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Slope stability problems in a part of western Singapore

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Abstract: Slope stability problems in residual soils and weathered rocks are described. These are related to periods of high rainfall, though no precise relationship between slope instability and rainfall has been established. Saturation of the near surface zone during prolonged periods of rainfall is offered as the main trigger of slope failure, saturation of the toe area being considered especially significant. This is considered in the light of infiltration rates, throughflow, permeability and rainfall characteristics. Long-term destabilisation of the slopes following regrading, stress relief and shear creep is offered as a possible mechanism causing the slope instability.

INTRODUCTION

This is a case study of slope instability on the campus of the Nanyang Technological Institute (NTI), Singapore. The campus is in the extreme western part of the island (Fig. 1) and covers about 200 hectares of low wooded hills. In August 1982, when observations were first made, the campus showed signs of old slips, some of

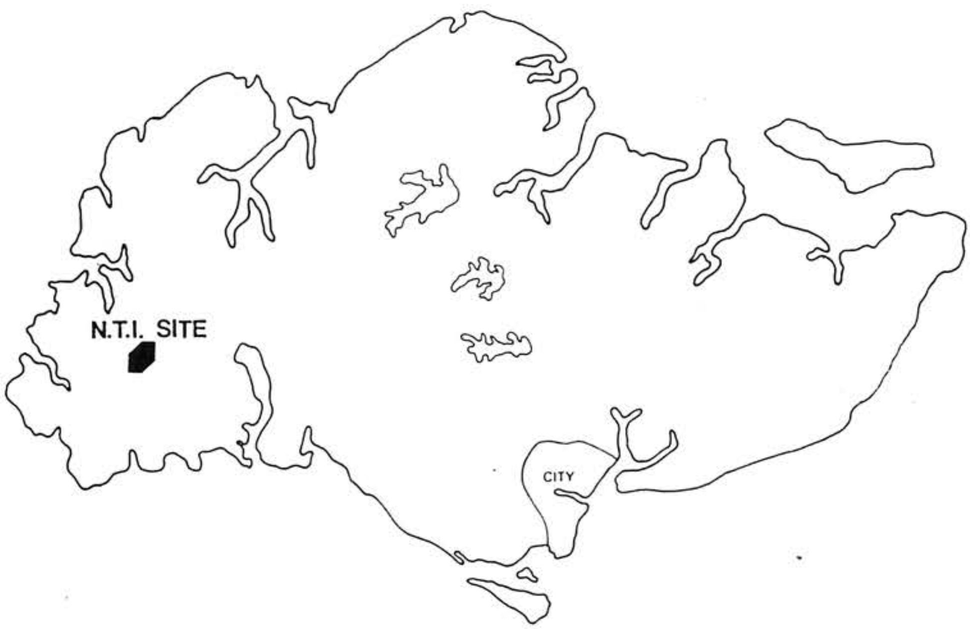

Fig. 1. Location of the Nanyang Technologial Institute (N.T.I.) campus.

which probably occurred at or immediately after the time at which the slopes were "landscaped" in the early 1950's. This is indicated by the presence of old retaining walls forming tiers up some of the slopes behind which are degraded backscars. Signs of slope creep were also in evidence, often indicated by deformed drain walls. After major rains in November 1982, January and March 1984, a large number of new failures developed. The form of many of these slope failures has been described by Pitts (1983).

Several of the slides show a significant amount of structural control of either the backscar usually by cleavage or jointing, or the failure surface by bedding planes. Additional influences, for example backfilled drains may also be present. Some recent events have included very wet failures in the form of mudlows.

The materials involved are residual soils and completely weathered rocks of the Jurong Formation details of which are given by Pitts and Kannan 1986. This formation comprises variably dipping siliclastic rocks ranging from conglomerates to a variety of mudrocks, the latter tending to dominate the succession at NTI. One particular argillaceous member which is a yellow with red mottling, fissured silty clay is particularly prone to slope failures. Slips in this material clearly indicate that the failure surface is not at the interface of the completely weathered rock and residual soil, but that it occurs just below the boundary within the completely weathered rock (Morgenstern and de Matos 1975).

Water tables are generally deep beneath the slopes, and records during the last rainy season indicate variation in the level of the water table of only about 1.0 metre.

RELATIONSHIP OF GROUNDWATER TO SLOPE STABILITY IN RESIDUAL SOILS

Slopes remain stable at relatively steep angles on the NTI Campus, most probably because of negative pore water pressures established in the near surface soils. Negative pore pressures normally reach 0.6 to 0.8 atmospheres in the residual soil cover during drier periods (Rahman, personal communication). Close to trees, the negative pore pressures may be higher. Trees have a "wilting limit" of –15 atmosphere. Hence, the gravitational effect on the flow net, the weight or increase in weight of soil during saturation, and even slope geometry may have little effect on stability.

Development of the flow net, advance of the wetting front and destruction of negative pore pressures depend on the characteristics of a particular storm and its effects. Flow net development also depends on the degree of saturation of the residual soil mantle prior to the storm; i.e. recent rainfall history (Morgenstern and de Matos, 1975).

Slopes formed from residual soils on at least some lithologies of weathered Jurong Formation drain well by throughflow (interflow). This is indicated by the variable particle size distribution and permeability characteristics for one example close to the boundary of weathering grade V and grade VI materials illustrated in Fig. 2. The origin of the "intermediate zone" is not known, but bears greater similarly texturally to the Grade V material than the residual soil. It is characteristically 20 cm or so thick and

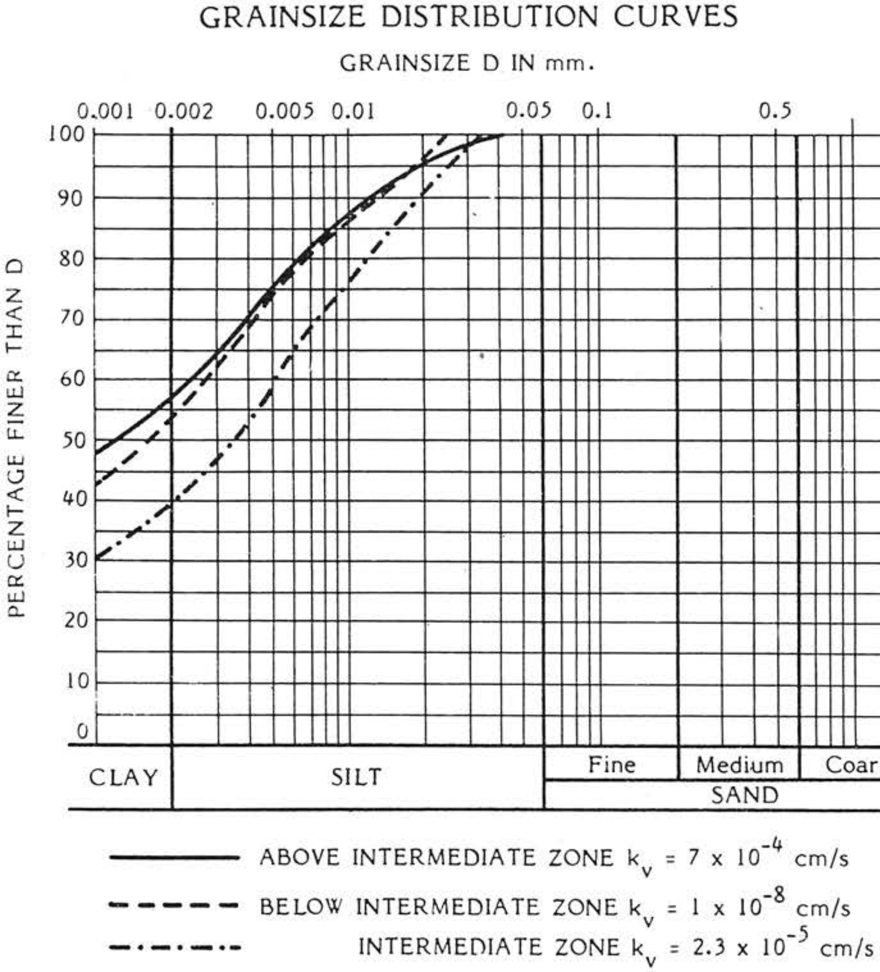

Fig. 2. Particle size and permeability characteristics close to the boundary of residual soil and completely weathered rock.

frequently possesses a set of sub-vertical fissures. The effect of this structure on the permeability may be partially lost by testing the coefficient of permeability in the laboratory. Infiltration for 8 to 10 hours is required to reach steady state on moderate slopes in materials of this type (Rahman, personal communication). Rainfall seemingly needs to exceed the throughflow rate so that the wetting front can advance significantly.

The flow net develops from the crest to the toe of the slope, therefore, so does the wetting front. With an "impermeable" layer parallel to the slope formed from the main mass of the Grade V weathered material, flow will always be essentially parallel to the slope given a water source at the crown of the slope. This is generally the case on the

NTI campus as many slopes are terraced. Hence, the equipotential lines, or lines of head crop, will be approximately normal to the slope. Full flow nets will develop in saturated ground only with prolonged rainfall. Significantly therefore, negative pore pressures will be maintained longest in the toe of the slope and will be destroyed only in the most extreme cases of rainfall.

So, slope failures tend to occur only when groundwater flow from crown to toe of the slope is close to being fully developed, significantly reducing the negative pore pressures in the important toe region of the slope. This means that the position of the wetting front is unlikely to have physical significance with respect to the failure surface position since the pressure drops are normal, not parallel to the slope (Morgenstern and de Matos, 1975). It is more likely that the advance of the wetting front will reduce negative pore pressures to a sufficient extent to cause failure. It is not likely that the failure surface develops at a sharp interface between standard and partially saturated ground (Morgenstern and de Matos, 1975).

PATTERNS OF RAINFALL

Negative pore pressures in the soil mantle are destroyed by infiltration from the ground surface. To saturate the soil, rainfall intensity has to be at least as great as the permeability of the soil. For the soils in question this represents an intensity of 3 or 4 mm/hour, a figure frequently achieved. However, the duration of the storm is of course important, especially in view of the good throughflow characteristics of the slopes.

Ramaswamy and Aziz (1980) maintain that in Singapore, daily rainfall of 150 to 200 mm with an intensity exceeding 20 to 30 mm/hr are critical. In fact, this is a gross over-estimate, and the evidence probably suggests that no simple relationships can

TABLE 1

PATTERNS OF RAINFALL PRIOR TO PHASES OF SLOPE INSTABILITY

NOVEMBER 1982	
20th	80.7 mm
23rd	60.0 mm
24th	121.9 mm
27th	65.8 mm
SEPTEMBER 1983	
13th	5.9 mm
14th	61.4 mm
15th	21.2 mm
JANUARY 1984	
27th	11.0 mm
28th	0.7 mm
29th	12.1 mm
30th	59.3 mm
31st	24.0 mm

account for the incidence of slope failures. A daily rainfall of 150 mm has a return period of about 5 years for Singapore island as a whole. The failures of November 1982 were related to daily rainfall of 12 mm, which has a return period of less than two years for the island as a whole. The slips of 30 January 1984 resulted from a far lower rainfall than this, and the single slip of September 1983 from a similarly much lower rainfall (Table 1). So, although more slips occur with high magnitudes and intensities of rainfall, significant numbers of events can occur from quite moderate falls.

SHEAR STRENGTH

The effect of reducing negative pore pressures in a slope is to decrease the apparent cohesive strength of the soil and possibly, by a smaller amount, its angle of shearing resistance. It is probable that during drier or "normal" periods, that the effective stresses are far greater than the total stresses in the soil, accounting for the continued stability of many slopes at high angles. As the negative pore pressures are reduced, the apparent cohesion also decreases, and in a saturated state would probably be approximately zero, and correspond to the drained conditon. Some work undertaken at the Asian Institute of Technology (Ganeshan, 1982) highlights the significance of apparent cohesion at low normal stresses on remoulded soils. These results may well be under-estimates as natural cementing of the soils within the residual soil and completely weathered rock or features of the soil structure/fabric may produce still higher values of apparent cohesion. In remoulded samples, these effects would have been destroyed. Tests to check this are to be carried out at NTI on intact samples at an appropriate range of natural moisture contents.

Some strength tests on saturated samples have already been undertaken. In each case, the shear strengths are very low considering the geometry of the slopes supported,

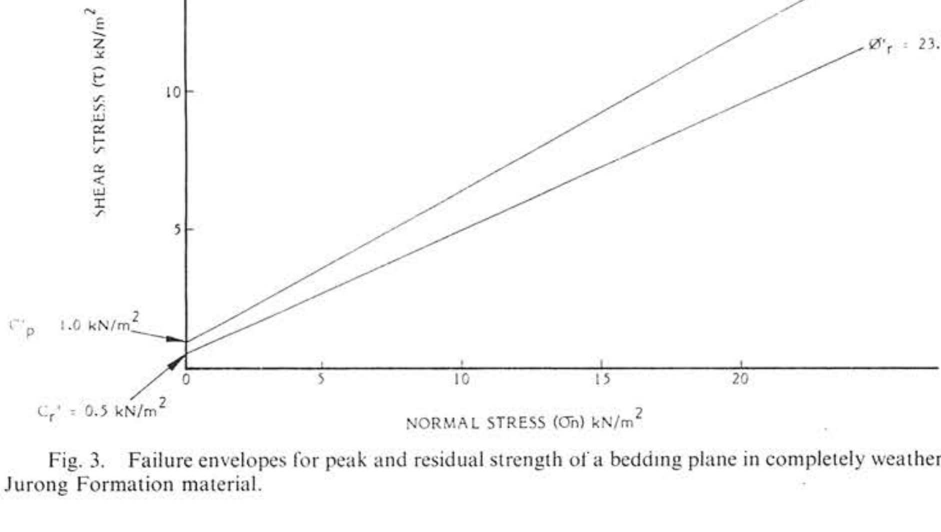

Fig. 3. Failure envelopes for peak and residual strength of a bedding plane in completely weathered Jurong Formation material.

commonly about 35° (Pitts 1983). In the case of the peak strength failure envelope illustrated in Fig. 3, this represents a bedding plane slip with some quite unusual features. The bedding was dipping at only 10° almost directly out of the face. In most cases it is felt that partial or total reduction of negative pore pressures is sufficient to cause failure. However, in this case, it seems necessary to invoke the generation of positive pore pressures as well. Even allowing for water flow along the bedding planes feeding from a backfilled drain, which will perhaps reduce the effective angle of shearing resistance (ø') by about half, it is difficult to explain failure without positive pore pressures. A standing head of water in the backfilled drain itself will also have added to the destabilizing moment.

DISCUSSION AND CONCLUSION

As is to be expected, there is an obvious although unspecified relationship between slope instability and rainfall in Singapore. In the example of the NTI campus presented here, the relationship is not a simple one. The three maps (Figs. 4a, b and c) indicate the distribution of landslips with time. During the first 30 years following the landscaping of the campus, landslips were relatively infrequent. A series of small slips occurred from time to time. Creeping slopes were an obvious feature in a number of locations.

Recent major occurrences of slope failure have taken place in November 1982, January 1984 and March 1984, so that the density of landslips on the campus has increased markedly. It is therefore possible that the incidence of slope instability is increasing with time, even though the rainfall events are no more extreme than several which have occurred during the period since 1950 i.e. the strength threshold of the slope is decreasing. It is suggested that a process of long-term destabilization is taking place in a number similar to that described by Skempton (1970). There is clear evidence from the construction site of the new NTI campus that excavation of the slopes in the Jurong Formation around NTI causes stress relief cracks to open. It is proposed that this is the initiation of significant shear creep leading to long-term failure of the slopes. Final failure of the slopes is then triggered by rainfall of magnitudes high enough to reduce negative pore water pressures in the toe areas of slopes (and hence the apparent cohesion of the soil) sufficiently for shearing to occur.

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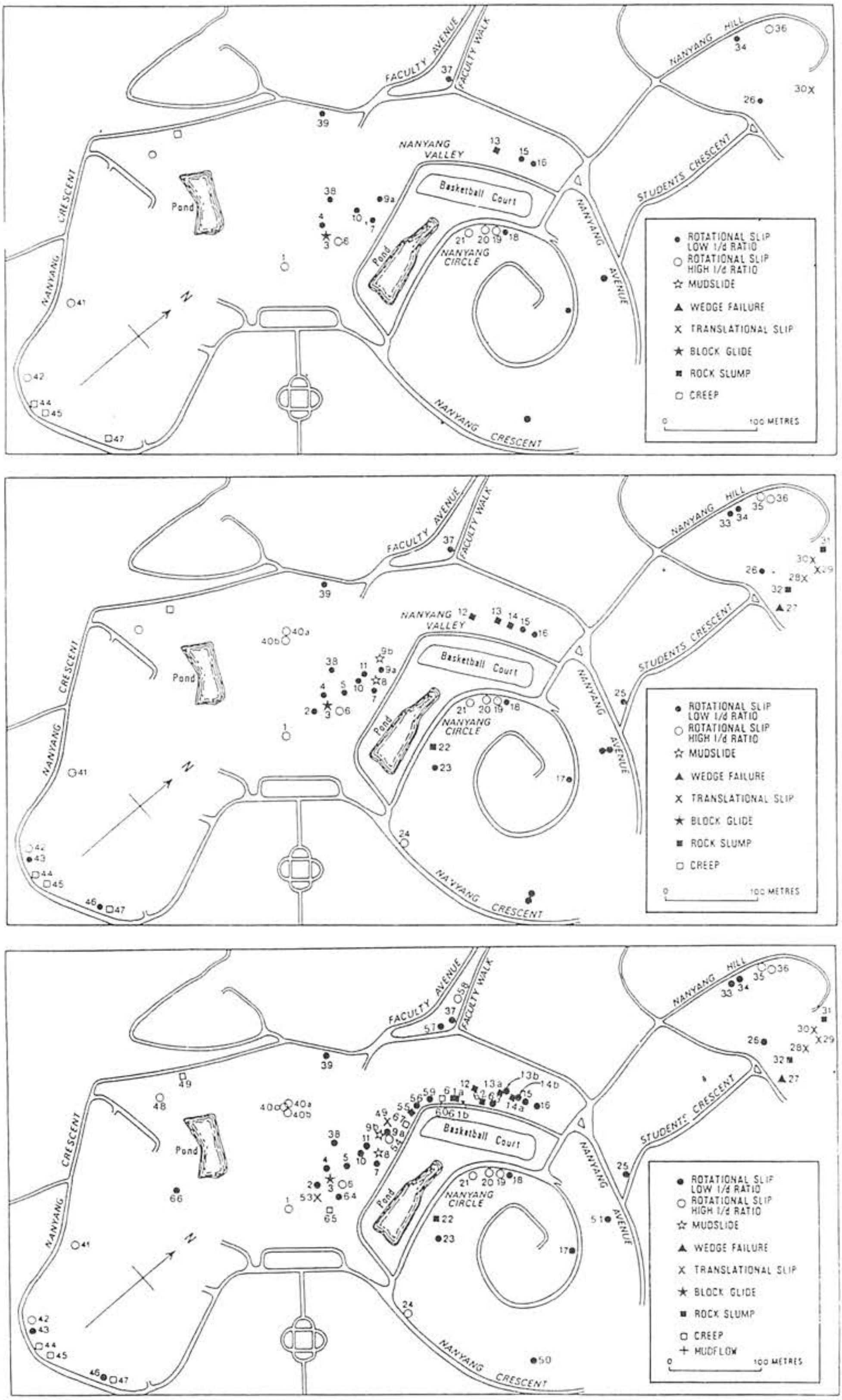

Fig. 4 The distribution of landslips and their classification (from top to bottom), (a) prior to November 1982, (b) after the slips of November 1982 (c) after the slips of January and march 1984.

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