REPORT OF THE INDEPENDENT REVIEW PANEL ON FILL SLOPES

GEO REPORT No. 86

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GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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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. A charge is made to cover the cost of printing. This report differs from others in the series in one aspect: it was neither prepared for nor by the Geotechnical Engineering Office. It is included in the series because of both its historical and technical value.

The Geotechnical Engineering Office also publishes guidance documents as GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these documents is given on the last page of this report.

R.K.S. Chan
Principal Government Geotechnical Engineer
March 1999

FOREWORD

It is hard to re-capture the sense of urgency that surrounded the preparation of this Report. At the time of the Sau Mau Ping disaster in 1976, Hong Kong was in the midst of an enormous public housing undertaking. The Sau Mau Ping landslide raised questions regarding public safety associated with this housing programme and I still vividly remember Sir Murray MacLehose, then Governor of Hong Kong, asking "Do I have to evacuate several thousand people each time it rains?"

The Government immediately accepted the recommendations made by the Independent Panel and set about implementing them. They have stood the test of time. Literally hundreds of slopes have been reconstructed following the guidelines outlined in the Report and all have performed in a satisfactory manner.

Of far-reaching significance for Geotechnical Engineering was the recommendation that a control organization be established within the Government. This, of course, has evolved into the Geotechnical Engineering Office. The GEO has raised standards of geotechnical practice in Hong Kong to among the best in the world and has made outstanding contributions to Geotechnical Engineering at both regional and international levels.

The Report of the Independent Review Panel on Fill Slopes was a major milestone in the development of Geotechnical Engineering and I am pleased to see it re-published.

Norbert R Morgenstern
University Professor of Civil Engineering
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and

Past-President, International Society for Soil Mechanics and Geotechnical Engineering

March, 1999

SUMMARY

Slope failures in natural and artificial slopes during periods of heavy rainfall are not unusual in Hong Kong. However, at Sau Mau Ping major failures have repeatedly occurred in fill slopes within the same estate. Seventy-one persons were killed in a mud avalanche in June 1972 and this disaster was reported on by a Commission of Inquiry. On 25 August 1976 a further fill slope failed, burying the ground floor of Block 9 and killing eighteen people. These failures resulted from the development of a seepage condition within a wetted zone as water penetrated into the face of the slope. Consequent loss of strength in the fill resulted in downhill movement and an almost instantaneous conversion of the slope into a mud avalanche with considerable destructive energy. Investigations have demonstrated that the face of the slope at Sau Mau Ping was formed by end-tipping of fill in a loose condition. In such circumstances, the wetted-zone can develop to a significant depth relatively quickly within the duration of heavy rainstorms such as occur every four or five years in Hong Kong. A limited study of other fill slopes in public housing areas in Hong Kong has demonstrated the presence of loose materials forming the slope surfaces. It is apparent, therefore, that the fill conditions at Sau Mau Ping are not unique, nor are the intense rainfall conditions rare. Although adequate specifications for the construction of fills have been available in Hong Kong since at least 1966, there is little evidence to suggest that these specifications have been applied to any significant extent in slopes. It is the view of the Panel that construction of fill slopes using inadequate compaction, and involving end-tipping, may have been general in Hong Kong. Thus, conditions such as those at Sau Mau Ping may be widespread; all fill slopes may be composed of loose material; and so are suspect. A detailed programme of investigation to identify such slopes is required as a matter of urgency. Potentially unstable fill slopes, once identified, can be stabilized satisfactorily by re-compacting a surface layer of fill, of a minimum thickness of 3 m, to a slope of 1 on 1.5, and providing suitable drainage, surface protection, and safeguards against leaking services. In view of the probable widespread occurrence of potentially unstable slopes in Hong Kong, in both public housing and other areas, and the need to ensure that proper standards of placement of fill are adopted in the future, the Panel is of the view that a special control organisation, with appropriate powers, should be formed within the Government.

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1. INTRODUCTION

1.1 On 25 August 1976 soon after 10 a.m. the fill slope immediately behind Block 9 of the Sau Mau Ping Estate failed (Fig. 1 & 2). The resulting mud avalanche buried the ground floor of the block killing eighteen people. This single disaster has, however, wider implications in that 71 persons were killed in a slope failure, also in fill and also at Sau Mau Ping, on 18 June 1972. The Final Report of the Commission of Inquiry (Ref. 1) concluded, with regard to the 1972 failure, that no fault was found "with the manner in which the design and construction of the embankment was carried out" (p.28). Against this background it must be recognised that fill slopes, constructed as the result of a need, often urgent, to create land for housing development, are wide-spread throughout Kowloon and the urban areas of Hong Kong Island. The engineering criteria used in the construction of such fill slopes are thus called into question. In these circumstances the Government of Hong Kong has sought independent authoritative opinion on the cause of the slope failure at Sau Mau Ping in 1976, and the safety of other similarly constructed slopes. To this end, it was decided to form an Independent Review Panel on Fill Slopes whose terms of reference would complement other investigations which were also being undertaken. The membership of the appointed Panel is listed in Appendix A.

1.2 The original terms of reference of the Panel were set out in a cable dated 3 September 1976 sent by the Governor to each of the four overseas members of the Panel. Subsequently, these terms of reference were expanded in a letter dated 21 September 1976 from the Acting Director of Public Works to the individual Panel Members, in which it was indicated that the Panel was required to report on the following:-

"(a) the cause of the recent failures

(b) assessment of risk of further failures in the recently failed slopes and in other fill slopes which may affect public housing areas

(c) feasibility of temporary and permanent remedial works for the recently-failed slopes

(d) assessment of risk of failures in fill slopes elsewhere taking into account past design and construction practice in Hong Kong

(e) recommendation on design of future fill slopes".

Aspects of the terms of reference, as set out in the cable from the Governor and the letter from the Acting Director of Public Works, were discussed by various members of the Panel and the Public Works Department (PWD) at meetings held on 14, 23 and 28 September. At these meetings the following was agreed:-

(i) all types of fill embankment, other than water-retaining embankments, would fall within the scope of the Panel's study,

(ii) in view of the limited time available, the Panel's report would be prepared in two stages, namely a report covering fill slopes in public housing areas to be available in December, and a second report, to be completed at a later date, dealing with fill slopes in other areas,

(iii) the Panel's report would be prepared as a separate, independent document and

(iv) the Panel could amend the terms of reference if necessary.

In personal letters dated 5 November 1976 addressed to Panel Members the Secretary for the Environment requested that the Panel report should be addressed to the Governor and be separate from, and include comments upon, the report to the Governor by the Consulting Engineers, Binnie & Partners (Hong Kong). During a subsequent meeting on 10 November 1976 the Governor requested the Panel to include hospitals and schools within the scope of its first report.

1.3 Immediately following the 1976 slope failure at Sau Mau Ping, Binnie & Partners were requested to carry out an investigation of this slope as a matter of urgency. This investigation was then broadened into a study of fill slopes with terms of reference which the Panel understands to be effectively identical to those given to the Panel. The primary role of Binnie & Partners has been to carry out detailed field, laboratory and office studies of the failure at Sau Mau Ping and other fill slopes. The Panel has reviewed the programme for, and results of, these studies with Binnie & Partners. Comments by the Panel on the report by Binnie & Partners (Ref. 2) have been specifically requested and these are given in Appendix B. Binnie & Partners were also directed to service the technical requirements of the Panel by acting as the agency for contacts with other Government Departments and by providing documentary or other material requested. The Panel wishes to acknowledge the efficiency and goodwill exhibited by Binnie & Partners in the discharge of their duties, which have considerably assisted the effective operation of the Panel.

1.4 All the members of the Panel were present in Hong Kong at differing times over the period 9 to 29 September 1976. No formal meetings of the Panel were held during this period because all six members were not present together. However, the Panel Members took this opportunity to familiarize themselves with background information, visit Sau Mau Ping and other fill slopes, review the proposed investigation with Binnie & Partners, make specific requests for further studies, and attend meetings with the PWD. The Panel convened for the first time in Hong Kong over the period 7 to 13 November 1976, documentation in the interim period having been circulated by Binnie & Partners. Meetings were held with the PWD on 9 November 1976 and with the Governor on 10 November 1976. Sau Mau Ping and four other selected sites where trial pits had been excavated were visited on 12 November 1976. At the end of this first session the Panel had prepared, and discussed, a first draft of their report. A second draft of the Panel report was circulated amongst Panel Members at the end of November. Portions of the report by Binnie & Partners were received by Panel Members in early December. The members then re-convened on 12 December 1976, finalised and agreed on the Panel report.

2. CAUSES OF INSTABILITY

2.1 In a slope, the gravity forces tending to move the sloping soil mass downhill are related to the angle of the slope. The soil strength which resists these forces is dependent on the type of material, its degree of compaction or density, and whether it is wet or dry. When these gravity forces exceed the strength of the material, failure occurs resulting in large movements of the material in the slope.

2.2 In a loose dry granular fill such as decomposed granite soil, the critical slope angle will be of the order of 33 degrees. When compacted to an acceptably dense state this critical angle will increase to at least 37 degrees. In practice soils are not perfectly dry as they contain some moisture and are often termed partially saturated soils. The forces of adsorption between the soil and the water cause the strength and therefore the critical angle for a partially saturated soil to be greater than for a dry soil. However, at some water content, as more water enters the soil and it approaches a saturated state, the strength reduces to a value of the order of that for a perfectly dry soil. For example, the critical angle for a loose saturated decomposed granite soil would be about 33 degrees compared with at least 37 degrees for a dense saturated soil.

2.3 As more water enters the soil, conditions in the soil itself such as layers of different densities, may cause seepage forces and downhill flow to develop, further reducing the strength of the soil and the stability of the slope.

2.4 Should instability occur, then some deformation of the soil will occur, and if the soil is loose, these deformations will tend to produce a decrease in volume, i.e. the soil contracts. If the soil is nearly saturated, then this contraction is resisted by the water in the soil pores, causing a rapid build up of seepage forces. The soil will flow in a liquid state and may move at a high velocity down the slope. These mud avalanches are very destructive as has been the case in Hong Kong.

2.5 If in contrast, a dense soil deforms, it will tend to increase in volume, i.e. expand. This expansion prevents a collapse and even though the slope may fail, there is no liquefaction. The material will move until stability is restored and the movement is arrested. The end result is a debris slump and not a mud avalanche.

2.6 From the general discussion above it is obvious that compaction, rainfall and ground water are the most important factors influencing the stability of fill slopes in Hong Kong. Some further general comments are made on these factors in relation to decomposed granite fill in slopes.

2.7 Compaction can improve stability in the following ways:

(i) The strength can be improved by the increased density resulting from improved compaction.

(ii) Structural collapse during shearing can be eliminated by compaction. Test data indicate that the fill material at a density of less than 85% standard compaction* can undergo structural collapse when sheared following inundation (Appendix C & Ref. 2). At a density of about 85% standard compaction, this tendency to collapse ceases for stresses comparable to those calculated at the failure surface. For higher densities, volume expansion will occur, tending to strengthen the soil.

(iii) The permeability of the soil is reduced by increasing the density. The test data suggest that the saturated permeability of the decomposed granite soil can be reduced tenfold by increasing the density from 80% to 95% standard compaction. As discussed later, this lower permeability will reduce surface infiltration of rain and depth of wetting, and therefore will restrict the development of seepage forces.

(iv) If the fill is deposited by end-tipping without compaction, distinct layering approximately parallel to the slope occurs. The effect of this layering will be to limit the depth of infiltration but increase hill-side seepage down the slope. While this factor will be discussed later, improved compaction in horizontal layers will produce a denser and more uniform fill.

2.8 The rainfall intensities measured during the 1976 storm are not rare events for Hong Kong, as similar intensities occurred in 1966 and 1972. The tests referred to in Appendix C indicate that in 1976 the intensity was such that most of the rainfall would enter the slope and that sufficient rain fell to saturate the soil to a depth of at least 4 m. They also indicate that compaction at 95% standard compaction would significantly reduce infiltration and depth of wetting.

2.9 While the tests did not model the actual sloping surfaces, the depth of wetting was at least the maximum depth of the failure, namely 4 m. The sloping surface would tend to increase surface run-off and reduce infiltration. However, this may be offset by the

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* It is customary to define the density state of a soil as the actual dry density in-place expressed as a percentage of the standard compaction density. Dry density is the ratio of the weight of the soil less water to the total soil volume. The standard compaction test gives a dry density corresponding to that achieved during construction with normal construction plant.

commonly observed trend that the permeabilities in slopes are higher than those measured in laboratory tests.

2.10 Layering of the fill would also tend to reduce the depth of wetting predicted by model tests. Even more important the layering would modify infiltration patterns, tending to cause a build-up of seepage forces within the wetted depth and greater seepage flow downslope. At the top of the slope, the infiltration dominates so that the flow will be nearly vertical. Further down the slope, the seepage flow increases, causing the direction of flow to become more parallel to the surface of the slope. Near the base of the slope, water may flow out of the slope i.e. the angle of flow is less than the slope angle. Any inhomogeneity can alter this simplified pattern of seepage. For example, a denser layer emerging at some point up the face of the slope may cause seepage out of the face at that point.

2.11 The worst situation from the stability viewpoint occurs when the flow is at the least angle to the horizontal, e.g. near the base of the slope or where seepage emerges from the face. However, unless localised failure occurs rendering the remainder of the slope unstable, the main design consideration would be the conditions in the bulk of the slope, where the flow would be nearly parallel to the slope.

2.12 The mud avalanche due to liquefaction is restricted to the wetted zone. It will occur only if the fill is poorly compacted. Good compaction to 95% of standard will not only significantly reduce the infiltration and depth of wetting but will also eliminate the possibility of mud avalanches.

2.13 Impervious covering of the slope will also prevent wetting due to infiltration from the surface. However, without proper compaction, the slope would remain potentially unstable should water enter from other sources as discussed below or from any defects which may develop in an impervious cover.

2.14 Rising ground water levels are one such source of water, which may reduce stability. Water levels have been monitored in natural slopes in Hong Kong and some have shown rapid response to rainfall. Water levels in fill slopes have not been regularly monitored, but seepage from weep-holes in retaining walls has been observed during the wet season. Therefore, the possibility of rising ground water levels in fills must be recognised. In thick fills deep-seated failures would be the result of this mechanism. While no such failures have been recorded in fill slopes in Hong Kong, they must be considered in the design of such slopes. However, for mud avalanches to occur, a significant portion of the moving material must be near saturation. This can only occur if the infiltration of the rainfall obtains simultaneously or water levels rise to near the surface of the slope, and this latter condition is a particular danger when the depth of the fill is small compared to the inclined length of the slope.

2.15 Leaking underground drains near the crest must be considered as a further source of water. This coupled with surface infiltration would lead to serious instability in uncompacted slopes. In this case, the greater instability would occur near the crest, whereas infiltration alone generally leads to greater instability down the slope.

2.16 Other factors such as leaching and ageing of soil have not been investigated but are considered to be extremely minor processes compared with those discussed above.

3. RESULTS OF DETAILED INVESTIGATIONS

Sau Mau Ping

3.1 The fill slopes at Sau Mau Ping have been a source of trouble since construction, and failures have ranged from minor sloughing and surface erosion to major slips involving thousands of tonnes of soil. The major incidents have resulted in the slipped soil mass either sweeping down-slope as a mud avalanche, not coming to rest until stopped by a building or on reaching level ground well beyond the toe of the slope, or slumping down as a heap of debris and coming to rest close to the toe. The mud avalanches of 1964, 1972 and 1976 have been the most serious events, with disastrous consequences in 1972 and 1976 when dwellings were overwhelmed. The debris slumps have caused no loss of life up to present, since their reach has not extended to dwellings, and the minor sloughings have had little consequence other than serving as a warning of potential dangers. Numerous repairs have been needed on many of the fill slopes at Sau Mau Ping after heavy rains and, in particular, at the site of the 1976 disaster, the surface of the fill slope behind Block 9 has had stone pitching, re-planting of grass, construction and re-construction of french drains, and chunam plastering applied over various portions in the past.

3.2 Good practice in building up a fill slope would call for the soil being spread in thin horizontal layers with each layer being compacted, by rolling or ramming with compaction plant, until it was in a sufficiently dense state to be stable, before the next layer was spread and compacted. The specifications in force for the site formation work at Sau Mau Ping stated that the fill "… shall be deposited in 5 foot layers and compacted subject to the approval of the Engineer as a result of compaction trials." (Section 4.6), and although horizontal layers were not actually specified, the Panel considers it reasonable to infer that horizontal layers were intended. However, photographs taken during construction (Ref. 2) show quite clearly that end-tipping occurred -- the soil being simply tipped or pushed over the edge of the valleys being filled in. With end-tipping each tip load trickles down-slope, burying the previous tip load, and the resultant fill is inevitably in a very loose state since it has been compacted by no more than the weight of the superimposed soil. Furthermore, the fill slope itself will consist of layers parallel to the slope surface and not of horizontal layers.

3.3 The Panel can find no records of compaction plant actually being used on the fill slopes nor of any measurements of the state of compaction during construction. Moreover 5 ft. thick layers are inconsistent with good practice.

3.4 After the disaster of 1972 caused by the failure of a fill slope between Hui Kwong Street and Tsui Ping Road, a report entitled "The Rainstorm Disaster of June 1972. A Report on the Sau Mau Ping Landslip" (Ref. 3) referred to observations of water seepage into the fill and postulated that "…. the failure was due primarily to a seriously high degree of saturation …. together with an increase in pore pressure on the slope surface ….". The Panel regards this as plausible, but has not been able to ascertain whether a rising water table was the dominant factor in causing the failure. The report also stated that "In view of the reported relative compaction, it is possible that a contributory factor may have been a low degree of compaction on part of the slip surface, but this is a matter of conjecture". The Panel agrees with this statement but notes that it conflicts with the conclusion in the 1972 Commission of Inquiry Report, namely …..

> "This certainly removed any suspicion of inadequate compaction of the embankment material" (Ref. 1, p.28). The dry density of the soil was in the range 1.4 to 1.55 tonnes per cubic metre (t/m^3), and these are low values. The soils at Sau Mau Ping can attain dry densities in the range 1.7 to 1.85 t/m^3, with an average of 1.78 t/m^3 when compacted under standard conditions and hence the soil at this fill slope was in a density state of only 80 to 85% of standard compaction. Good practice would call for at least 90% of standard; a value as low as 80% corresponds to no compaction at all.

3.5 After the disaster of 25 August 1976, a detailed investigation was made into the soils in the fill slope behind Block 9. The results of this investigation are described fully in Ref. 2, and can be summarized for present purposes as follows:

(i) The soil type on the fill slope was decomposed granite soil, a coarse-grained sand with appreciable silt and clay content, of a texture well-known in Hong Kong and having no special peculiarities.

(ii) The soil on the slope was in an extremely loose state to a depth of at least 2 m below the slope surface, the dry densities being in the range of 1.25 to 1.55 t/m^3 (average 1.35 t/m^3), corresponding to about 75% of standard compaction.

(iii) The soil on the slope was definitely layered parallel to the slope surface, with layers between about 100 and 300 mm thick.

(iv) Beyond the crest of the slope, at Sau Po Street, the dry densities of the soil were low but variable to a depth of 7 m, dropping from about 1.65 t/m^3 to about 1.2 t/m^3 (90 to 70% of standard compaction) showing a gradient of densities with depth consistent with the soil having been placed in horizontal layers 1 to 3 m thick. At greater depths the dry densities were around 1.5 t/m^3 (85% standard compaction) to a depth of 20 m below the surface.

The dry densities and the parallel layering on the slope itself are what would have been expected for loosely tipped fill with no attempts made to compact after filling; the dry densities and layer thicknesses below Sau Po Street are what would have been expected for soil just below formation level being spread in thick layers with no compaction other than that from the haulage lorries driving over the area.

3.6 The implications of having loose decomposed granite soil forming the main body of a thick fill were discussed in the previous section and can be summarized as follows:

(i) The soil strength is very much less than would be obtained with well-compacted fill.

(ii) Rainwater falling on the surface of a loose soil can percolate readily into the soil mass, wetting the soil to an appreciable depth and reducing the strength even further.

(iii) If the soil is almost saturated, during shearing the soil may collapse, lose its strength, liquify, and cause a mud avalanche.

3.7 From tests described in Appendix C it can be said that the Sau Mau Ping soil will contract if at a dry density lower than 1.5 t/m^3 (about 85% of standard compaction) but will expand at higher dry densities. Consequently the upper few metres of fill material in the slope can be stated to have been in a potentially collapsible form.

3.8 A collapse of the soil with subsequent failure as a mud avalanche can only occur if sufficient water is available to almost saturate the pores in the soil. This water could come from one or more of the following three principal sources as discussed previously.

(i) Infiltration of rain water falling on the slope surface.

(ii) Water injected into the fill from burst or leaking drains, sewers, water mains, or even from badly back-filled trenches carrying service cables if surface flooding occurs during heavy rains.

(iii) Saturation of the soil mass by a rising ground water level.

There is no strong evidence that this third source, a rising ground water level, had any influence on the 1976 disaster, but this mechanism cannot be precluded.

3.9 For direct infiltration of rainwater, the depth of potential collapse is controlled by the rate at which water can percolate through the soil, by the rate and duration of the rains, and by the initial water content of the soil. As described in Appendix C it is estimated that the depth of wetted potentially collapsible soil, that could have developed at Sau Mau Ping during the August 1976 rainstorm, is of the order of 2 to 6 m. The actual thickness of failed material producing the mud avalanche was about 4 m (Ref. 2). Consequently, rainwater infiltration into loose fill is the prime suspect for the disaster.

3.10 Beyond the crest of the slope, at Sau Po Street, the level area here was paved and used as a market. A surface-water drain, of glazed-ware pipe, had been laid parallel to the back of the market shops and approached as close as one metre to the crest of the slope. The portion of this drain immediately above the failed section of the fill slope had been demolished before it could be tested for leakage, but a portion still intact was tested and did leak slightly. Glazed-ware pipes are brittle and inflexible, and slight movement due to settlements of the loose fill would be sufficient to cause serious cracking with consequent leakage during heavy rains. The Panel suspects that the drains above the slope could have contributed to the failure, and considers all such drains above fill slopes to be potentially dangerous. It is a matter of deep concern to the Panel that no up-to-date records are kept showing the locations of surface-water drains, sewers, etc., in the public housing estates.

Other Sites

3.11 A preliminary appraisal has identified potentially dangerous fill slopes in fourteen areas other than Sau Mau Ping, and these slopes are described in a report by Binnie & Partners (Ref. 4). Trial pits were excavated at three of these areas, at Tai Wo Hau Estate, at Shek Lei Estate and above So Uk Estate, and also at Ngau Chi Wan Estate where site formation work is currently in progress. Density tests were carried out in the pits and standard compaction tests performed on representative samples for each site.

3.12 At Tai Wo Hau Estate, the fill slope behind Block 1 failed in 1966, possibly as a mud avalanche but fortunately with no loss of life. Above the top of the slope the surface water drainage system is far from being satisfactory, and there are obvious signs of settlements. The soil on the slope is very loose, dry densities to a depth of two metres ranging from 1.25 to 1.5 t/m^3, equivalent to 75 to 85% of standard compaction.

3.13 At Shek Lei Estate, a retaining wall near Tai Long Street has cracked severely and portions of the wall have moved outwards. The wall retains fill, sloping steeply upwards from the top of the wall to the terrace in front of Block 3. As at Tai Wo Hau the surface-water drains are unsatisfactory and there are signs of settlements along the terrace. Dry densities of the soil on the slope ranged from 1.3 to 1.8 t/m^3 (average 1.54 t/m^3, standard compaction density 1.94 t/m^3), equivalent to a range of 65 to 90% of standard with an average about 80%.

3.14 At So Uk Estate a retaining wall behind Peony House has moved slightly. This wall retains fill forming a road embankment carrying Ching Cheung Road. The fill was apparently constructed in horizontal layers of 250 to 300 mm thickness, but the upper metre or so of soil on the slope was loose. The dry densities ranged from 1.3 to 1.55 t/m^3, but increased to about 1.6 to 1.7 t/m^3 at two metres depth. Standard compaction density was 1.82 t/m^3 and hence the upper layers of this slope were at 70 to 85% of standard, indicating that the compaction at the outer edge of the embankment was not entirely satisfactory.

3.15 At Ngau Chi Wan Estate (under construction), a fill slope failed during the August 1976 rainstorm but did not develop into a mud avalanche, the debris slumping down to the toe of the slope. The fill material here was more clayey than at any of the other sites investigated and had a lower standard compaction dry density of 1.67 t/m^3. Dry densities on the slope were more uniform and slightly larger than elsewhere, ranging from 1.4 to 1.6 t/m^3 (average 1.49 t/m^3) and the state of density was in the range of 85 to 95% of standard.

3.16 To sum up the results of all investigations, the state of the fill soil in the surficial layers of these slopes is unsatisfactorily loose except for the one instance at Ngau Chi Wan. Although the slope at Ngau Chi Wan did fail as a debris slump, the fact that the average state of compaction was about 90% of standard and that no mud avalanche developed is of great significance. At all other sites where the state of compaction was of the order of 80% on average, the chances of mud avalanches occurring in the future are high.

4. EVOLUTION OF PRACTICE REGARDING FILL SLOPES IN HONG KONG

4.1 The previous section dealing with the Sau Mau Ping failures drew attention to the presence of poorly compacted fill, and the implications of the presence of poorly compacted fill have been discussed in Sections 2 and 3. If the occurrence of poorly compacted or even uncompacted soil comparable to that encountered at Sau Mau Ping is widespread in Hong Kong, then potential instability is equally widespread.

4.2 Reconnaissance surveys have identified locations other than Sau Mau Ping where evidence of instability exists (Ref. 4). Moreover there is a history of failure of slopes in fill in some public housing areas. For example, slips have occurred and signs of instability currently exist at Tai Wo Hau Estate. Slips have also occurred at Kwai Chung Estate and considerable evidence of instability is present at Shek Lei Estate. The history of slipping in fills and the indications of instability on filled slopes and of associated retaining walls lead the Panel to the view that the occurrence of poorly compacted soil with its attendant dangers when saturated is common at locations other than Sau Mau Ping. The sites mentioned in Section 3 confirm the suspicion of the Panel that poorly compacted soil is common in Hong Kong.

4.3 In order to further evaluate the occurrence of potential hazards associated with unstable fills and possibly to account for them, the Panel has reviewed the evolution of design, specifications and construction control practice as they relate to fill slopes. This review has been undertaken through study of various specifications and contract documents as well as by discussion with engineers familiar with practice in Hong Kong.

4.4 It is conventional practice in Hong Kong to construct fill slopes at 1 on 1.5. This practice has developed more in an empirical manner than by geotechnical evaluation. For example, Ref. 1 cites a letter circulated to Authorized Architects in 1963 which includes the following statement:

> "The Building Authority will offer no objections to an angle of slope not greater than 35° for filling and 50° for cutting"

While the material available for fill in Hong Kong is mainly decomposed granite, it is not always so and a rational application of soil mechanics would lead to the view that an acceptable slope angle depends upon the material being used and the manner in which it is being placed. Empirical design criteria based on past experience are entirely appropriate so long as construction methods, scale of projects, and quality of control remain unchanged. When factors such as these change, empirical designs should be re-evaluated to ensure their adequacy. Alternatively, construction specifications should be modified so that the new conditions that prevail will lead to performance at least comparable to the past.

4.5 Since the Panel was unable to detect any evolution in the design of fill slopes, it reviewed the development of earthwork specifications as they related to fill slopes, in order to evaluate whether the specifications were such that they would ensure that the design was adequate, provided that construction proceeded according to the specifications. It appears that at the time of construction of Sau Mau Ping several different specifications regarding compaction were being employed. No overall instructions had been given and the choice was left to the individual Engineer under the authority of the appropriate Chief Engineer. Hence each contract had its own specification for compaction.

4.6 In the case of Sau Mau Ping, Contract Nos. 40, 285, and 342 were issued in 1962 while Contract No. 356 was issued in 1966. These four contracts had the same specification for the formation and compaction of filling areas. It states that:

> "Unless otherwise directed by the Engineer all excavated materials with those exceptions referred hereunder shall be deposited in 5 foot layers and compacted subject to approval by the Engineer as a result of compaction trials."

It is the understanding of the Panel that it was not customary to conduct field density tests in these instances and therefore any judgement as to the adequacy of compaction would have been subjective. Moreover, it is the view of the Panel that this specification could not lead to a suitably dense fill, particularly at the outer few metres of the slope where compaction is difficult.

4.7 In contracts issued between 1961 and 1968 for a variety of public housing projects (Sau Mau Ping, Ho Man Tin, Kwai Chung, Sam Ka Tsuen, Lung Cheung Road) the following specification applied to the formation and compaction of filling areas:

> "Unless otherwise specified, all materials placed in Filling Areas shall be deposited in 3-foot layers and compacted by construction traffic …"

This is an apparent improvement over the specification discussed in 4.6 above because the layers are only three feet thick. However, in the view of the Panel the specification was still inadequate and would not ensure adequate homogeneous compaction of filled slopes.

4.8 Some of these same contracts also contained a specification for filling with <u>special compaction</u>. It is of interest to quote this in detail:

> "4.13 Where specified, the formation of road embankments and high filling slopes etc. shall receive "special compaction" and the fill shall then be deposited, spread, watered and compacted as described below, but will otherwise comply with the preceding clause:

(a) Material used for special compaction shall be obtained only from excavation areas approved by the Engineer. It will normally be coarse decomposed granite.

(b) Where specified, tests will be carried out on samples obtained from excavation areas prior to excavation to determine compaction characteristics, Proctor dry density, moisture content, etc. A minimum compaction of 90% of the Proctor dry density as determined by the British Standard Compaction Test will normally be required in specially-compacted material. The density of the compacted fill will be checked at intervals to be specified by the Engineer. No subsequent layer shall be placed until the density of the previous layer has been accepted. It is not anticipated that this will delay the work of placing adequately-compacted fill. The tests shall be carried out at the PWD laboratory or such other place or places as the Engineer may direct. The Contractor shall provide casual labour for the taking and delivery of soil samples to the place of testing and such other assistance as the Engineer may require.

(c) The filling shall be raised in layers of compacted thickness not exceeding six inches, being watered as required by the Engineer with sprays. The layers shall be compacted by rollers weighing not less than 8 tons or other approved compacting devices. The number of passes over the materials compacted shall be determined by the Engineer, but in no case shall be less than 8 passes. Where the main compacting equipment cannot be used, the filling shall be compacted with power rammers or other approved devices so as to attain the required density. The method and sequence of spreading and compacting shall be to the Engineer's approval and shall be modified by the Contractor as may be required."

It is the view of the Panel that where this specification has been implemented the fill will be dense enough so that it will not flow even when surface instability arises. Moreover, fill placed in this way would lessen greatly the possibility of instability being initiated. However, it is the understanding of the Panel that this special compaction has only been applied beneath roadways and not to high fill slopes. Even if special compaction is implemented in the construction of the slope, subsequent end-tipping of material over the slope will result in a veneer of loose unstable material.

4.9 The Panel understands that after 1970 high fill slopes were no longer constructed but fill continued to be placed in three foot layers without special compaction control. The Panel has not found a definition of "high filling slopes" but assumes that a slope higher that 50 feet would be “high” in accord with the convention for “high dams”.

4.10 Following the events of 1972, the Building Authority issued a Circular (Ref. 5) advising Authorised Architects that future building submissions should include details relating to standards for compaction of fill and type of material to be used in support of data and calculations to place beyond reasonable doubt the safety of the earthworks envisaged. In August 1973, the Buildings Ordinance Office, PWD, issued a guide to site investigation and earthworks (Ref. 6). This recognised the need to ensure proper compaction and stated that:

> “In future all embankments will have to reach certain minimum standards of dry density throughout their depth and regular testing during placing of fill may be required by the Buildings Ordinance Office”.

4.11 After the failures of 1976 instructions were issued within PWD requiring fill in slopes to be placed at 95% of standard density and the slope analysed for stability under fully saturated conditions.

4.12 In order to fulfill the intent of a design and associated specifications it is essential that control be exercised on the construction operations. In Section 3 above and Ref. 2 evidence is cited for end-tipping of fill during the construction of slopes at Sau Mau Ping. This procedure results in very loose fill and is normally precluded by the requirement that fill be placed in thin horizontal layers. The fact that end-tipping did occur at Sau Mau Ping must call into question the quality control applied to the filling operations on public housing estates. This is supported further by the density results cited in Section 3.

4.13 As a result of its evaluation of the design of fill slopes, the specifications governing their construction, the weaknesses in quality control, and the performance of the slopes, the Panel is of the view that it is prudent to regard all fill slopes as composed of loose material and therefore suspect of instability. Hence, the only positive approach to avert future disasters is to identify those slopes needing major remedial work on the basis of density tests obtained from exploration pits. Fill slopes that are high and adjacent to buildings should be given the highest priority in these investigations since they constitute the greatest threat to public safety.

5. DESIGN AND CONSTRUCTION REQUIREMENTS FOR FUTURE FILLS

5.1 From the results of the investigations the Panel concludes that future fills can still be constructed to the same average slope of 1 on 1.5 as in the past, provided that the fill is typical decomposed granite; is compacted adequately; is placed on a stable foundation; and is not subject to a rising water level. Typical decomposed granite is discussed in Refs. 2 & 7.

5.2 For such fills up to a maximum height of 20 m the compaction requirements as given in the 1975 Edition of the General Specification for Civil Engineering Works, Civil Engineering Office and Highways Office, Public Works Department, are in general adequate, but some additional requirements are considered to be necessary, particularly for the treatment of the outer edges of the slopes. It is recommended that the fill be constructed slightly oversize and then trimmed back to the desired profile, ensuring that all fill at the slope face is well-compacted. Fill within 4 m of the ultimate face should be compacted to 95% of standard density. Moreover, all drains, services and other pipes should be prohibited from being placed in fill nearer to the crest of the slope than a distance equal to its vertical height. Where such a restriction cannot be met then it is recommended that the pipes be laid in shallow lined channels with continuous covering, suitably drained and with inspection manholes at intervals.

5.3 The prevention of mud avalanches is conditional on the strict enforcement of the specifications for compaction and surface protection, and site control of the construction work is absolutely essential. Despite such strict enforcement of these specifications, debris slumps may still occur which will require immediate maintenance. To prevent such debris slumps would require much flatter slopes with attendant increased costs.

5.4 When the slope is higher than 20 m or where the fill is other than typical decomposed granite or where the foundations may be unstable or where the fill is subjected to a rising water level, the average slope should be selected on the basis of specific site investigations tests and analyses in accordance with current international geotechnical practice.

5.5 Where rising ground water levels are possible it is prudent to incorporate drainage measures in the design of the slope. In the case of thick fills, free-draining material at the toe of the slope is often useful whereas in the case of thinner fills on water-bearing foundations drainage at or below the whole interface should be provided. In addition when rising ground water levels can occur and there is a possibility of a deep-seated slip, it is essential that monitoring of ground water levels be carried out during and after construction of the fill.

5.6 In all cases slope design should incorporate measures to eliminate surface erosion and facilitate maintenance; berms are useful in this regard.

6. REMEDIAL MEASURES FOR EXISTING FILL SLOPES

6.1 Existing slopes which are potentially liable to cause mud avalanches can be identified by the presence of undesirably loose fill in the upper few metres and by signs of settlement and cracking of pavements and drains.

6.2 The Panel has considered very carefully just what is the minimum treatment that need be given to such potentially dangerous slopes before the next rainy season, in order to eliminate incidents similar to those at Sau Mau Ping. Treatment of the slope surface to reduce the rate of rainfall infiltration would reduce the chance of a severe failure but, since saturation from this and other sources cannot be prevented completely, the Panel considers that surface treatment alone is insufficient.

6.3 The Panel considers that the minimum treatment would consist of removing the loose surface soil by excavating each suspect slope to a vertical depth of not less than 3 metres, and re-compacting to an adequate standard. This re-compaction along the slope and beyond the crest must be done in accordance with the recommendations of Section 5 following the requirements for new fills. Drainage of the fill behind the re-compacted surface layer must also be provided at the toe of the slope.

6.4 The Panel recommends that the priority order for these remedial measures be based on an assessment of the risk to public safety. The extent of the areas that could be affected by mud avalanches can be estimated for each suspect slope from the observed behaviour of the mud avalanches which occurred at Sau Mau Ping.

6.5 All remedial re-compaction should start from the top of the slopes. If treatment of the entire slope has not been completed by the onset of the rains then, provided that the upper portion has been prevented from collapsing, the failure of the lower portion should not have such disastrous consequences. As a temporary measure only, incompleted portions should be covered with heavy canvas, properly secured, and regularly inspected in order to minimize infiltration during a rainstorm. It should be emphasized that this is purely an emergency measure and in no way reduces the need for the reconstruction discussed above.

6.6 The development of deep-seated slips, arising from ground water changes, is slow and not immediately as catastrophic as mud avalanches. Therefore, in order to avoid deep-seated failures, it will be sufficient to monitor ground water levels and provide drainage when necessary. In some cases where fill of limited thickness overlies a water-bearing foundation, re-compaction of the upper few metres of fill may, although improving surface stability, in fact make matters worse by inhibiting free drainage. In these instances it may be preferable to achieve stability by a variety of methods such as slope flattening, deep drainage, or replacement of fill with free-draining material. The design should be selected on the basis of the actual site conditions.

7. ORGANIZATION FOR MONITORING AND MAINTENANCE

7.1 The Panel is well aware of the major problem which Hong Kong has had to face in the post-war years and which it will continue to face in the years immediately ahead - that of trying to house its rapidly growing population on its limited land area with steeply sloping terrain and difficult ground conditions. It is also aware of the concern felt in government circles for public safety following the disasters of 1972 and 1976. In proposing the organisational structure necessary to ensure that the recommendations contained in this report are carried out effectively and expeditiously the Panel has been motivated by this primary concern.

7.2 The soils, climate, topography and urban land use of Hong Kong combine to generate a set of special conditions which influence slope stability and associated soil engineering problems. Because of these conditions much greater control of geotechnical work is warranted than in other places where conditions are less rigorous. The Hong Kong Government has recognised these conditions and is now preparing a manual for slopes. But this development should be regarded as the beginning of the controlling system rather than the end, for regulations, unless they are effectively implemented, are of little value.

7.3 In earlier sections of this report it has been stressed that design, construction and maintenance must be closely correlated and integrated to ensure lasting stability, and economy. Leaving aside the problem of fills constructed by the private sector, since it is not a matter of such immediate priority the Panel has concentrated its studies on those fills undertaken by the Government or through government consultants. In general, the majority of such fills are constructed to form housing estates, hospitals, schools, and public highways. Much of the formation and earthworks involved in housing estate development is undertaken by the Development Division of the Public Works Department. It is then handed over either to the New Territories Administration or to the Housing Department, depending on location, for further development. Construction of housing blocks, estate roads and ancillary buildings may then be carried out by the Architectural Office of the Public Works Department, the Housing Department itself or by outside consultants engaged by the Housing Department. In the case of hospital and school precincts the building works and access roadworks are normally designed and supervised by the Architectural Office. Maintenance of housing estates lies within the responsibility of the Housing Department whereas that of school and hospital precincts is undertaken by the Architectural Office. The Highways Division of the Public Works Department designs, constructs, and maintains all highways and highway embankments but in the case of embankments within housing estates adjoining the embankment toe the Panel is unaware of any universally applied rule as to where, with respect to the sloping face of the embankment, the division of responsibility ends. There is thus no centralised body responsible for co-ordinating all aspects of geotechnical engineering in the Government.

7.4 To ensure adequate performance of embankments, fills and cuttings there is a vital need for continuity throughout the whole process of investigation, design, construction, monitoring and maintenance, with feed-back and collaboration between all stages. To achieve this objective centralized control is essential. The Panel considers that the situation in Hong Kong warrants such control and it recommends the setting-up immediately by the Government of such a controlling body with powers and capabilities adequate for its work.

7.5 The control organization must have genuine power together with authority at the decision making levels. It should be the approving authority for all embankment, filling and cutting work which might endanger human life, whether undertaken either by the Government or by the private sector. It should be headed by a fully-qualified soils engineer or civil engineer with wide experience in soil mechanics and foundation engineering. His qualifications and experience should be sufficient to command the respect of all other engineers both inside and outside the Government. He should have adequate back-up facilities in terms of staff and resources to ensure that the controlling process outlined in Section 7.4 is both effective and complete.

7.6 The Panel also recommends the setting-up of an Appeals Board against decisions of the control organisation in the event of dispute over such decisions. The Appeals Board should be selected from a panel of experienced engineers resident in Hong Kong and elsewhere as might be appropriate to the particular nature of the appeal.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 The Sau Mau Ping slope failure of 1976 was the result of infiltration during intense rainfall, in end-tipped, loose fill, followed by loss of strength and consequent conversion of the upper few metres of the fill into a destructive mud avalanche.

8.2 Loose fill has been found in other slopes in public housing areas in Hong Kong. A review of specifications for compaction adopted in Hong Kong and actual construction practice has indicated that poorly compacted and end-tipped fill could be widespread in Hong Kong. This is contrary to the views put forward by the 1972 Commission of Inquiry (Ref. 1).

8.3 Since the conditions at Sau Mau Ping are not unique and since long periods of intense rain cannot be regarded as rare events, it is a matter of some urgency to identify all potentially unstable slopes that constitute a threat to public safety, and to undertake remedial works.

8.4 Where a slope is identified as unsafe, a major programme of remedial works will be required. In some instances this will involve the re-compaction of a surface layer of fill not less than 3 m in thickness at a slope of not steeper than 1 on 1.5. In other instances the design will have to be established according to the conditions of the site. In addition suitable drainage, surface protection, service modifications and monitoring programmes will be required.

8.5 Specifications have been given for the design and construction of future fill slopes at an inclination of 1 on 1.5. In the application of these specifications it is particularly important to identify whether the fill is to be constructed of typical decomposed granite and whether the foundations of the fill are stable and free of water. Where these conditions are not met, additional measures are needed to achieve stability.

8.6 It is recommended that a control organisation be established within the Government to provide continuity throughout the whole process of investigation, design, construction, monitoring and maintenance of slopes in Hong Kong.

9. REFERENCES

Ref. 1 Final Report of the Commission of Inquiry into the Rainstorm Disasters 1972, Government Printer, Hong Kong, November 1972.

Ref. 2 Report on Slope Failures at Sau Mau Ping 25th August 1976, Vols. 1, 2 and 3, Binnie and Partners (Hong Kong), December 1976.

Ref. 3 A Report on the Sau Mau Ping Landslip, November, 1972 in "Embankment Reinstatement at Hiu Kwong Street, Kwun Tong" Chief Engineer, Structural Design Division, Highways Office, PWD, Hong Kong.

Ref. 4 Notes on Fill Areas Adjacent to Public Housing Areas, unpublished report, Binnie and Partners (Hong Kong), September 1976.

Ref. 5 Building Proposals - Site Investigation and Earthwork Proposals, Circular Letter No. 60, Building Authority, PWD, December, 1972.

Ref. 6 A Guide to Site Investigation And Earthworks For Authorized Architects And For The Information Of Prospective Developers, Buildings Ordinance Office, PWD, August, 1973.

Ref. 7 General Nature of the Soils of Hong Kong by P. Lumb, Symposium on Hong Kong Soils, p19-32, Hong Kong Joint Group of I.C.E., I. Mech. E., and I.E.E., 1962.

Figure 1 - View of Catastrophic Mud Avalanche of 25 August 1976 at Sau Mau Ping
(Courtesy of the South China Morning Post Ltd. Hong Kong)

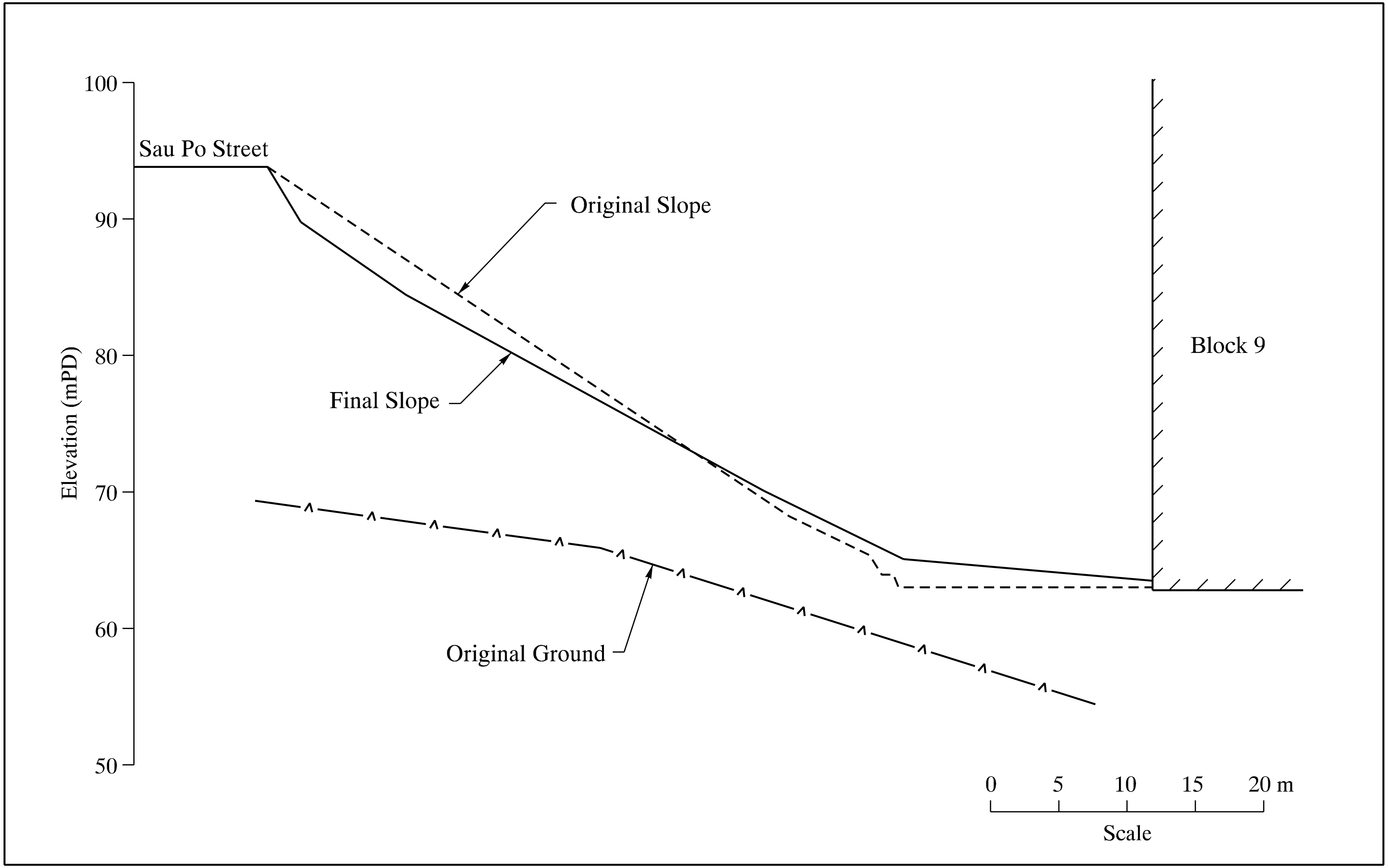


Figure 2 - Typical Section

APPENDIX A

MEMBERSHIP OF THE INDEPENDENT REVIEW PANEL ON FILL SLOPES

J. L. Knill	Professor of Engineering Geology Imperial College University of London United Kingdom
P. Lumb	Professor of Civil Engineering University of Hong Kong Hong Kong
S. Mackey	Professor of Civil Engineering University of Hong Kong Hong Kong
V. F. B. de Mello	Professor of Civil Engineering Polytechnic School of Engineering University of Sao Paulo Brazil
N. R. Morgenstern	Professor of Civil Engineering University of Alberta Canada
B. G. Richards	Principal Research Scientist Commonwealth Scientific and Industrial Research Organisation Australia

APPENDIX B

MEMORANDUM

To : Binnie and Partners (Hong Kong) Date : 14 December 1976

From : Independent Review Panel on Fill Slopes

Subject : Comments on Report entitled "Report on Slope Failures at Sau Mau Ping 25 August 1976"

The Panel has reviewed your report and is in general agreement with the factual content and interpretation dealing with the slope failures. However, the Panel has taken a more flexible approach with regard to the requirements for both remedial works and future design. The Panel also places different emphasis on certain items discussed in your report. The detailed comments of the Panel on the main body of your report are given below :

Section 1.1 The Panel prefers the use of the term mud avalanche rather than flowslide because it is a more graphic description with implications of high velocity.

Section 2.9 The Panel wishes to point out that it concurs with the emphasis on compaction, and wishes to point out that compaction is the most reliable method available to reduce the mobility of these landslides, and that it is important to stress this factor in any future design or remedial undertaking.

Section 6.8 The Panel wishes to caution against assuming that slumps initiate slowly and with warning.

Section 7.6(1) The Panel agrees that these water pressures in some instances can be important and that deep drainage would be appropriate. Nevertheless, the Panel doubts that water pressures at the bottom of the slope contributed to instability at the time of this failure because failure did not occur at the slope bottom.

Section 7.6(2) The Panel believes that the role of leaking pipes may be underemphasized. It should be noted that the actual stormwater drain at the top of the slope had been removed before it could be tested.

Section 7.6(7) The Panel wishes to point out that it places great emphasis on the influence of density and permeability gradients within layers of the fill. This variability can dominate the performance of the soil.

Section 7.10	The Panel is of the view that the role of compaction in improving soil behaviour is well established and that even modest compaction results in greatly reduced infiltration capacity and increased stability.
Section 9.7	The Panel has taken a less analytical point of view. It places the greatest emphasis on ensuring that fill be so compacted and drained that no mud avalanche or other catastrophic sliding will occur. It is less concerned with the need to eliminate all slides in fill under the conditions prevailing in Hong Kong.
Section 9.8	While this recommendation would be appropriate under ideal conditions, and where it is necessary to eliminate all slides, the Panel is of the view that it is excessively restrictive for Hong Kong. The Panel is of the view that a class of slopes can be defined which are amenable to treatment in a more routine manner.
Section 9.9	Consistent with the position outlined above, the Panel feels that many slopes can be reconstructed in an adequate manner by compacting the outer few metres of the fill and by providing drainage.
Section 9.10	The Panel does not approve of relying on an impermeable layer (chunam or gunite) placed on loose fill.
Section 9.13(4)	While the Panel agrees that instrumentation is valuable in many instances it wishes to stress that increased surveillance during intense rainstorms is more effective than reliance on instrumental readings in order to ensure that the appropriate maintenance measures are undertaken in time.
Section 9.13(8)	Provided that the control organisation recommended by the Panel works effectively, it remains to be seen whether this additional proposal is warranted.
Section 9.17	The Panel finds these requirements burdensome because it is possible to identify a class of routine problems that can be handled in a simpler manner.
Section 9.18	The Panel is of the view that “standard” designs may be used but that care must be taken to identify the exceptions and design accordingly.

APPENDIX C

SOIL BEHAVIOUR

Strength and Volume Change

C.1 The change in volume during deformation was measured for the Sau Mau Ping soil by shear-box tests carried out at the University of Hong Kong. Samples were prepared at various dry densities ranging from very loose to dense, loaded to a vertical pressure of 25 kPa (corresponding to a soil depth of about one metre), and then deformed by shearing the sample at a rate slow enough to allow unrestrained volume change. As the shearing displacement increased, the shear force resistance and the volume changes were measured up to failure of the soil, as shown in Fig. C.1 to C.5. Table C.1 and Fig. C.6 to C.8 summarize the results of these tests to show the influence of the dry density on:

(i) The ratio of Shear Force Q to Vertical Force P, at failure
(ii) The ratio of Total Change in Volume v to Initial Volume V, at failure
(iii) The incremental Ratio of relative volume change v/V with increasing Shear Deformation x, at failure

Table C.1 Results of Shear-Box Tests

Dry Density t/m^3	Strength Ratio Q/P	Volume Change v/V	Rate of Volume Change $\frac{d(v/V)}{dx}$
1.39	0.70	-0.06*	0
1.49	0.82	-0.005	0
1.57	0.88	+0.01	+0.5*
1.69	1.05	+0.01	+1.2
1.82	1.58	+0.01	+2.0

C.2 These results show that the dry density affects the volume change characteristics very strongly, although the strength is not affected much unless the soil is denser than a dry density of about 1.6 t/m^3. For loose soil, with dry densities lower than about 1.5 t/m^3, the soil contracts during shear until it reaches the failure point and then fails at constant volume. For soil with densities greater than about 1.5 t/m^3 the soil first contracts slightly at small strains but then expands significantly and, at failure, is still expanding.

* A negative value denotes contraction; a positive value denotes expansion.

Infiltration and Wetting of Soil

C.3 The depth to which the Sau Mau Ping soil could become significantly wet during rainstorms was determined from results of laboratory tests on a soil of similar grading to the Sau Mau Ping soil. In these tests (Ref. C.1) the rate of infiltration of water into vertical columns of dry soil was measured (the soil being compacted to various dry densities) and the depth of wetting in the soil columns was observed.

C.4 Provided that the rainfall rate is at least equal to the infiltration rate of the soil, then marked wetting-front will develop and will penetrate deeper and deeper into the soil until the rain ceases. The looser the soil the larger the infiltration rate, and the greater the rainfall rate necessary to produce a wetting-front. The wetter the soil before infiltration starts, the more rapid the rate of penetration of the wetting-front.

C.5 Assuming that no significant wetting occurs if the rainfall rate is less than the infiltration rate, and that the infiltration rate into the sloping fill surface at Sau Mau Ping is the same as for a vertical soil column (two reasonably conservative assumptions), the depth to which the wetting-front could have penetrated during the August 1976 rainstorm is as given in Table C.2. The minimum depth is for soil initially “dry”, at 50% saturation; the maximum depth is for soil initially “wet”, at 70% saturation.

Table C.2 Penetration of Wetting Front

Dry Density t/m^3	Depth of Wetting Front Metres	
	Minimum	Maximum
1.3	2.7	5.4
1.4	2.9	5.8
1.5	2.0	4.0
1.6	1.2	2.4
1.7	0.9	1.8

C.6 On the slope at Sau Mau Ping the dry densities in the upper zone of fill were in the range of 1.25 to 1.55 t/m^3 and the degree of saturation (measured after the rainstorms) ranged from about 50% to 70% at shallow depths. Consequently the range to which the soil could have become appreciably wetted is between about 2 m (dry density 1.5 t/m^3, saturation 50%) and 6 m (dry density 1.4 t/m^3, saturation 70%).

C.7 Reference

C.1 Wong Hong-Yau (1966) ‘Infiltration of Water into Unsaturated Soils’. M.Sc(Eng.) Thesis (unpublished), University of Hong Kong.

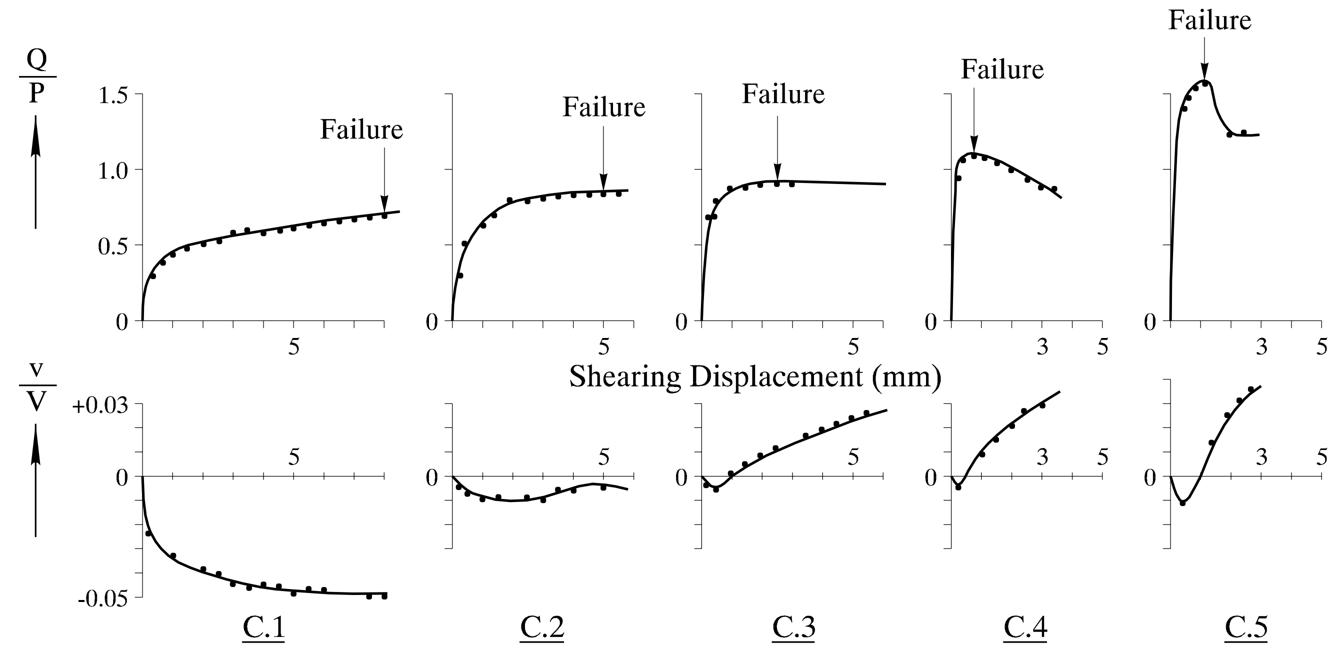
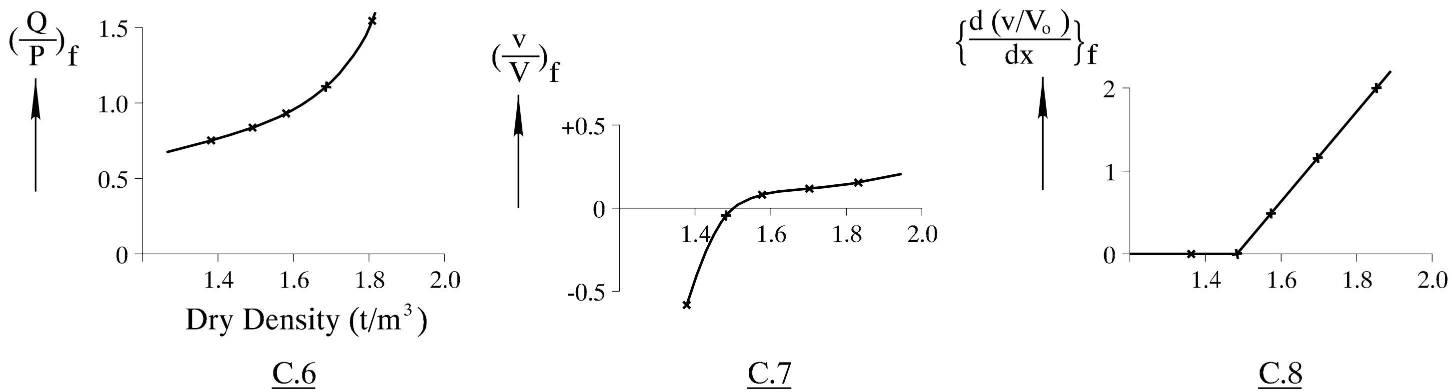


Fig.	Dry Density (t/m³)
C.1	1.39
C.2	1.49
C.3	1.57
C.4	1.69
C.5	1.82



Figures C.1 to C.8