effect of some typical soil structures on the hydraulic gradient at the critical soil layer. In Figure 8(a), the presence of less permeable clayey materials immediately above rockhead would induce a hydraulic gradient

$$i = h_w/L = 1 - (L - h_w)/L$$

where L = thickness of the less permeable layer; $L - h_w$ = height of the perched water table developed at the less permeable layer.

Hence the presence of the more clayey layer above rockhead would induce a higher seepage force at the critical layer and favours the formation of sinkholes. This is the case in Florida as reported by Gardanger (1984).

In Figure 8(b), the presence of less permeable inter-layers in the soil will result in a high lateral/vertical permeability ratio. As a result water from any source will spread before it reaches a slot with a corresponding decrease in hydraulic gradient. Sinkholes are unlikely to form under such circumstances.

6. CONDITIONS FOR SINKHOLE FORMATION

The likely magnitude of body forces that can be induced by various factors on the critical layer are discussed in Sections 3 to 5. They are summarised in Table 1.

It is seen from the Table that the worst effect is caused by ponding over thin soil with groundwater table below rockhead. The increase in body force at the critical layer would be equivalent to that caused by a downward seepage gradient of $i = 2$ to 5.

It is important to decide what minimum increase in body force is required to initiate soil cavity and sinkhole formation. A search through over 30 papers on sinkhole formation gives a case in Florida where the smallest hydraulic gradient leading to sinkhole formation was recorded (Jammel (1984)). In this case, the hydraulic gradient at the critical layer may have been less than 0.5 at the time of sinkhole formation.

Apart from the hydraulic gradient and the relative position of groundwater table to rockhead, there are other factors which may affect sinkhole formation. For example, wider slots will increase the risk of sinkhole formation. Small cavities would not have enough space to accommodate the bulked collapsed soil and soil cavity propagation will stop when the cavity is full. Likewise, soil transportation is limited in less steeply inclined slots which tend to block and hence reduce the tendency for sinkhole formation.

7. EFFECT OF GEOLOGICAL HISTORY

From the geological information available to-date, it seems that the karst features in Yuen Long area were formed during a period when the sea level was much lower and the marble bedrock was exposed or thinly covered by top soil. There is evidence that the solution cavities were then above the groundwater table (Pascall, 1987).

The solution activity was followed by a period of active deposition of landslip debris above the marble bedrock (Langford 1988). The groundwater table rose gradually during this period when about 15 m of landslip debris was deposited. Thereafter, surface deposition was dominated by alluvium implying that the groundwater table was close to the ground surface.

It is seen from Table 1 that a combination of groundwater table below rockhead and surface ponding on the thin soil cover constitutes the most favourable condition for sinkhole formation. This happened at least at the early stage of debris deposition in the Yuen Long area. The groundwater table was definitely well below rockhead. The soil cover was very weak and was thin, lying between a few cms to a few metres in depth. Landslips occurred as individual events yielding tongues of slip debris on the ground surface. This caused ponding which in turn led to sinkhole formation where suitable cavities/slots existed in the bedrock around. The sinkhole would pond water leading to more piping of materials into the cavity system until the particular slot or cavity was blocked or full. This phenomenon of active sinkhole formation in newly buried karst areas is described in White et al (1984), Grawford (1984), Wegrzyn et al (1984) and Soto & Marales (1984). It is very likely that during that period, lasting at least several thousands of years, most slots/cavities favourable to sinkhole formation were filled. This is to some extent supported by the fact based on limited ground investigation, that in Yuen Long most cavities near rockhead have been filled.

The karst features were then covered by over 20 metres of superficial deposit with the groundwater table rising and remaining near the ground surface. From Table 1 in Section 6, the maximum possible increase in body force at the critical layer for the case of groundwater table not drawn down to below rockhead is below γ_w. This is far less than the seepage force which has been in operation in the recent geological past. It is therefore unlikely that such a condition can reactivate sinkhole formation by itself.

With the groundwater table drawn down below rockhead, the picture is different. The maximum possible increase in body force at the critical layer would be greater than 2 γ_w. There is also the effect of possible partial vacuum in the enclosed cavities and the dragging force on soil when the water table fluctuates at the bottom of the critical layer. Under such circumstances, some of the stabilised slots may be reactivated to cause further sinkhole formation.

8. CASES OF SINKHOLES IN HONG KONG

Three sinkholes are alleged to have been observed in the Yuen Long area to date. These include one at the Yuen Long Industrial Estate and two at the Yuen Long LRT Interchange site.

The location and the geometry of the sinkhole at the Yuen Long Industrial Estate is shown in Figures 9 and 10. At the time of writing this Note, the engineer for the development of the site is preparing a report on the causes and mechanisms leading to the formation of the sinkhole. Initial investigation has however revealed that the shallow hole was probably a combination of the results of poor drilling which led to the washout of materials and the erosion of surface materials to deep cavities through the unfilled hole left by the drilling. This is not typical of subsidence sinkholes which have been examined in this Note.

The sinkholes in the Yuen Long LRT Interchange site are briefly mentioned in Pascall (1987). The information is inadequate for determining their nature. The shallow sinkhole formed during intensive drilling activities. Drilling was done by the same contractor who carried out the drilling at the Yuen Long Industrial Estate. It may have also been the result of poor drilling techniques. The deeper one formed during a pumping test and may either be the result of reactivation of an old sinkhole in the immediate vicinity of a pump, or the erosion of surface materials to deep cavities along unfilled drillholes.

In all three cases, the sinkholes formed during or subsequent to drilling activities. They should not be taken as any indication that a general sinkhole risk exists in the area. Further study is required however into their formation mechanisms so as to ensure that similar holes do not form in the future. Meanwhile, contractors and engineers should be made aware of the dangers of using excessive flushing water during drilling and the importance of backfilling drill holes immediately after their completion.

9. SUMMARY AND DISCUSSION

The following points can be summarised from this review :-

(a) Sinkhole formation was active in the geological past when the groundwater table was below rockhead and the soil cover was thin. This period of active piping and sinkhole formation might have filled all slots/ cavities in the marble that were favourable to sinkhole formation.

(b) With the water table above rockhead, the greatest increase in body force at the critical layer in or above a slot is less than γ_w. This is far less than the forces in operation during the period of active sinkhole formation and is unlikely to be strong enough to reactivate further sinkhole formation.

(c) With water table below rockhead, the greatest increase in body force at the critical layer in or above a slot is larger than $2\gamma_w$. This is accompanied by the unknown erosional effect of a partial vacuum in an enclosed cavity space and the drag forces on soil fragments when the water surface drops below the critical layer. These forces operating together could reactivate some of the slots or cavities to cause sinkhole formation.

The above points are supported by published cases of sinkhole formation e.g. Newton (1984), Brink (1984), White et al (1984), Crawford (1984), Liao & Lin (1987), Yao et al (1987) and Waltham & Smart (1988). All these papers describe karst in paleozoic limestone/marble formations that are being buried or were buried gradually sometime ago.

These arguments are not applicable to young limestone formations covered by soft surface materials deposited before the formation of karst features. Such ground conditions are found in areas which were in the shallow sea environment of the Tertiary and Pleistocene period and which have been uplifted to above sea level recently. In these situations the karst features start to form actively under the superficial deposit which is being subjected to piping forces for the first time. Sinkholes can therefore form under much less severe hydraulic condition as described in Beggs & Ruth (1984), Koch (1984), Garlanger (1984) and Jammel (1984) and in a less demonstrative manner in Metcalfe (1984), Wergzyn et al (1984) and Soto & Morales (1984).

10. CONCLUSION

Based on the geological history of Yuen Long area and the findings in this review, it can be concluded that wide spread sinkhole formation is unlikely in the Yuen Long area as long as the groundwater table remains above rockhead.

Three alleged sinkholes recently observed in the Yuen Long area are all associated with construction activities. Their formation mechanisms are being examined in detail so that if necessary, procedures can be introduced to prevent similar occurrence in the future.

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LIST OF TABLES

Table 1 - Increase in Body Forces at the Critical Layer

Case No.	Condition	Water Table Below Rockhead [(1)]	Water Table Above Rockhead [(1)]
1	Without recharge	$\gamma_w + 0$	$0 + < \gamma_w$
2	With underground recharge above slot/cavity	$\gamma_w + \gamma_w$	$0 + < \gamma_w$
3	With underground recharge not above slot/cavity	γ_w + side erosion	0 + very limited side erosion
4	With rapid drawdown in enclosed cave system	γ_w + effect of partial vacuum	$0 + < \gamma_w$
5	Surface Ponding	$\gamma_w + >> \gamma_w$	$0 + > \gamma_w$
6	Less permeable layer above rockhead + recharge	$\gamma_w + > \gamma_w$	$0 + > \gamma_w$
7	Less permeable layers in superficial deposit + recharge	$\gamma_w + < \gamma_w$	$0 + < \gamma_w$
8	Fluctuation around rockhead level	Suction force of unknown order operates every time water surface drops below underside of soil	
Note :	(1) First term denotes effect of loss of bouyance. Second term denotes effect of seepage flow.		

LIST OF FIGURES

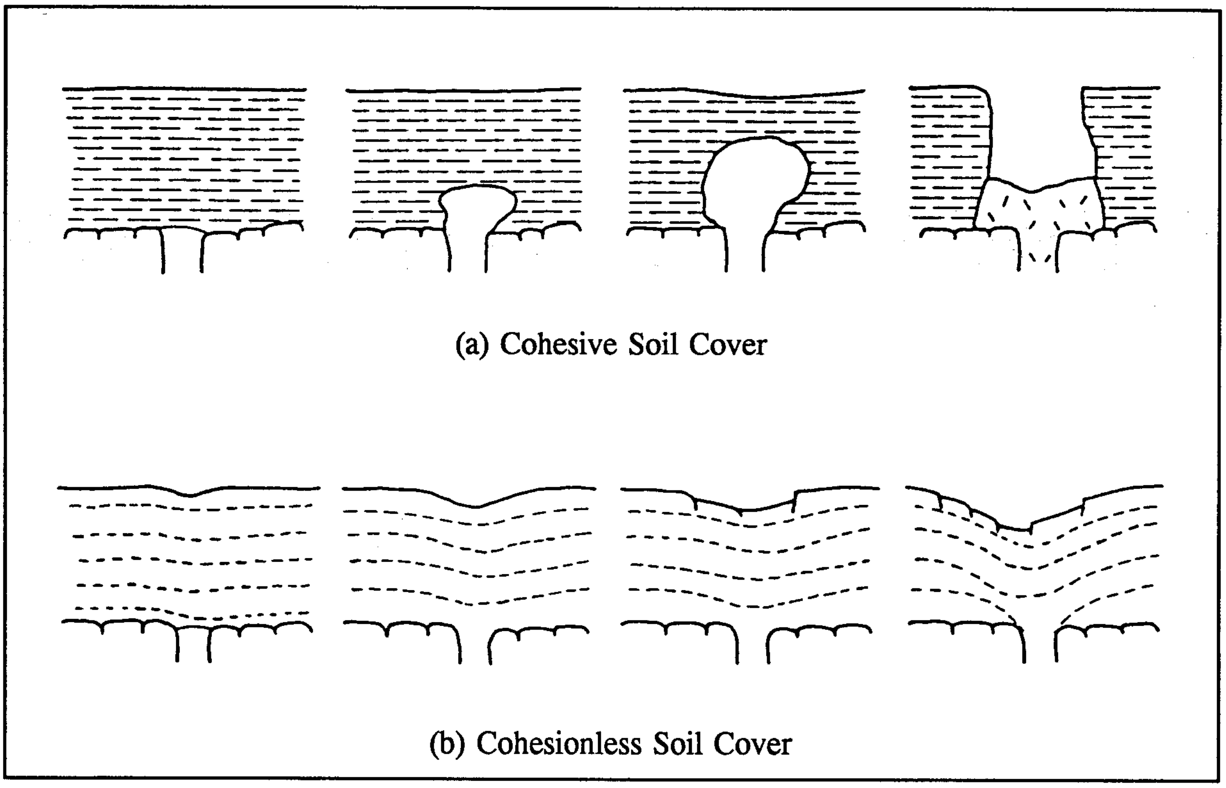


Figure 1 - Mechanics of Sinkhole Formation (after Culshaw & Waltham, 1987)

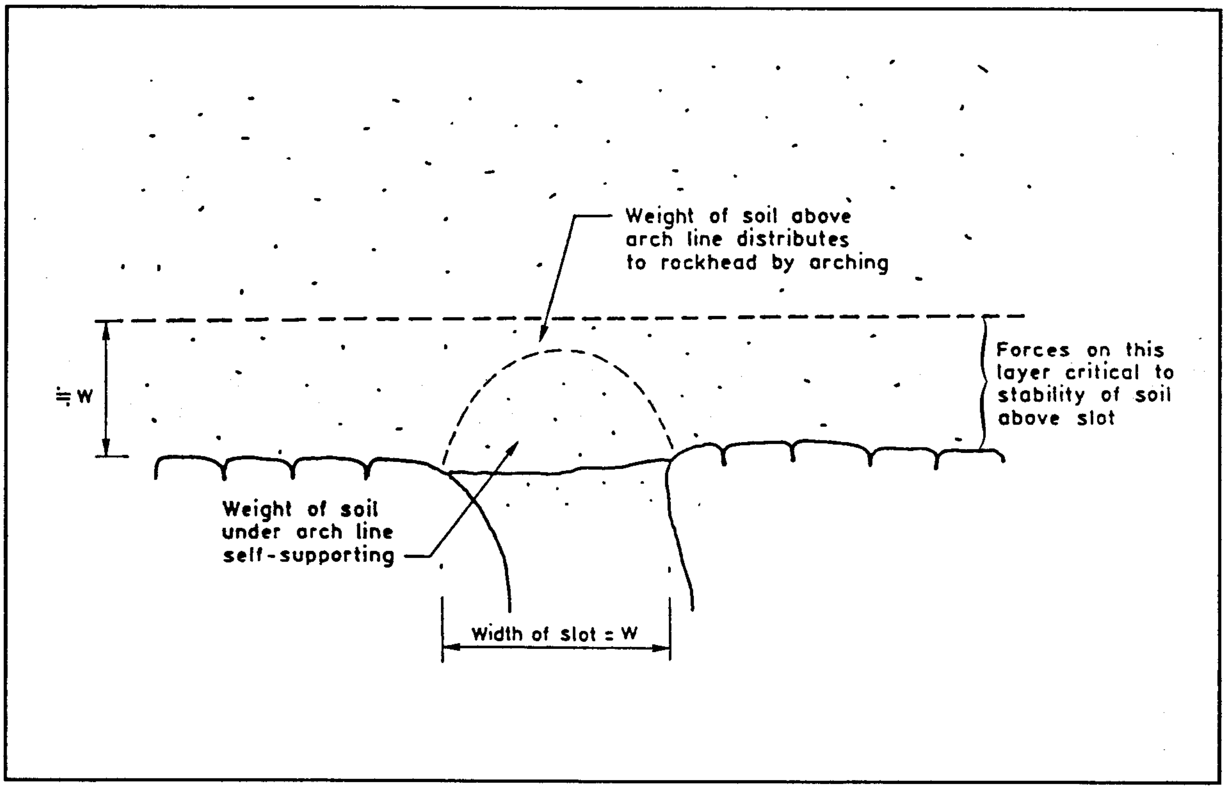
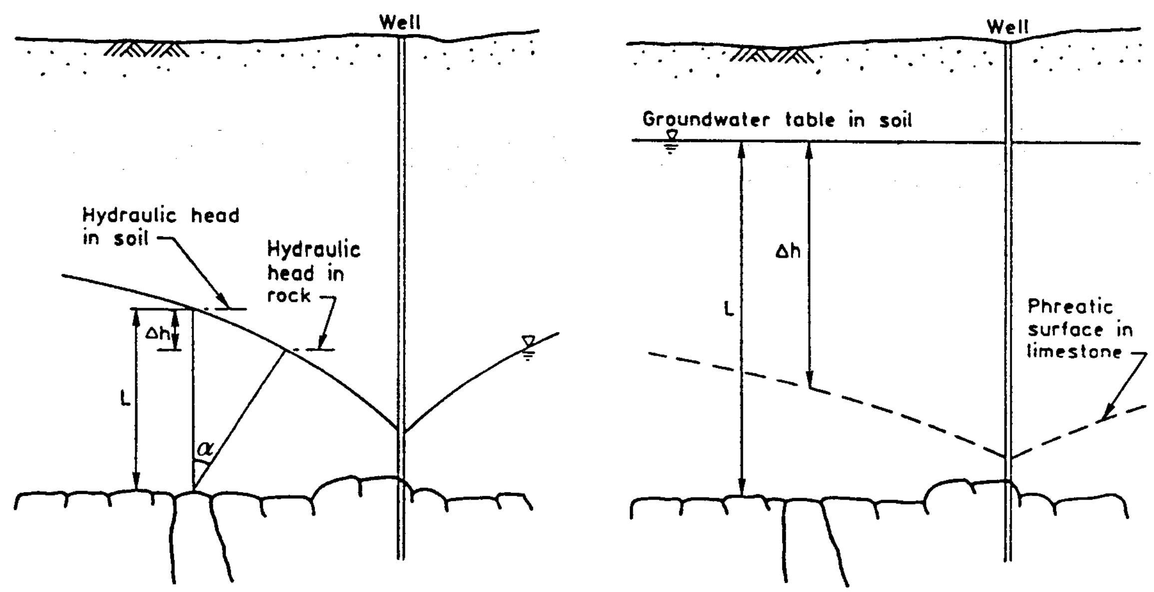


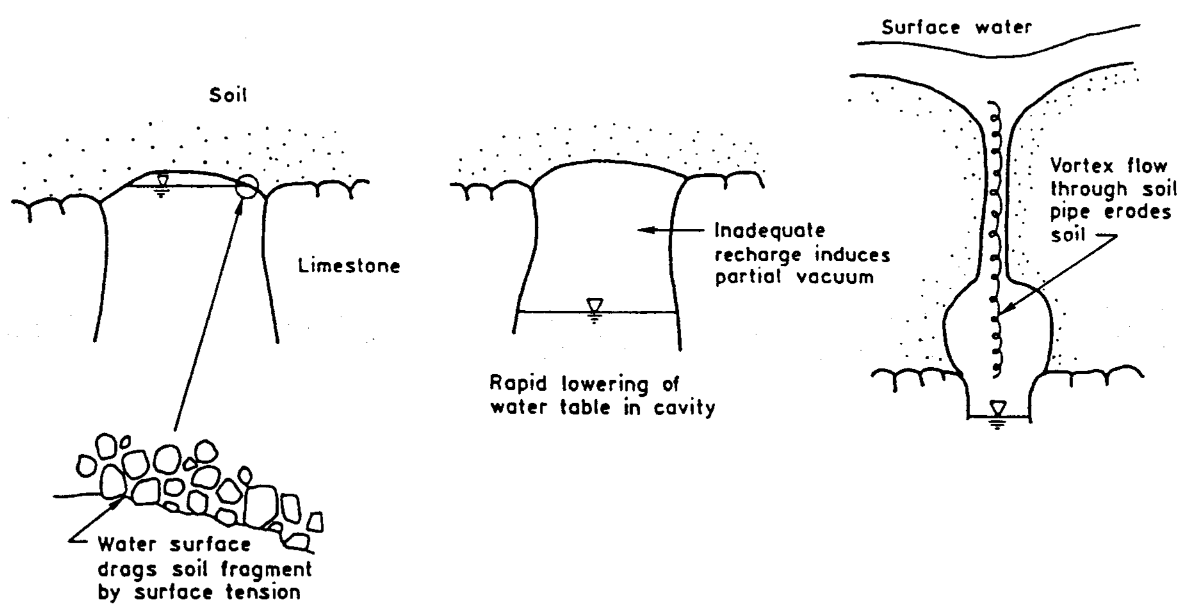
Figure 2 - Critical Soil Layer for Sinkhole Formation



(a) Limestone as Unconfined Aquifer

(b) Limestone as Confined Aquifer

Figure 3 - Groundwater Lowering and Vertical Hydraulic Gradient in Soil



(a) Surface Tension Effect

(b) Suction Effect

(c) Vortex Effect

Figure 4 - Effects of Lowering Groundwater Table to below Rockhead

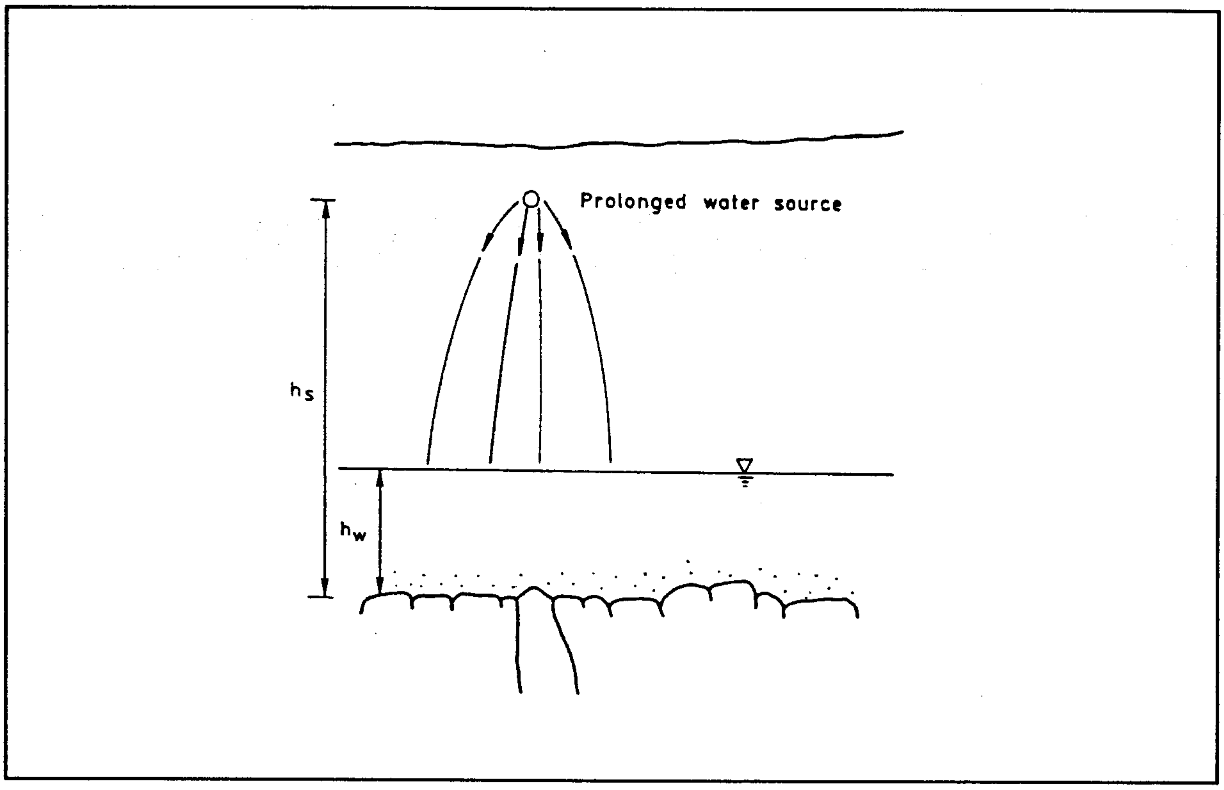


Figure 5 - Underground Water Recharge above Cavity in Bedrock

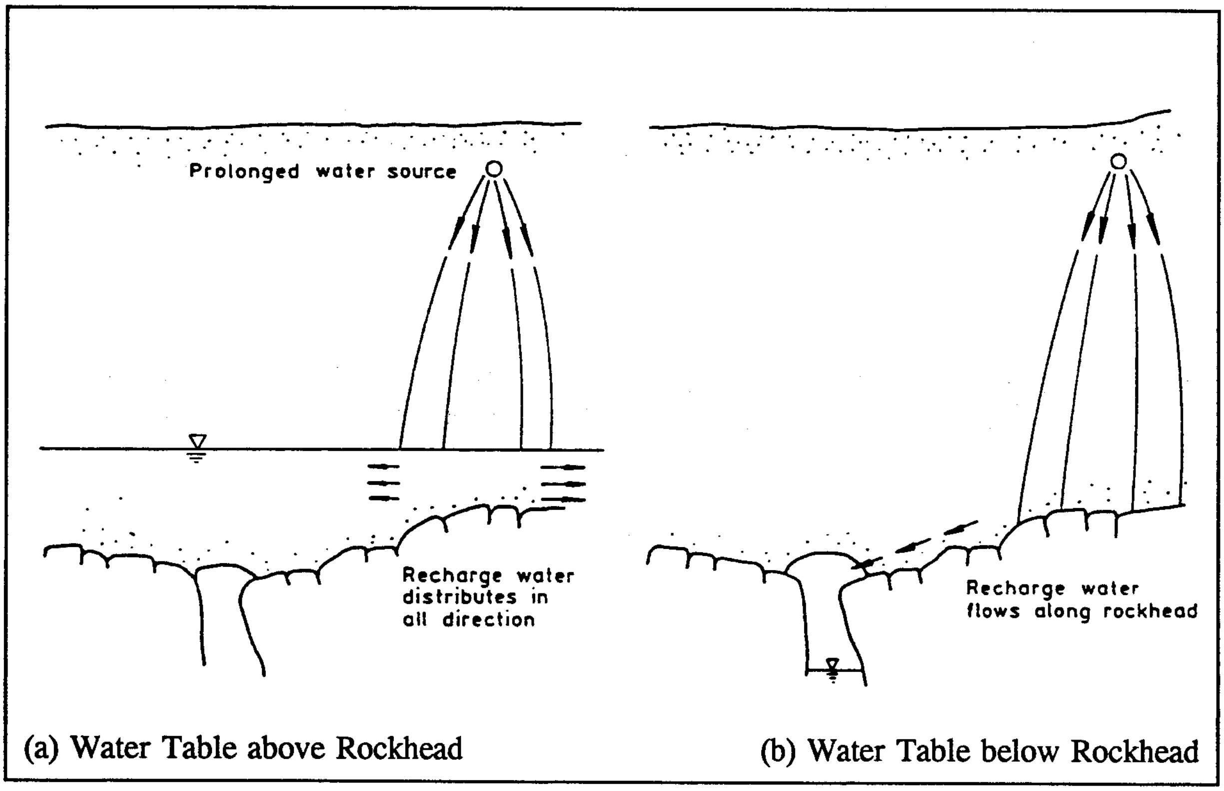


Figure 6 - Underground Water Recharge Not above Immediate Vicinity of Cavity

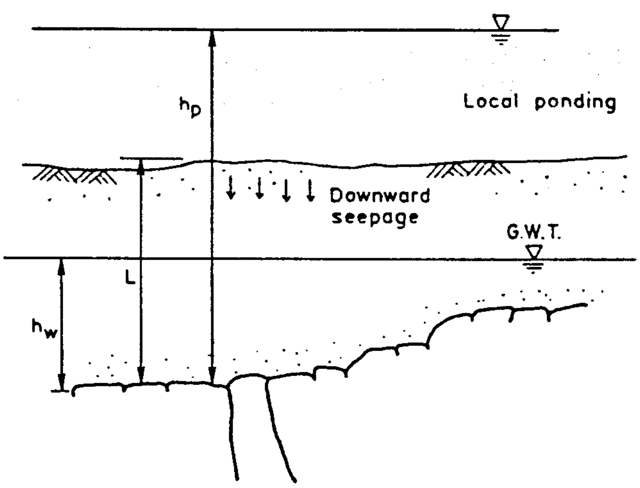
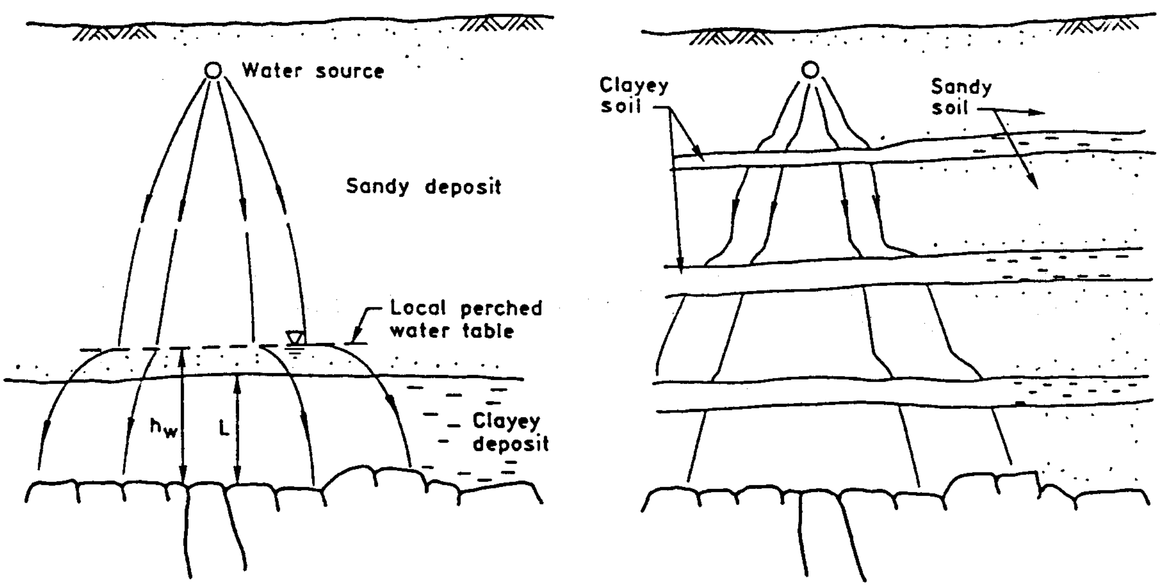


Figure 7 - Recharge by Surface Ponding



(a) Clay Layer above Slot

(b) Clay Layers in Sandy Deposit

Figure 8 - Examples of Effects of Ground Structures on Groundwater Recharge

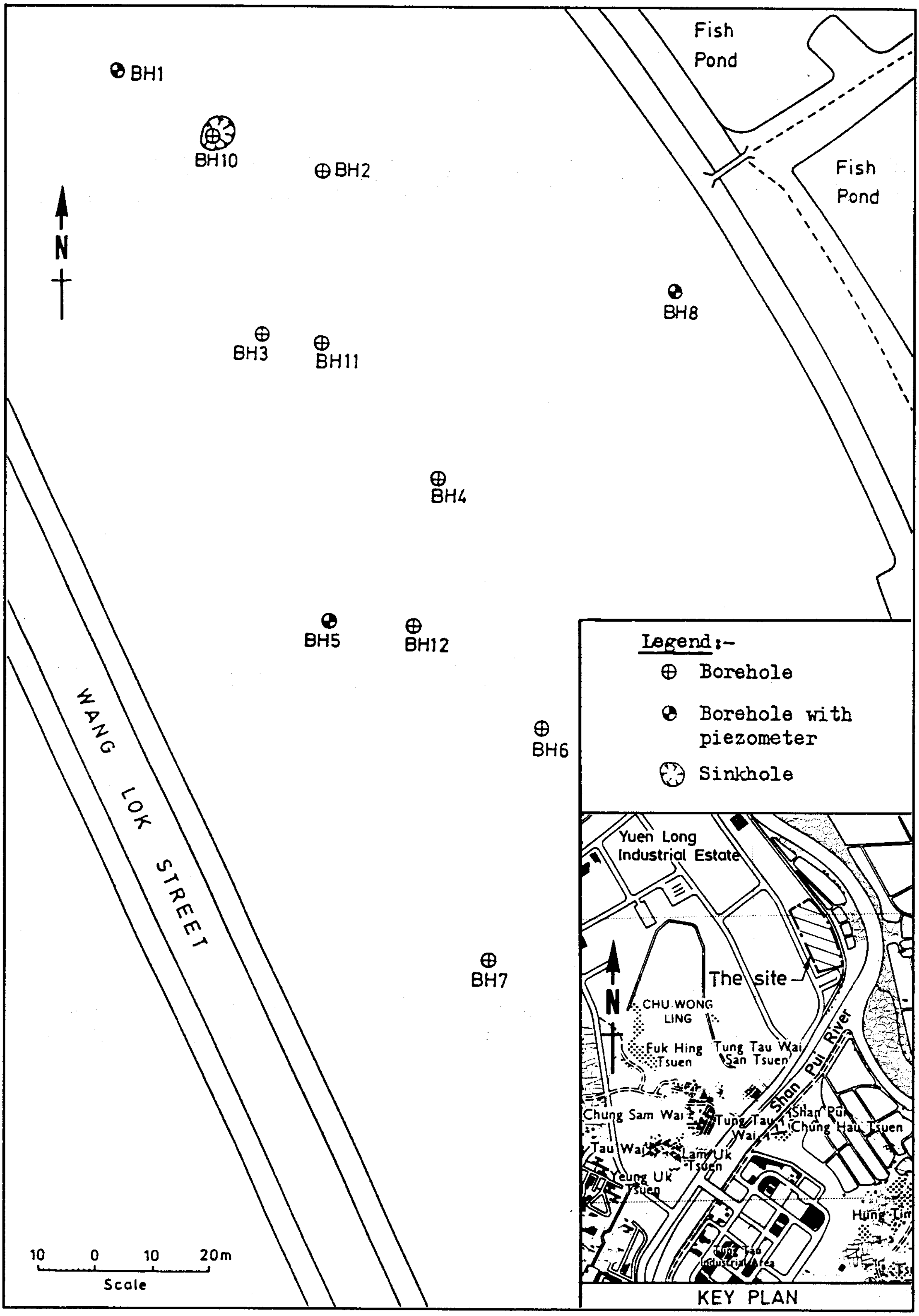
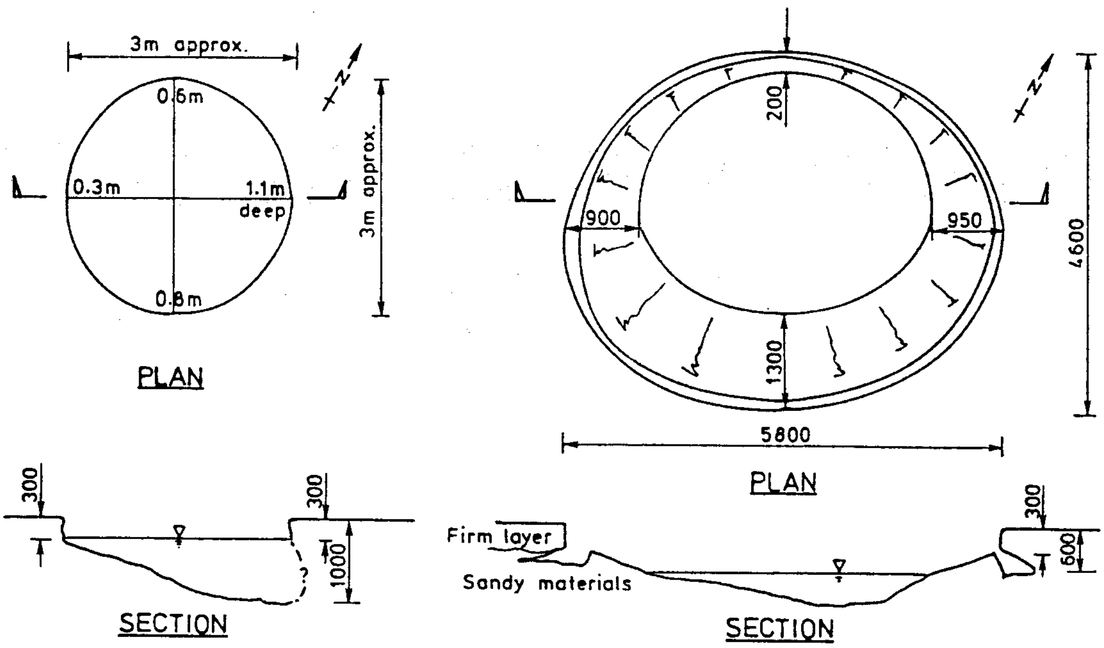


Figure 9 - Location of the Sinkhole at Yuen Long Industrial Estate



(a) On 13/4/88

(b) On 22/4/88

Figure 10 - Geometry of the Sinkhole at the Yuen Long Industrial Estate

APPENDIX A
ANALYSIS USING ELECTRICAL ANALOGUE METHOD

A.1 INTRODUCTION

In order to check the validity of using average hydraulic gradient to evaluate sinkhole potential, a project was set up for a summer student to examine the local hydraulic gradients at the critical layer (the soil layer immediately above a slot). This Appendix reviews the results of the exercise and discusses its implications on the conclusions in Section 10 of this report.

A.2 METHOD

The conducting paper electrical analogue method was used to determine equipotential lines from which flow nets could be sketched. Details of the method and the equipment are described by Craig (1985). The method is for two dimensional situations. It is relevant for the present case because slots usually occur as linear features on the marble rockhead.

A.3 BASIC GROUND PROFILE

Because the review is to study sinkhole risk in the Yuen Long area, the typical ground profile in the area has been adopted for the analysis (see Figure A1). For simplicity, the slots are taken to be 2 m wide at 20 m spacing. The simplification should not affect validity of the results as only the relative hydraulic gradients at a particular slot at different stages of the geological past are of interest in the present study.

A.4 CASES FOR ANALYSIS

Figure A2 shows the cases to be analysed for the hydraulic gradients under past and future conditions. The resulting flow nets will be discussed in Section A6.

A.5 MODELLING ASSUMPTIONS

In the present exercise, the materials were assumed to be isotropic with respect to permeability. The adopted permeability values are shown in Figure A1. This assumption of isotropy is over-simplified for the alluvial beds for which horizontal permeability is much higher than vertical permeability. However, such simplification is acceptable because it will only cause some over-estimation of hydraulic gradient for the adverse cases and is therefore conservative to the present study. Moreover, the limited ground information would make further refinement meaningless.

Figure A3 shows the result of two approaches to find the flow nets for case (d) in Figure A2. The left half of the Figure was obtained by squaring out voids in the lower part of the conducting paper to reduce its average permeability by one order. It can be observed from the Figure that the head loss in the alluvium is so small as to be neglegibe. Also, the effect of squaring out voids is such that the equipotential lines immediately above the slots are ill-defined and unreliable. As a result, a simplification was made by assuming zero head loss for flow through the alluvium. The result is shown on the right half of Figure A3.

Figure A4 shows the pattern of flow from recharge sources of large lateral extent into slots at regular intervals. The flow patterns are repetitive. It is therefore enough to model a space bounded by the centre-line of the slot and the midway line between the slots.

A.6 HYDRAULIC GRADIENTS IN THE GEOLOGICAL PAST

The flow nets for cases (a), (b) and (c) in Figure A2 are shown in Figures A5, A6 and A7 and the critical hydraulic gradients are tabulated below :-

Case	Condition	Figure	*Hydraulic gradient
(a)	Thin cover over slot, ponding at ground surface	A5	0.8 x total head = 0.8 x (2+2) = 3.2
(b)	Medium soil cover over slot, ponding at ground surface	A6	0.33 x total head = 0.33 x (2+8) = 3.3
(c)	Full debris deposit over slot, ponding at ground surface ground water table near ground surface	A7	0.24 x total head = 0.24 x (2+12-h_m) = 3.36 - 0.24 h_m = 0.5 for $h_m \simeq 12$

* The hydraulic gradients are measured from the flow nets as the average across a 1 m thick critical layer from the void at the centre line of the slot. The total heads are as listed in Figure A2.

A.7 HYDRAULIC GRADIENT AFTER DEWATERING

The flow nets for cases (d) and (e) (of Figure A2) are shown in Figures A7 and A8. The flow pattern for case (f) is shown in Figure A9 from which it can be seen that the flow net in Figure A7 is also applicable. The hydraulic gradients corresponding to these cases are tabulated below :-

Case	Condition	Figure	*Hydraulic gradient
(d)i	Full water table in alluvium. Phreatic surface in marble one metre above rock head	A7	0.24 x total head = 0.24 x (12+12-h_m) = 0.24 x (24-1) = 5.52
(d)ii	Ditto, but water table at top of debris deposit	A7	0.24 x total head = 0.24 x (12-1) = 0.24 x 11 = 2.64

(e)	Same as (d)i but slot partially soil filled	A8	0.16 x total head = 0.16 x (24-1) = 3.68
(f)	General groundwater table lowered to great depth, water recharge at the surface	A7	0.24 x total head = 0.24 x (12-h_m) = 2.64

* The hydraulic gradients are measured from the flow nets as the average across a 1 m thick critical layer from the void at the centre line of the slot. The total heads are as listed in Figure A2.

A.8 SUMMARY OF FINDINGS

It can be seen from Sections A.6 and A.7 that the average hydraulic gradient increased slightly during the early deposition of the debris layer. The hydraulic gradient decreased as groundwater table rose to above rockhead. The hydraulic gradient in the case of recharge to a lowered groundwater table is small being of the order of 2.5. However, for the extreme case of full drawdown in the marble bedrock but zero drawdown in the alluvium, the hydraulic gradient at the critical layer could be over 5. This hydraulic gradient will be drastically reduced if the slot is partially filled, e.g. 4 m soil in a slot will reduce the hydraulic gradient to about 3.5.

It should be noted that the values discussed above are for 2 m wide slots. For slots of other width, the general pattern remains but the absolute values will be different.

A.9 IMPLICATIONS ON THE CONCLUSIONS OF THE MAIN REPORT

The conclusions in Section 10 remains valid for partially infilled slots and cavities that are very common in the Yuen Long area. However, for the special combination of an unfilled slot with no change in groundwater table in the alluvium but large drawdown in the marble, one of the important findings in the main report may not be totally correct. Hence, the hydraulic gradient and body forces on the critical layer could exceed the past maximum although the phreatic surface in the marble remains above rockhead. This special condition should form one of the action criteria for interpreting monitoring and analytical results regarding groundwater level changes in the Yuen Long area.

A.10 REFERENCES

Craig, D.J. (1985). Effects of a Drainage Tunnel Determined by Electrical Analogue Techniques. Geotechnical Control Office, Design Study Report DSR 1/85, 29 p.

LIST OF FIGURES

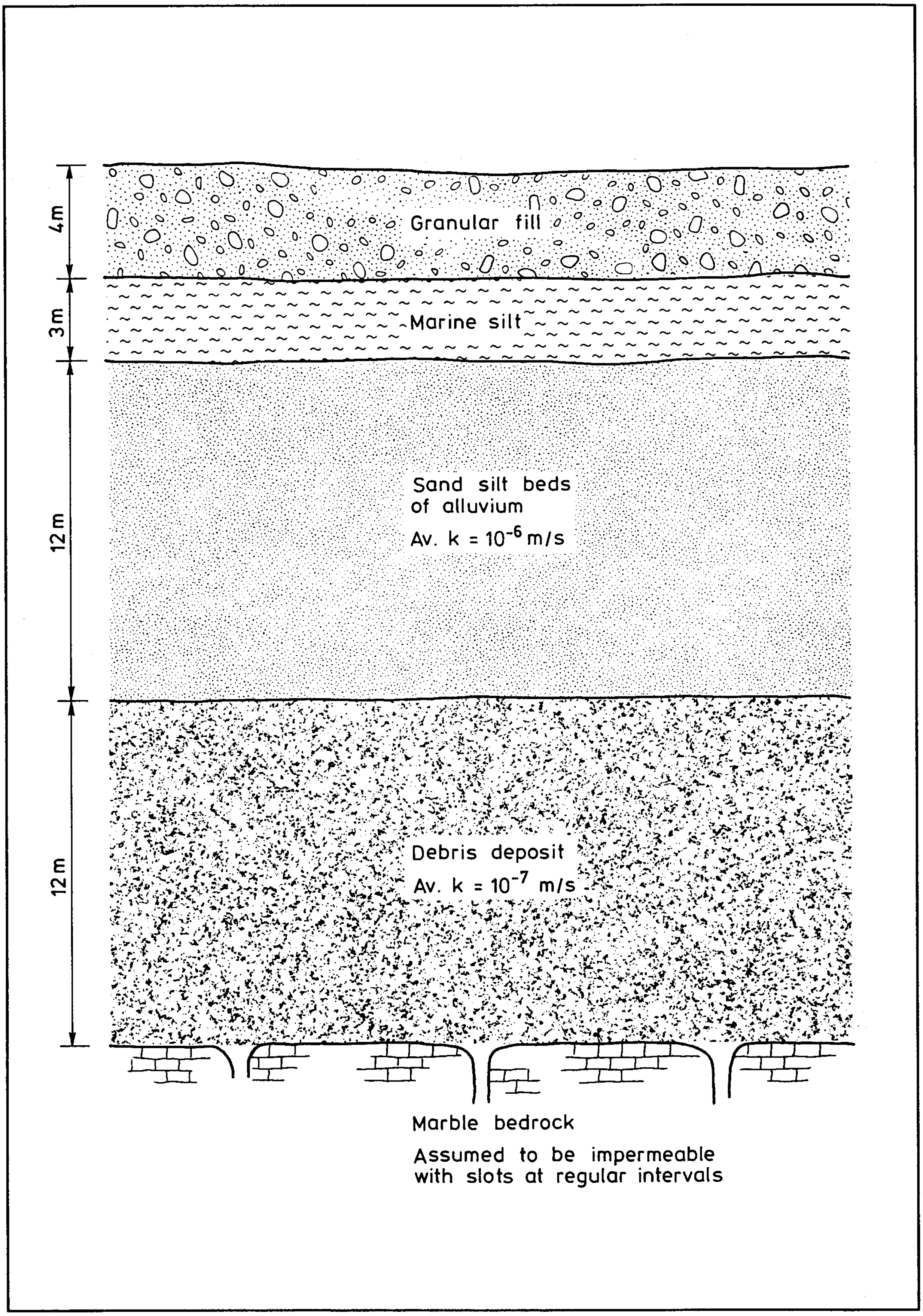
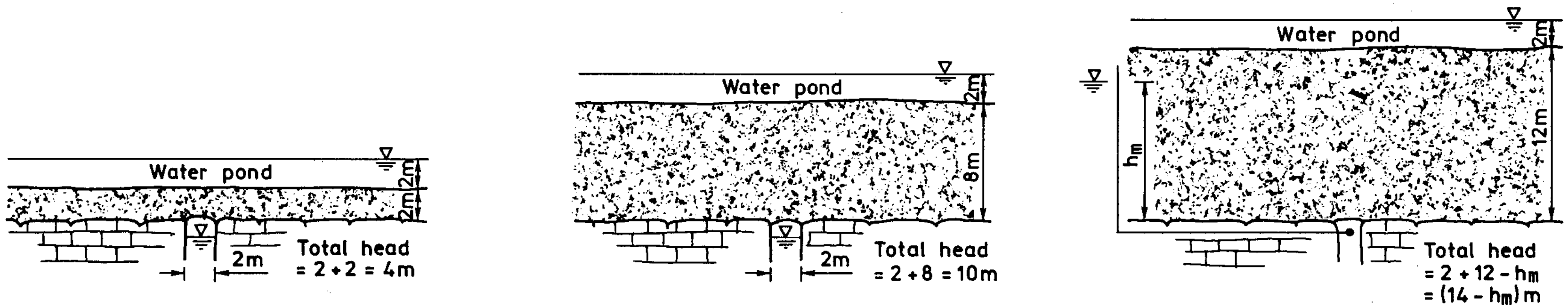


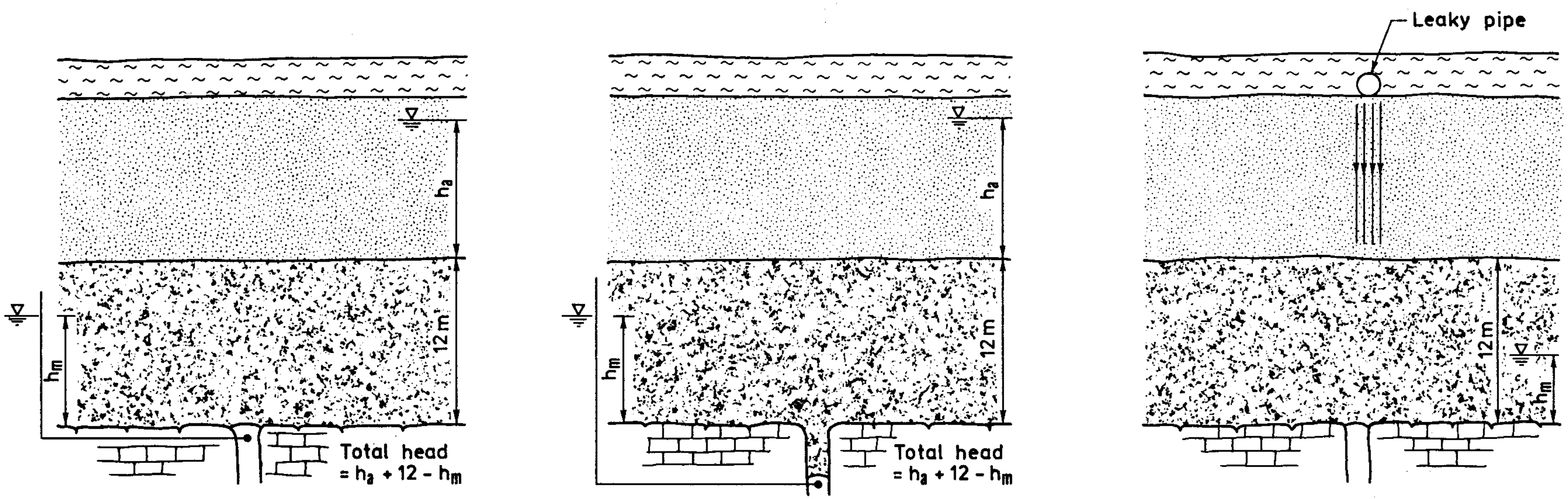
Figure A1 - Typical Ground Profile in Yuen Long Area



(a) Thin Debris Deposit over Marble

(b) Medium Debris Deposit over Marble

(c) Full Debris Deposit over Marble



(d) Full Soil Profile over Marble, Groundwater Extraction from Marble

(e) Full Soil Profile over Infilled Slot

(f) Leaky Pipe Recharge onto Lowered Water Table

'Note : See Figure A1 for legend.

Figure A2 - Cases to be Analysed

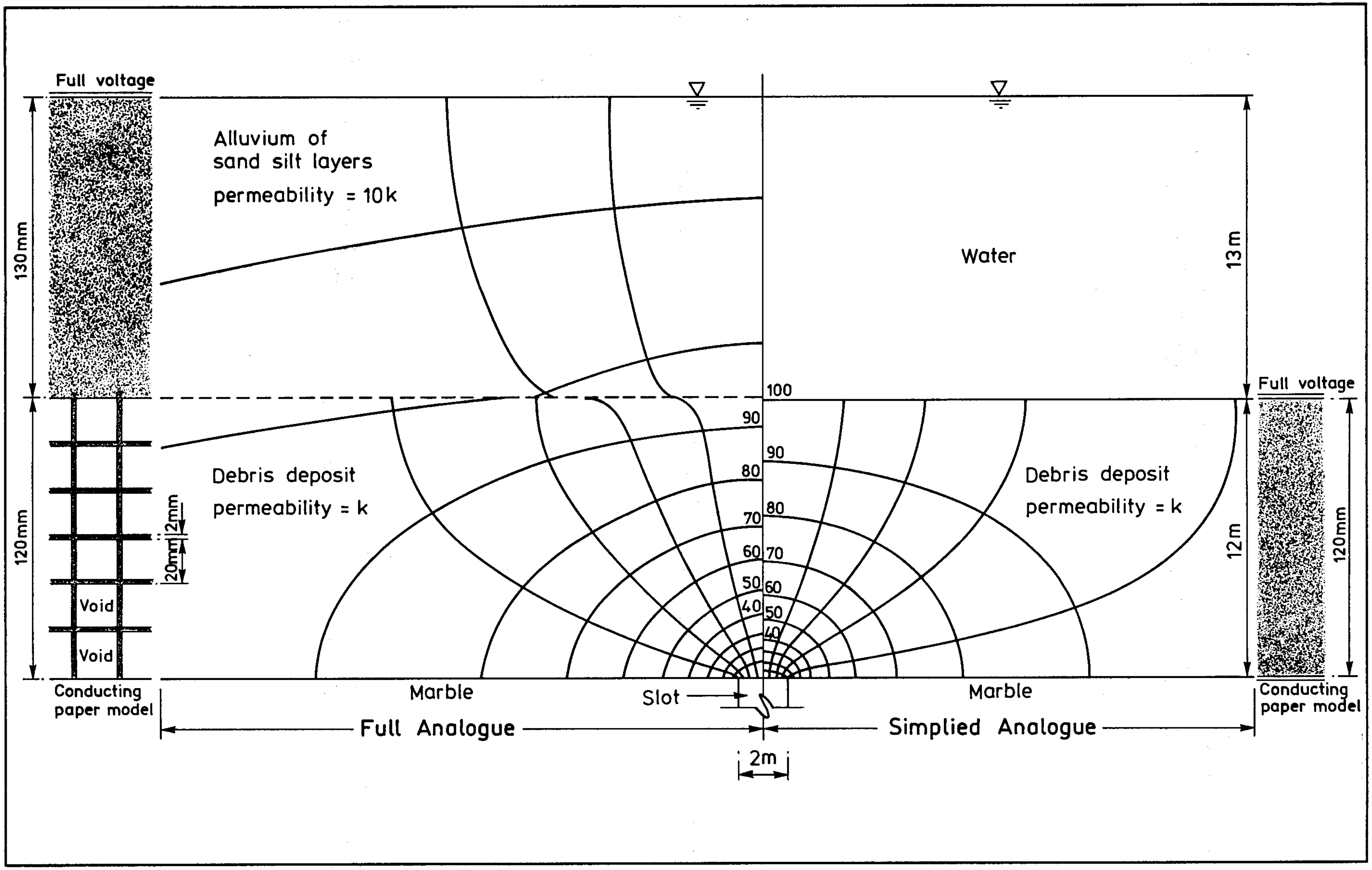


Figure A3 - Flow Nets over Slots with Full Soil Cover - Trials

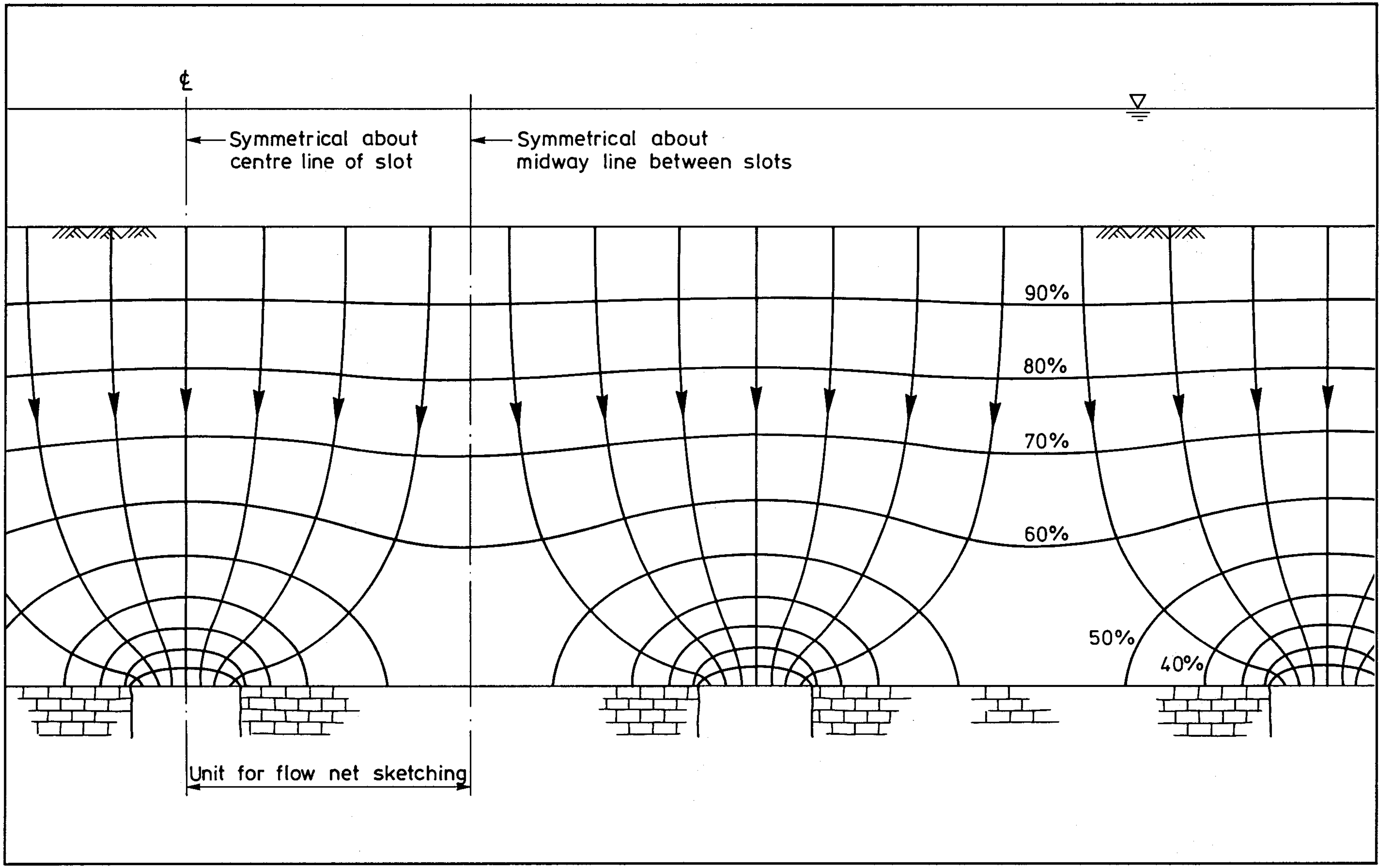


Figure A4 - General Pattern of Flow into Slots

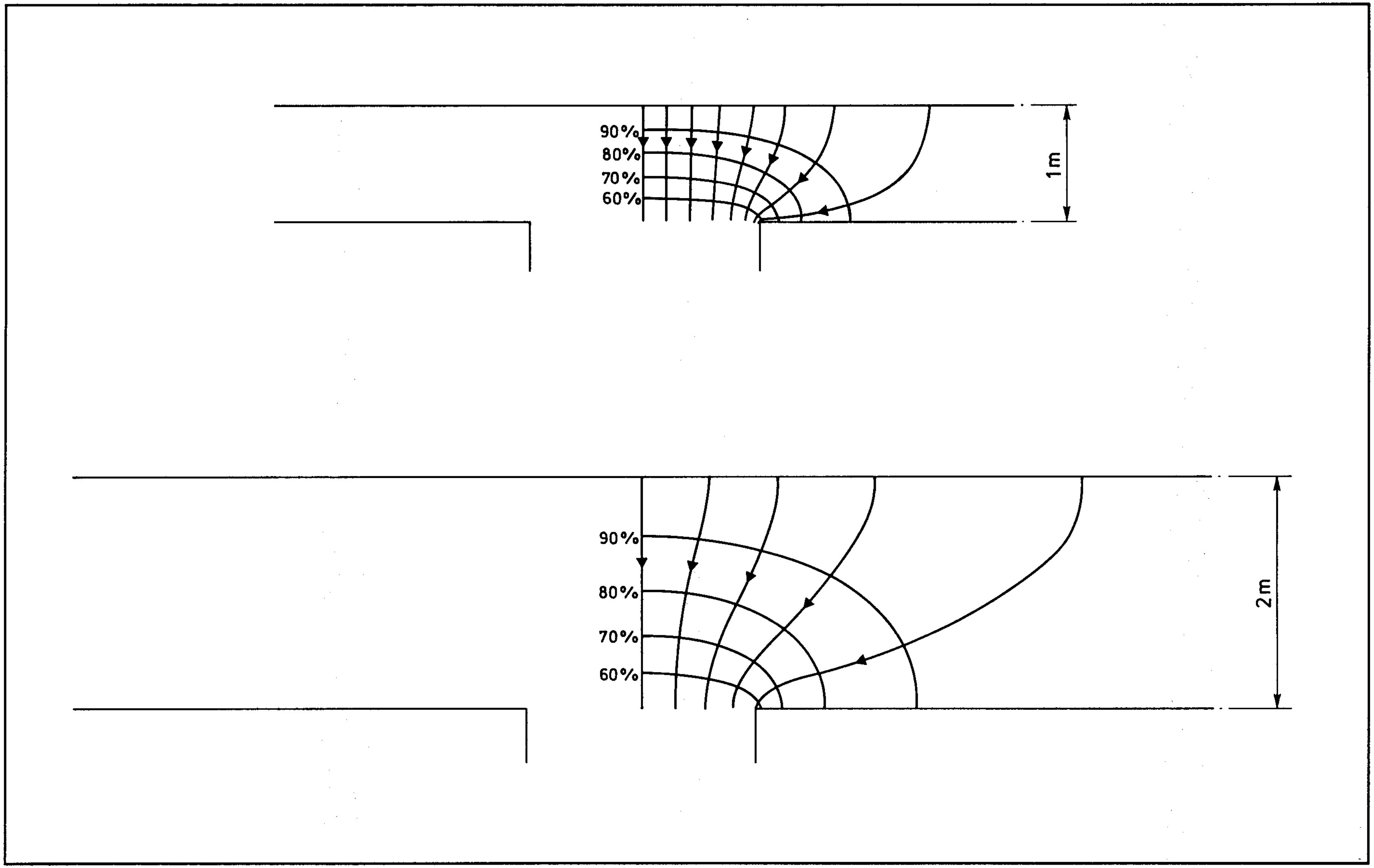
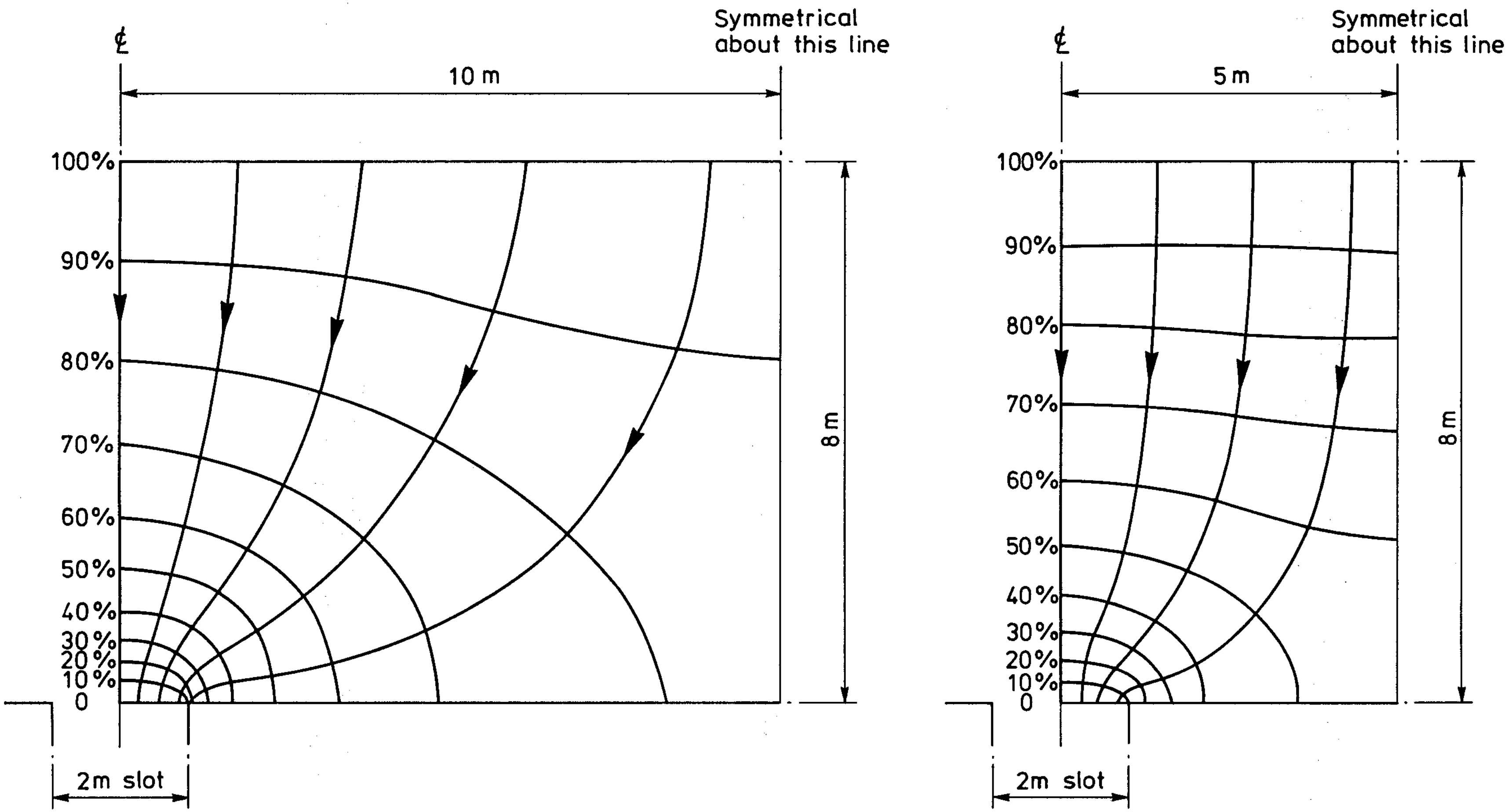


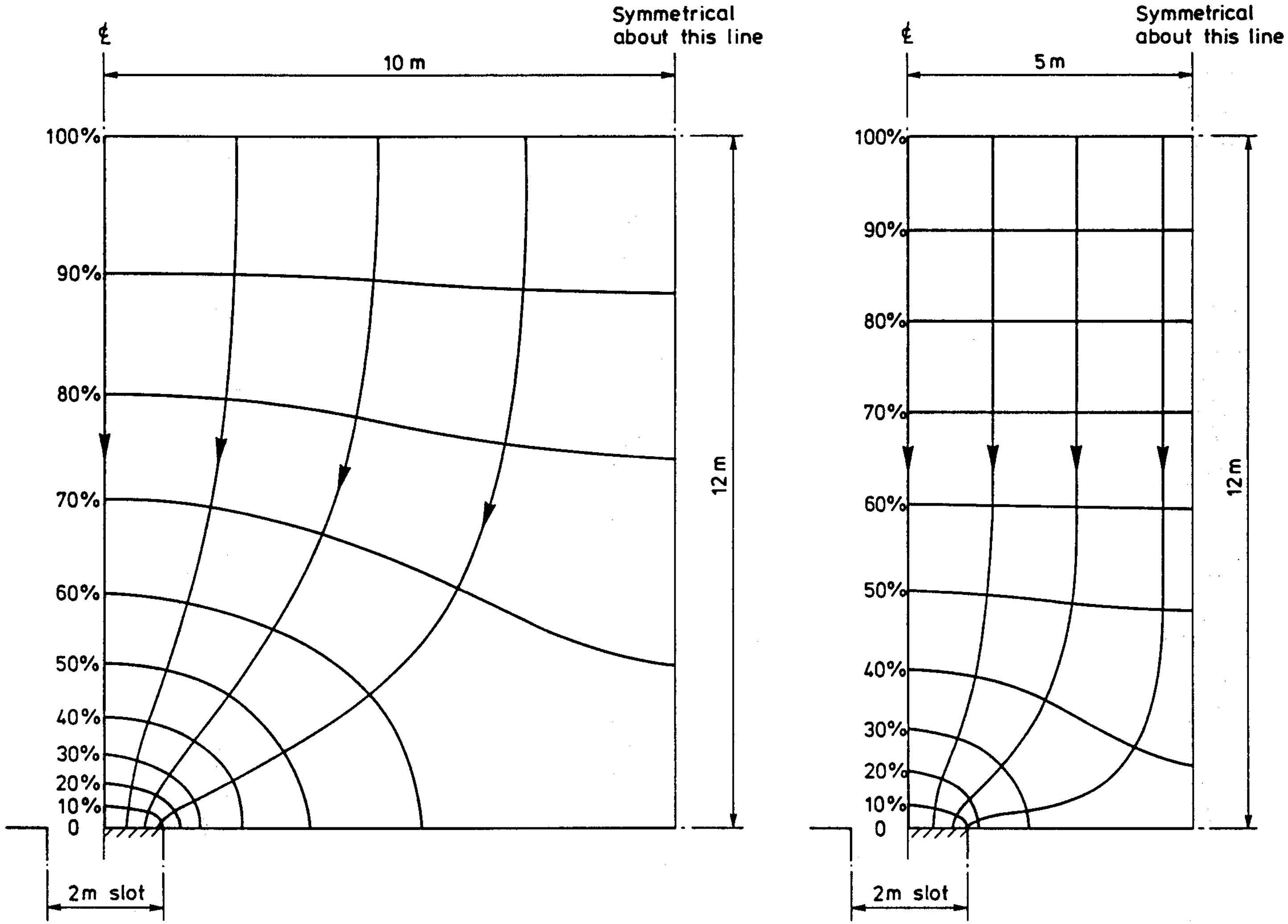
Figure A5 - Flow Nets over Slots for Thin Cover



(a) 2m Slot at 20m Centres

(b) 2m Slot at 10m Centres

Figure A6 - Flow Nets over Slots with Partial Soil Cover



(a) 2m Slot at 20m Centres

(b) 2m Slot at 10m Centres

Figure A7 - Flow Nets above Slots with Full Soil Cover - Simplified Analysis

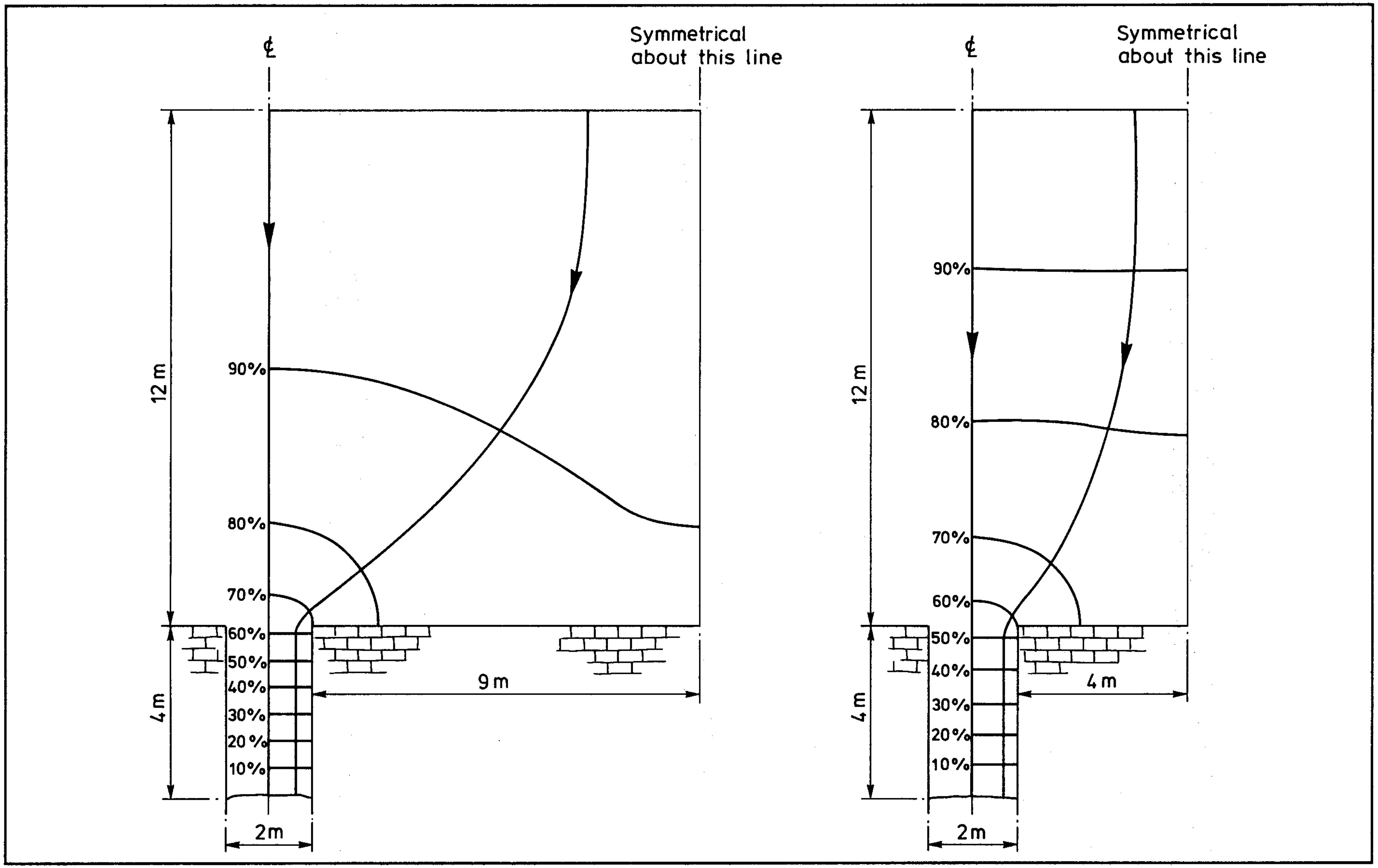
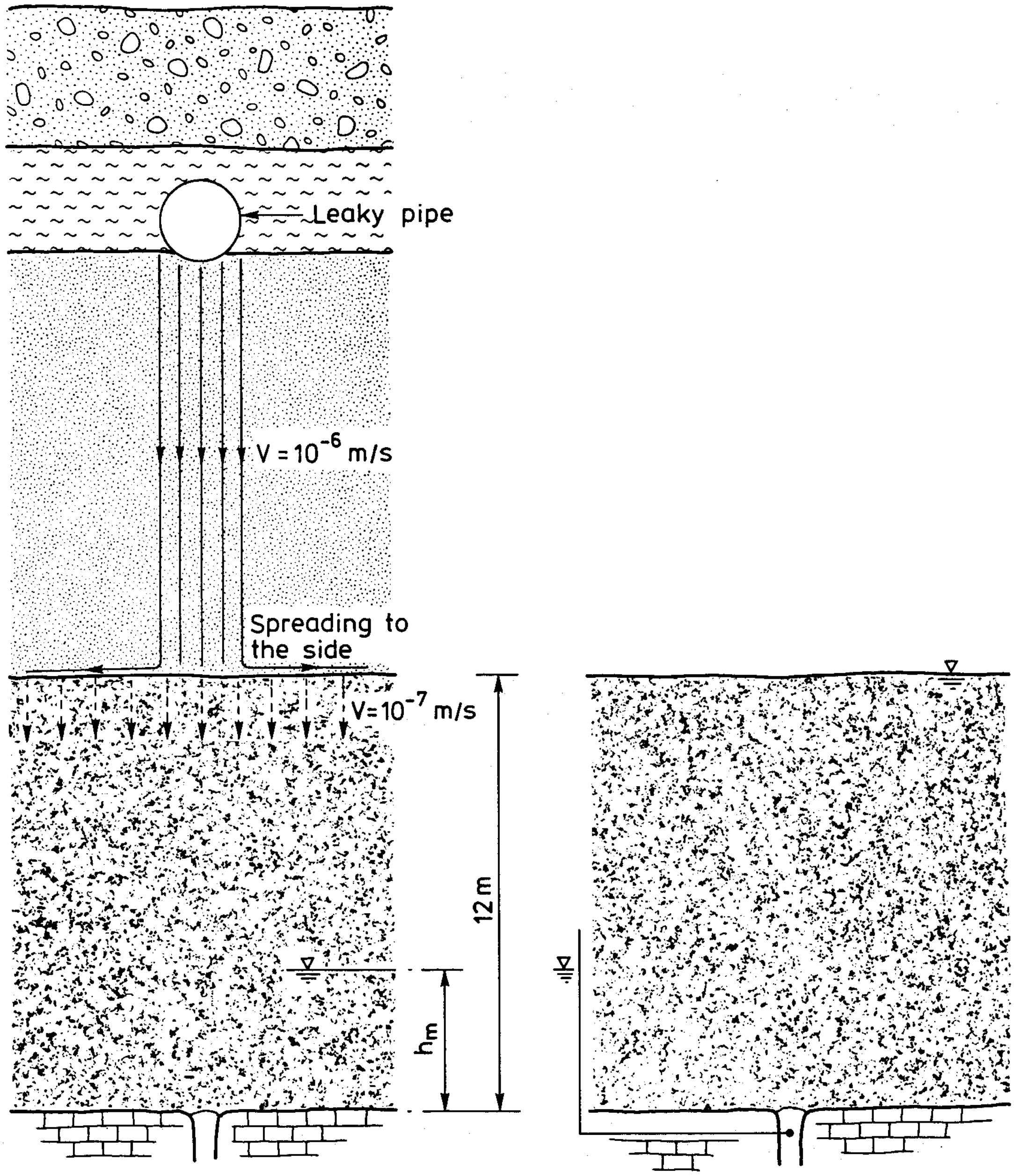


Figure A8 - Flow Nets above Soil Filled Slots with Full Soil Cover



(a) Recharge from Leaky Pipe

(b) Equivalent Situation

Note : See Figure A1 for legend.

Figure A9 - Recharge to Lowered Groundwater Table