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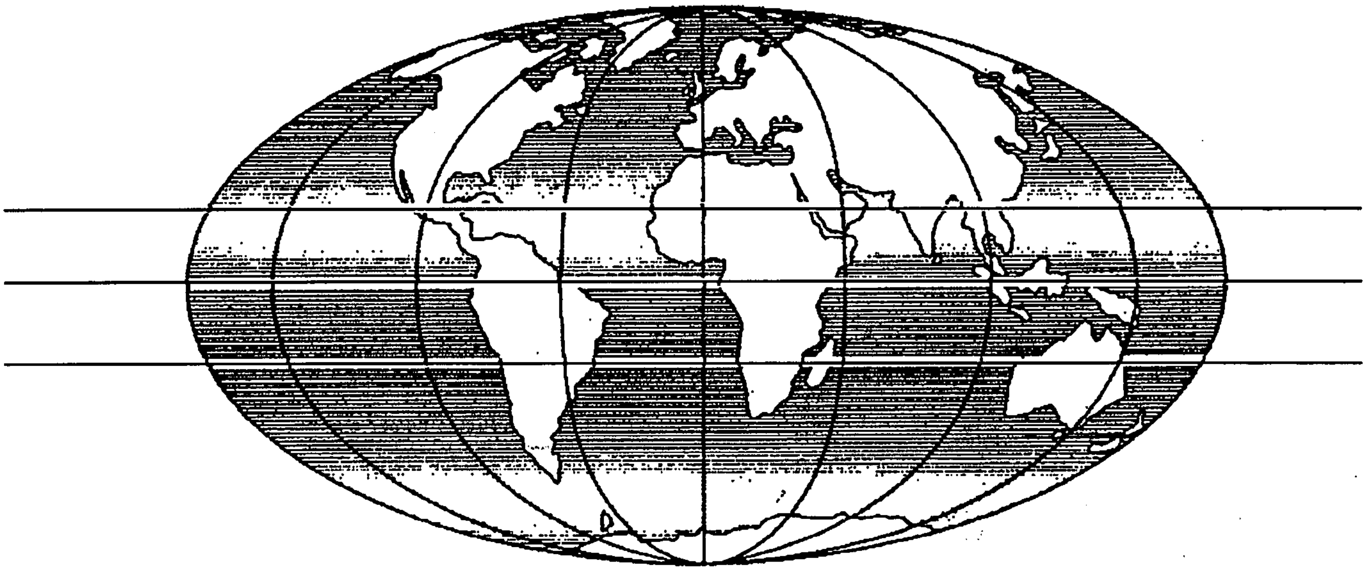
by W Heath, B S Saroso and J W F Dowling



Overseas Centre
Transport Research Laboratory
Crowthorne Berkshire United Kingdom

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HIGHWAY SLOPE PROBLEMS IN INDONESIA.

by

HEATH W. Transport & Road Research Laboratory, (UK)
SAROSO B.S. Institute of Road Engineering, (Indonesia)
DOWLING J.W.F. Transport & Road Research Laboratory (UK)

ABSTRACT.

In Indonesia, and many other mountainous tropical countries, slope failures create significant difficulties for road construction and maintenance. As in most other aspects of highway engineering such problems can only be dealt with empirically by applying the experience that has come from effectively dealing with similar problems elsewhere. In applying such experience the first stage is to identify the main type of instability in terms of the mechanisms and general characteristics of failure. This approach was used in one part of Indonesia, Java, and involved an overall study of the extent of slope failure problems together with a detailed investigation of groundwater, soil properties and the depth and rates of failure at a number of representative landslide sites. From this research the principal mechanism of failure, that caused most damage to roads in Java, was identified.

INTRODUCTION.

1. In many countries, particularly in South-east Asia where major roads are often constructed in very mountainous terrain, major problems involving slope failure can occur after the road has been opened to traffic. Within two to three years of construction the costs of dealing with such problems may, on occasion, exceed the original expense of building the road. This situation arises because the problems of slope instability and its effect on the life of a road is difficult to predict despite recent advancements in slope engineering.

2. The reason why engineers are unable to predict such problems, and provide adequate designs accordingly, is because of the wide range of complex factors involved. For example in South-east Asia many of the new road projects traverse large areas of steep terrain within which many potential slope failure situations are likely to occur. Within such units of terrain the conditions influencing instability may vary considerably and also actual failures may stem from a wide range of triggering mechanisms including very high rainfall, seismic activity, erosion or the disturbances caused as a road is constructed.

3. In terms of road engineering there is generally little opportunity to investigate all of these effects, on individual slopes, and consequently it is seldom possible to develop reliable models that can be used to express the likely extent of potential instability. However from experience of slope problems collected, there are distinct patterns of geology, ground

conditions, rainfall and slope geometry which seem to govern the distribution and characteristics of failure. Such patterns of failure can be used to develop empirical guildlines related to potential risk assessment and slope control. However first it is essential to determine, by regional studies and detailed site investigations, what the general characteristics and patterns of failure are for a particular region.

4. With the aim of identifying the key factors that influence wide spread highway slope instability in Indonesia, a joint study was undertaken by the Transport and Road Research Laboratory, United Kingdom, and the Indonesian Institute of Road Engineering. Because of the vast area and wide range of conditions existing in Indonesia the present study was largely restricted to one region, Java, with its extensive network of roads. For the purpose of the study a number of slope failure sites were chosen where detailed investigations, based on instrumentation results and observations, could be made. This report describes the sites, the methods used to collect information and the relative value of such techniques in terms of further slope failure investigations in similar terrain. Finally the influence on failure, both in terms of climatic conditions and soil properties, and the mechanisms involved is compared with similar situations reported in the literature.

DETAILS OF THE STUDY.

5. A study into the problems of slope failure and its effect on road construction and maintenance in Indonesia was carried out at the Institute of Road Engineering in Bandung, Indonesia. The main field work was undertaken between, 1980-82 and 1983-85, and consisted of measuring and observing the main features associated with slope failure at a number of selected sites. Prior to this a study was made of the geology of the landslide sites and all information relating to slope instability reviewed.

The geology of Java;

6. The island of Java forms part of the Sunda-arc group of islands which are all of a similar geological age consisting of Late-Tertiary and Quaternary limestone, sandstone and shale sediments. Tectonic uplift and volcanic activity, which commenced in this period, is the result of a subduction of part of the Pacific-plate beneath the Sunda-arc. This is still continuing and as a result soils derived from volcanic ash and debris cover much of the landscape. It is also responsible for the rugged mountainous terrain in the southern part of the island, which consists mainly of uplifted and folded sediments, and also a continuous belt of active volcanoes, with uplifted sediments on their flanks, in the central zone. In the north the terrain is flat consisting of recently emerged coastal sediments. Highway development is almost completely restricted at present to the flat coastal planes in the north and the lower flanks of the volcanic peaks in the central zone. Much of the highway slope failure occurs in areas where colluvium, which originates mainly from volcanic-breccia or limestone, overlies deposits of poorly drained shale. A comprehensive description and review of the geology of Indonesia has been carried out

by van Bemmelen (1949) and this provides a more detailed insight into the extremely complex nature of the terrain.

Extent of slope failure problems;

7. At the commencement of the study it was known that slope failure was very common in Indonesia but there was little understanding about the characteristics of such failures. The only previous references to slope failure problems were those by van Bemmelen (1949), which mainly related to lahar slides, and Wesley (1977) in which the characteristics of failure in volcanic residual soils are described. During the study an overview of slope failure problems in South-east Asia, Brand (1984), was published and this provided the first appraisal of the scale of slope failure problems in Indonesia. Table 1. shows the range of slope failure problems existing in Indonesia and their effect on road development.

TABLE 1. Summary of slope failure problems in Java.

TYPE OF FAILURE.	TERRAIN COMPONENT.	TYPE OF SOIL/ROCK.	RISK FACTOR TO ROADS.	COMMENTS.
1) HOT LAHAR	VOLCANIC ERUPTION	HOT VOLCANIC WATER & MUD	SMALL	GENERALLY INFREQUENT; AREAS OF RISK ARE DEFINED AND ROAD DEVELOPMENT RESTRICTED.
2) COLD LAHAR	VOLCANIC SIDE SLOPES	SATURATED MUD AND DEBRIS	MODERATE	RISK EXTENDS OVER LARGE AREAS. MINOR ROADS OFTEN DAMAGED.
3) STEEP ROTATIONAL SLIDES	MID-SLOPE	RESIDUAL SOILS.	MODERATE	RISKS ARE MAINLY TO SMALL MOUNTAIN ROADS.
4) CREEP AND TRANSLATION SLIDES.	LOWER FOOTSLOPE	CLAYEY SOILS	HIGH	MAJORITY OF SLOPE PROBLEMS ARE OF THIS TYPE.
5) CUT ROCK SLOPES	UPLIFTED SEDIMENTS	WEAK SHALES & MARLS	LOW	SOME PROBLEMS, (MAINLY ANGLE OF BEDDING INTO CUT FACE) INVESTIGATED IN SUMATRA.
6) CUT SOIL SLOPES	MID-SLOPE	RESIDUAL SOILS	LIMITED	MAINLY EROSION PROBLEMS DUE TO SPLASH-BACK AND RUN-OFF
7) SIDE-SLOPE EMBANKMENTS	SIDES OF STEEP SLOPES	VOLCANIC MATERIAL	INSUFFICIENT INFORMATION	METHODS OF PARTIAL CUT AND FILL HAS BEEN USED IN THE PAST. SOME SLOPES NOW RISKY

8. Of the range of problems identified in Table 1. those listed under the headings 1 to 4 can be described as natural failures and 5 to 7 as failures reflecting some problems in slope design. The characteristics of natural failures are shown in Table 2. The present study has concentrated on these natural slope failure events as they cause the most significant problems to roads.

Highway slope problems:

9. In terms of highway construction and design the extent of problems connected with unstable slopes depend upon; 1) the steepness of terrain, 2) the amount of rainfall, 3) the presence of groundwater, 4) the nature

and degree of weathering of slope materials, 5) the design standards of the road and 6) the methods used to construct the road. Table 3. shows the relevance of these factors.

TABLE 2. Characteristics of slope failure in Java.

SLOPE FAILURE	SLOPE ANGLES	SLIDING VELOCITY	MECHANISM OF FAILURE.	EFFECT ON ROADS.
1a) LOWER SLOPES.	$12-20^0$	1-15mm/day	SLOPE CREEP AND TRANSLATIONAL SLIDING.	HIGH RATE OF SUCH FAILURES.
1b) FOOT SLOPES	$4-6^0$	10-100mm/year	CREEP ONLY.	MODERATE NUMBER OF FAILURES.
2) ACTIVE FAULTS	$20-60^0$	1-5mm/week	COLLAPSE AND SLUMP.	UNDETERMINED.
3) LAHAR	5^0-45^0	3-4m/sec	AVALANCHE SLIDES.	INFREQUENT.
4) RESIDUAL SOILS	$40-70^0$	0.5-1m/sec	STEEP ROTATIONAL	MAINLY MINOR ROADS AND CUT SLOPES.

TABLE 3. Factors associated with highway slope problems.

FACTOR	INFLUENCE	COMMENTS
1) SLOPE STEEPNESS	VERY STEEP TERRAIN IS WHERE MOST RISK OCCURS	RAPID FAILURES WHICH ARE HAZARDOUS AND INVOLVE HIGH REPAIR COSTS ARE MORE COMMON IN VERY STEEP TERRAIN.
2) RAINFALL	HIGH INTENSITY STORM RAINFALL	GENERALLY MOST SIGNIFICANT WHEN RATES EXCEED 2,500 mm/YEAR; or 70 mm/HOUR.
3) GROUNDWATER	IMPERMEABLE SHALES/HIGH DISCHARGE FROM UPSLOPE	TRAPPED GROUNDWATER MEANS SOILS MOSTLY SATURATED AND DEVELOPMENT OF WEAK CLAYS,
4) WEATHERED SLOPE MATERIALS	WEAK CLAY MATERIALS; FRAGMENTED ROCKS	SOILS WITH LOW SHEAR STRENGTHS. PARTICULARLY SMECTITE CLAYS. WEAK AND FRAGMENTED ROCKS PARTICULARLY SHALES.
5) DESIGN FACTORS	GRADIENT OF ROAD/ SLOPE ANGLES.	STEEPNESS OF CUT SLOPES IS INFLUENCED BY CHOSEN MAXIMUM GRADIENT OF ROAD ALIGNMENT
6) CONSTRUCTION METHODS	AMOUNT OF CUT AND FILL;	ROADS MAY BE CUT INTO SLOPES OR FILL USED ON THE SIDE OF SLOPES. DISTURBANCE TO DRAINAGE AND VEGETATION CAUSES PROBLEMS.

The highways and their slope features in Indonesia:

10. In Indonesia the majority of roads are constructed on shallow slopes and little road development has extended into the steep mountainous regions. Despite this slope failures are extremely common although there are few major catastrophes and the main problems relate to highway maintenance costs. The amount of annual rainfall is high and not infrequently there are exceptional storms when a significant number of failures occur. The main slope materials tend to be colluvium which, because of high temperatures and rainfall, has rapidly weathered to

produce a range of weak cohesive soils.

11. As the present generation of roads tend to follow the natural topography the alignments are often steep presenting problems to traffic, on steep gradients, but avoiding the need for large cuttings and embankments. In terms of construction major problems occur after roads are widened. Also new roads attract urbanization and land-use and these factors create large scale changes to the characteristics of slope drainage and so affect stability. Areas of slope failure in Java encompass long sections of road ranging in length between 4 to 9 km. Within such zones there may be as many as twenty individual failure sites, see Figure 1 .

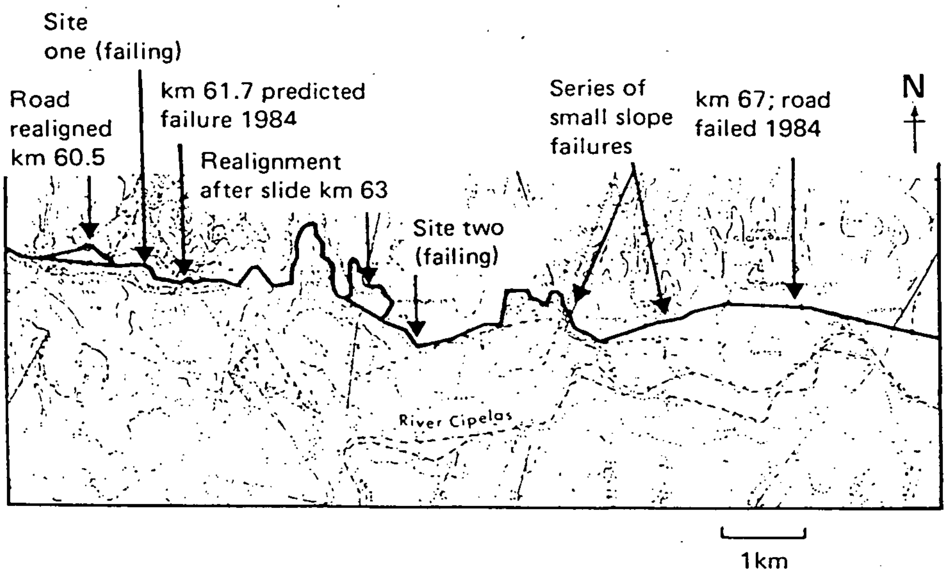


FIGURE 1. Slope failures on one section of Java's road network

12. Failure is commonly a circular slump of up to 30 metres in length that is preceded by a gradual deformation and change in camber of the pavement. The period of this deformation and cracking depends upon the plasticity of the asphalt and may take place over months or years. However it can be recognised so that areas of potential failure are identifiable and the opportunity exists to carry out repair work before the road collapses. Plate 1. illustrates a road two months before failure and subsequently the damaged section with the pavement collapsed in a circular slump to a typical depth of between 0.5 and 2 metres.

13. The road collapse is generally the result of much more extensive failures, involving creep and translational sliding, which occurs on the slopes below the road and this may continue for many years before a loss of support puts the road at risk. The slopes where such failures occur generally have good drainage within the first few metres of colluvium and are underlain by an impermeable layer of shale. Slope angles are generally between 12 and 20 degrees. Identifying the movement on such slopes is extremely difficult without suitable instrumentation such as inclinometers because there is very little surface evidence and vegetation tends to obscure what there is.

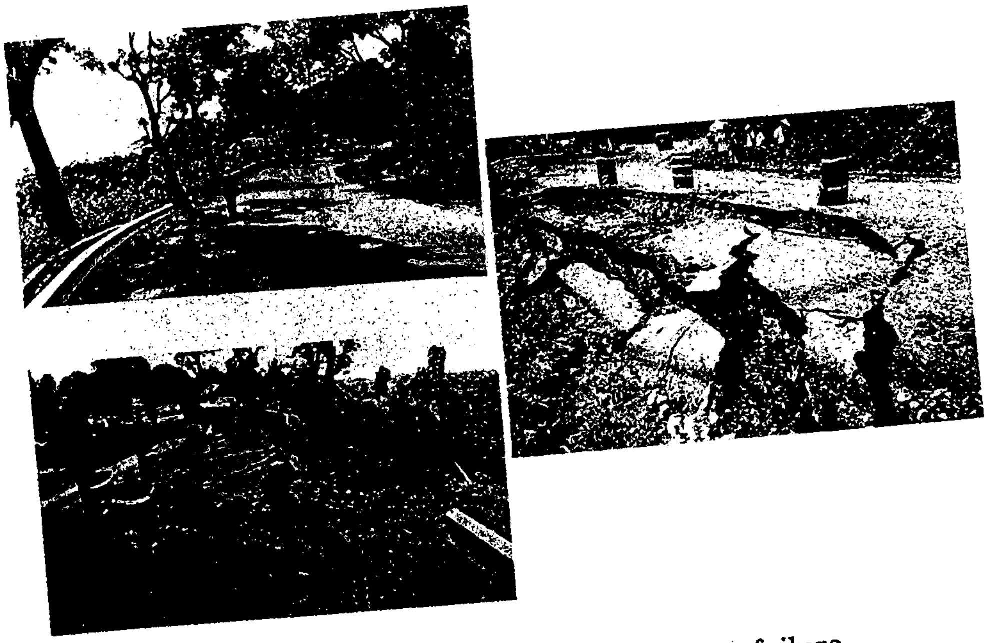


PLATE 1. Section of a road prior and after failure.

Selection of test sites.

14. Table 4. provides a list of the sites studied. Prior to selecting these sites a detailed appraisal of all highway slope problems in West and Central Java, was carried out on a large number of slopes.

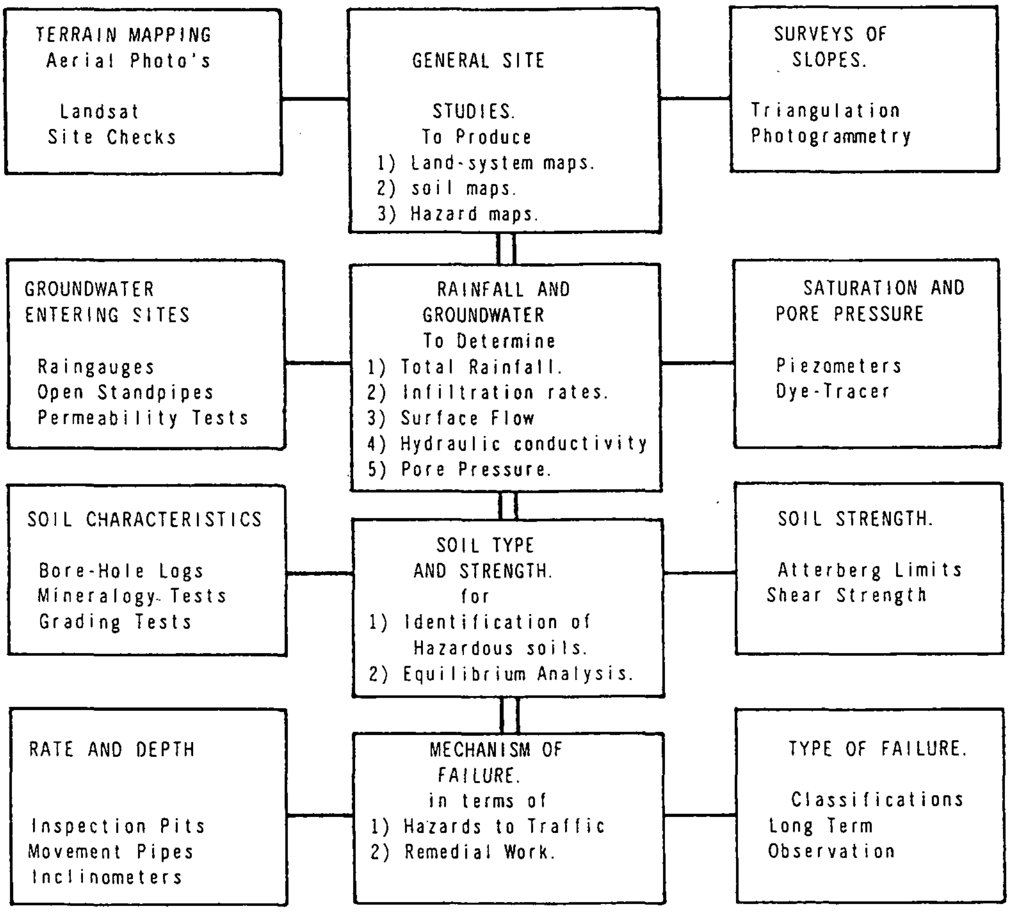
TABLE 4. List of slopes investigated.

SITE	ROAD LOCATION	CHARACTERISTICS OF UPPER SLOPE.	UNSTABLE PART OF SLOPE.	EFFECT ON ROAD.
1) km 61 TO 64	BANDUNG-CIREBON ROAD	STEEP SLOPES OF VOLCANIC BRECCIA	COLLUVIUM AND SHALE	DEFORMATION; CIRCULAR SLUMPS OCCUR IN ROAD
2) km 21 TO 24	BANDUNG-JAKARTA ROAD	STEEP ANTICLINE OF REEF LIMESTONE	COLLUVIUM AND SHALE	CIRCULAR SLUMPS AS ABOVE.
3) km 53 TO 60	WELERI-SUKAREJO ROAD	FOLDED BRECCIA AND SEDIMENTS	COLLUVIUM AND SHALE	MAINLY SLUMPS BUT ALSO LATERAL SLIDES.
4) km	CIANJUR-SELATAN ROAD	FOOTSLOPE OF LARGE VOLCANO	COLLUVIUM AND SHALE	ROAD ADJACENT TO MASSIVE FAILURE SCARPS CAUSED BY MANY FAILURES.
5) km 87 TO 88	JAKARTA-BANDUNG ROAD	STEEP RESIDUAL/ VOLCANIC SOILS	OLD SLIDE DEBRIS	ROAD THOUGHT TO RUN ACROSS ACTIVE FAULT
6) km 45 TO 55	BANDUNG-CIAMIS ROAD	ANDESITE BRECCIA AND DEBRIS	COLLUVIUM AND SHALE	DEFORMATION; CIRCULAR SLUMPS OCCUR IN ROADS

INVESTIGATION OF SLOPE PROBLEMS.

15. The study of the selected sites including four main investigation phases; a desk study, instrumenting slopes to determine groundwater, collecting and testing soil samples and determining the depth and rate of failure, see Figure 2

FIGURE 2. Main tasks of the landslide study.



16. These studies consisted of 1) An overall study of the terrain characteristics associated with unstable slopes. This mainly relied upon observation but use was also made of techniques such as aerial photography, terrestrial photogrammetry and both hydrological and geological terrain mapping. 2) A study of slope hydrology using rainfall data, open standpipes, Casagrande piezometers and dye tracer techniques. 3) Soil investigations based principally on laboratory testing of borehole samples to determine grading, plasticity, moisture contents, bulk and dry densities, clay content, mineralogy and shear strength. 4) Methods to determine both the rate and depth of failure including surface marker pegs, surveys and inclinometers.

General site studies.

17. Surveys of all slopes were carried out in order to produce maps and profiles from which the main slope characteristics could be determined,

further changes could be recorded, and the employment of instrumentation and sampling planned. Techniques of photogrammetry were tried following the successful application of such methods in other countries, Heath and Dowling (1978), but proved to be less successful on the shallow slopes in Indonesia. The advantages and limitations of such techniques are described by Heath (1989).

18. Terrain and soil mapping of areas surrounding landslide sites was based on Landsat satellite images and black and white survey photographs at scales of 1;60,000, Saroso, Dowling and Heath (1983). In terms of the individual landslides these small scale images proved to be of particular value in interpreting detail at Site 3. Part of the landsat image of this area is shown in Plate 2.

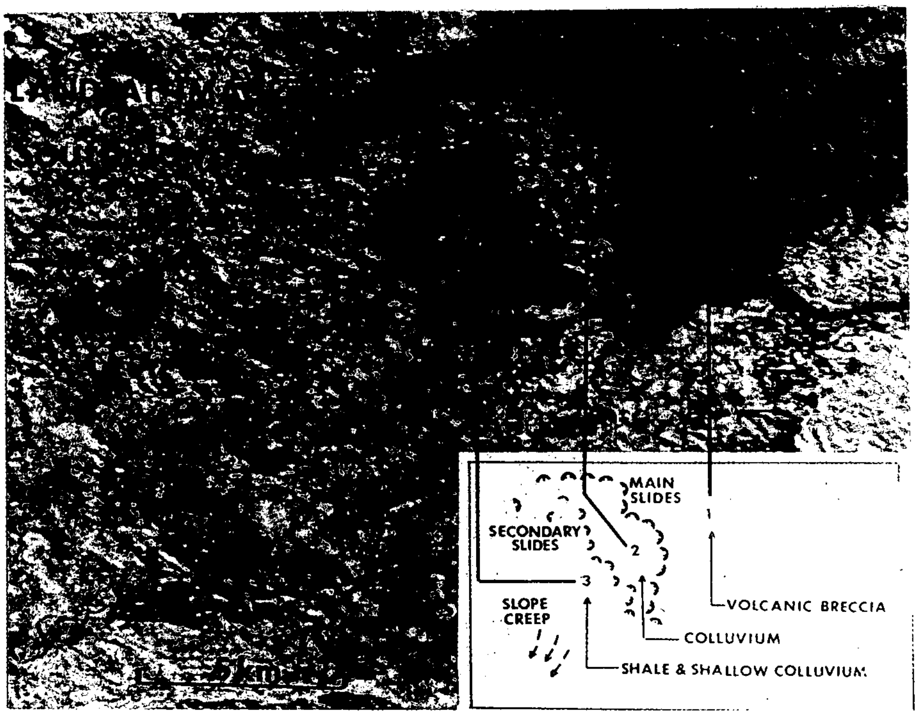


PLATE 2. Landsat image of southern part of Java.

19. The main failure scarp is composed of many ancient slump failures which occur at the edge of the steep volcanic breccia section of the slope, Zone 1 on the image. These individual failures are typically 25 to 30 metres in height and up to 50 metres long. The overall circular pattern of failures results from slope drainage characteristics with the main flow of water, and hence greatest instability, in the centre of the scarp. Within Zone 2. there is secondary failure involving deep colluvial material above shale and the failure mechanism is likely to be deep seated translational sliding and creep. These colluvial deposits, through processes of erosion and sliding, thin out into Zone 3. so that in this location shallow failures are common place. These secondary failures in Zones 2 and 3 are similar to events commonly occurring along much of the highway network in the rest of Java. Figure 3. illustrates the zones and the general position of roads in such terrain.

20. In order to obtain more detail of the failing slopes large scale colour aerial photography was produced of four sites using a simple low cost technique, described by Heath (1980). An examination of this photography was significant in highlighting relic drainage features which contributed to failures occurring at Site 1., kilometre 64, and are described by Saroso, Dowling and Heath (1984). In this case gradual failure occurs on the lower slope where toe material is eroded by a river. This leads to slumps of the road adjacent to where groundwater is entering the weakest zones. Despite the use of many remedial techniques at this site, including concrete piles, retaining walls and lightweight fill, the main problems, involving the failure of the lower slopes and excess water directed onto the road, have not been tackled and consequently failure continues to occur.

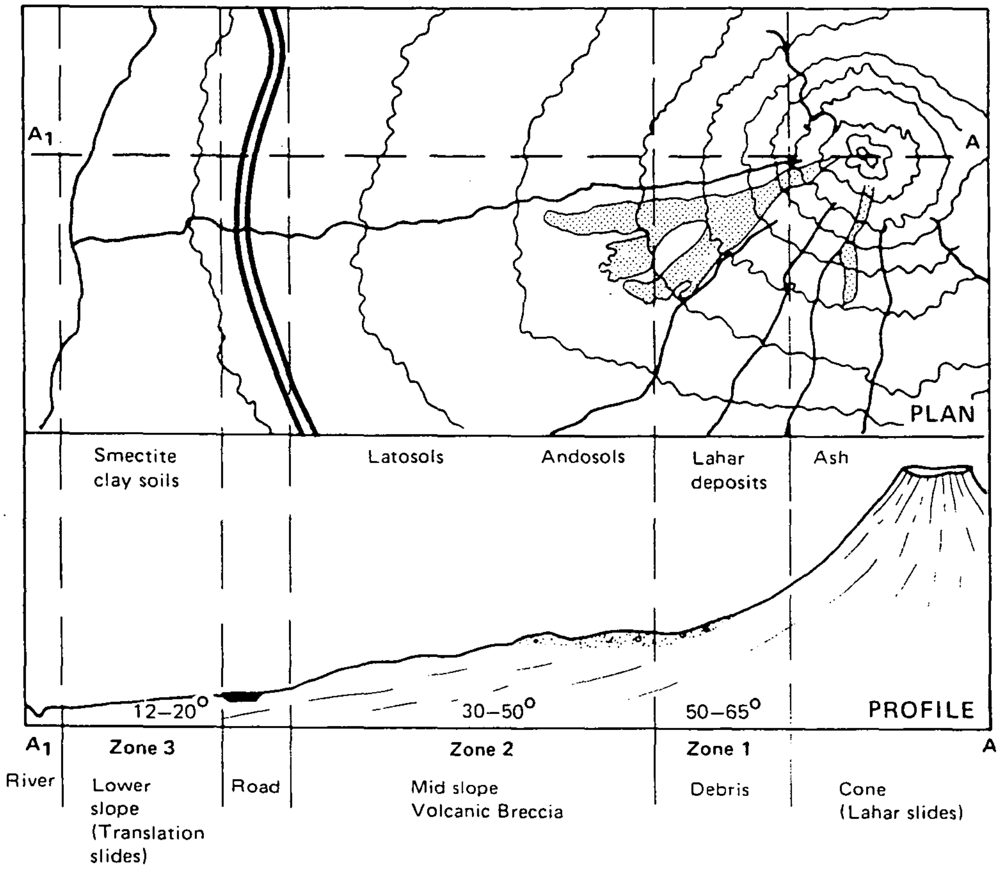


FIGURE 3. Plan and profile showing zones of instability.

21. At Site 3., on the edge of a massive upthrust block of limestone, slope problems are frequent. Maps of the alignment and an examination of aerial photographs indicated that the rainfall catchment and drainage features of the limestone both provide groundwater concentrations into these unstable sections of road, see Figure 4.

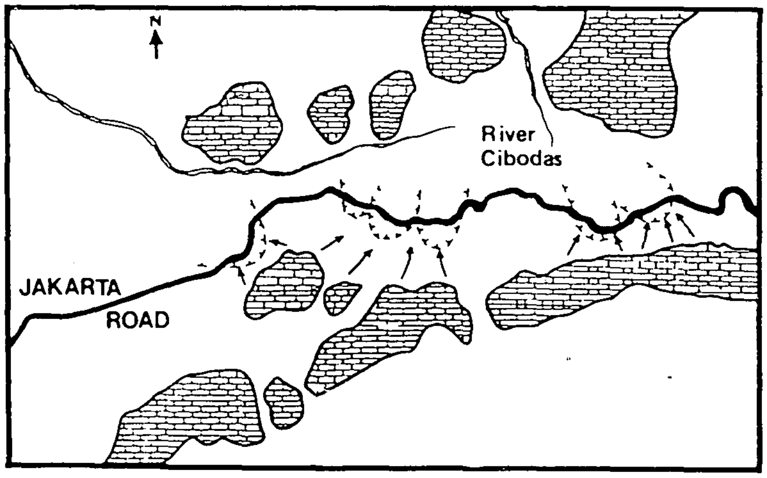


FIGURE 4. Groundwater concentration into failing sections of road.

22. This type of problem was identified by Deer and Patton (1971) who suggested that the characteristics of colluvium, derived from hard rock sources, was to be coarse graded at the top, thereby allowing the free ingress of groundwater, and, being more weathered, finely graded towards the bottom where the hydraulic conductivity is consequently restricted. This type of permeability gradient would provide a rapid back-up of soil saturation in the slope during periods of heavy rainfall.

Climate and groundwater conditions.

23. Indonesia has a climate that provides one of the most active chemical-weathering environments to be found anywhere in the world. However for tens of thousands of years volcanic processes and tectonic uplift have resulted in accretion rates that have kept pace with denudation. Consequently the terrain and particularly its slopes are in a constant phase of adjustment to the two processes. This influence of climate on the landform of Indonesia has been described by Verstappen (1975).

24. Much of the climatic variation is influenced by inter-tropical convergence patterns which is described by Koteswaram (1974) and Wild and Hall (1982). Within Java periods of peak rainfall occur between January and February and again between March and early May. This corresponds to the times when the majority of landslides are reported; as details for slope failures, in West Java for the period 1982 to 1984, shows; see Table 5.

25. Very detailed records of rainfall have been collected for more than sixty years and are described by Berlaga (1949). The amount of annual rainfall is largely dependant on the characteristics of the transitional phases of the inter-tropical convergence towards the north. A slow transitions normally implies an increase in annual rainfall. Fluctuations

in wind direction, during this period, result in dry air being carried out to sea were it picks up considerable moisture. A change in wind direction then carries the saturated air back over land where precipitation occurs. Table 6. shows the average precipitation values for different parts of Java as described by Berlaga.

TABLE 5. Serious landslides which occurred between 1982-84.

PERIOD	DATE	LOCATION	COMMENTS.
JAN-FEB	15-1-82	SUMADANG	ROAD DAMAGED.
"	25-1-83	CIAMIS	100 m SLIDE MASS BLOCKED ROAD.
"	9-2-84	E-BANDUNG	NO DETAILS.
"	20-2-84	GARUT	70 m OF ROAD DAMAGED.
"	23-2-84	CIREBON	20 m LONG SLIDE DESTROYED ROAD.
"	27-2-84	CILOTO	99 HOUSES DESTROYED; 30 m OF ROAD DAMAGED.
"	28-2-84	CIAMIS	46 HOUSES BURIED; 385 HOUSES DESTROYED.
MAR-MAY	22-3-84	SUKABUMI	85 HOUSES DESTROYED; 121 HOUSES DAMAGED.
	19-4-84	CIAMIS	26 FAMILIES EVACUATED; DAMAGE AT $170,000 (US)
	30-4-84	GARUT	7 PEOPLE KILLED; ROAD EXTENSIVELY DAMAGED.
	4-5-84	SUMADANG	17 MAJOR ROAD CUTTINGS FAIL.
	11-5-84	BANDUNG	174 PEOPLE EVACUATED; SLIDE LENGTH 1,000 m.
OTHER PERIODS;			
	29-8-84	GARUT	ROAD DAMAGED.
	14-9-84	GARUT	DAMAGE AT 14 LOCATIONS ON ROAD.
	17-9-84	BANDUNG	6 HOUSES DAMAGED.

26. This shows the effect of the mountainous topography, in the south of the country, in influencing rainfall as well as the dryer climate towards the east were fewer landslides are reported. Slope failure is generally considered to be connected with high intensity, rainfall events, and precipitation rates in excess of 70 mm/0.5 hours have been quoted by both van Bemmelen (1949) and Brand (1984) in terms of likely landsliding.

TABLE 6. Characteristics of rainfall in Java. (BERLAGA 1949)

AREA	AVERAGE			PERIOD OF WET-SEASON.
	ANNUAL RAINFALL	INFILTRATION RATE	EVAPOTRANSPIRATION RATE	
WEST JAVA (NORTH)	1,800mm	690mm	980mm	8 MONTHS
WEST JAVA (CENTRAL)	1,970mm	1,360mm	710mm	8 MONTHS
WEST JAVA (SOUTH)	3,450mm	2,820mm	410mm	10 MONTHS
EAST JAVA (NORTH)	1,740mm	830mm	1,340mm	7 MONTHS

27. However experience, in Java, indicates that high annual rainfall is also linked to an increase in the number of slope failures. As one example of this; a review of historic records shows that at Site 4. two major landslide disasters, involving the death of 150 people and the loss of three villages, occurred in 1900 and 1925 when Schmidt and Schmidt-Ten Hooper reported the highest average annual rainfall for 100 years.

28. Groundwater conditions; On slopes where a relatively impermeable

soil underlies a more permeable horizon the processes of groundwater flow have been frequently modelled and is described in most text books, Whipkey and Kirkby (1978). At a certain level of rainfall the upper soil horizon reaches the limits of its hydraulic conductivity and then a back-up of saturation occurs and continues up the slope, see Figure 5.

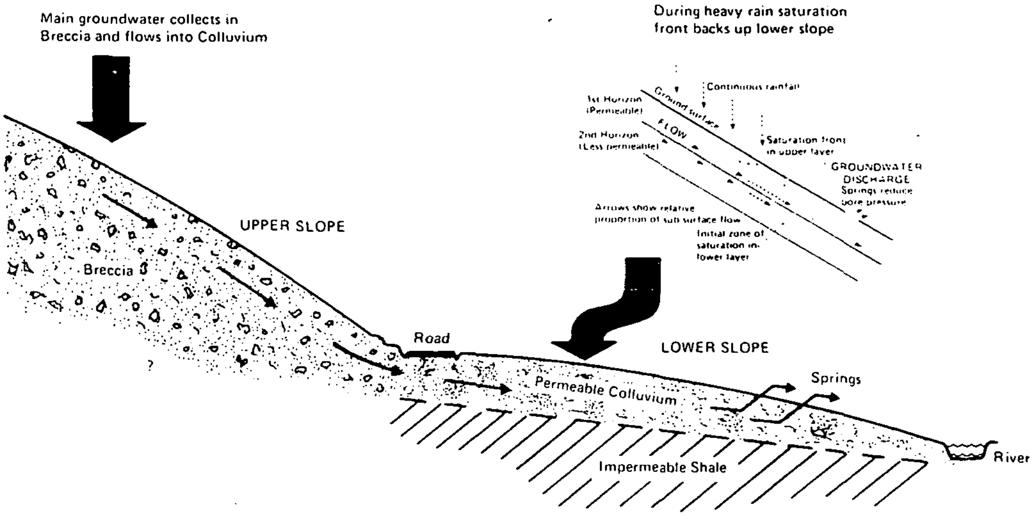


FIGURE 5. Conditions of groundwater on slopes in Java.

29. Such soil-water conditions occur on the majority of slopes investigated and the effects were measured, in terms of an increase in pore water pressure, at Site 1. during a two month period when the slope was failing.

30. Fifteen open-hydraulic Casagrande piezometers were installed on the slope, in four groups, to depths which ranged from 1.9 to 14 metres. Initially the piezometers were monitored manually, at two day intervals, using a dip probe. Subsequently an acoustic method of automatically monitoring six of the piezometers at more frequent intervals was installed, Heath and Dedi (1989). Problems occurred with both the response of the piezometers, which was estimated to be in excess of 10 hours and the reliability of the monitoring technique. These difficulties have been described by Heath and Saroso (1988). Despite such problems useful information relating to hydrology and failure was obtained.

31. Significant slope movement occurred at Site 1. in early April 1984 during a period of exceptionally heavy rain. The rainfall conditions and pore pressures for the period of slope failure are shown in Figure 6.

32. Many of the shallow slopes in Java have developed secondary permeability characteristics, such as piping, to cope, in conjunction with springs which provide groundwater release, with high rainfall and considerable groundwater. However when there is very high continuous rainfall this capacity is exceeded and higher than normal pore pressures develop. The mechanism of flow, that of natural pipe and fissure networks,

also provides localised weaknesses and zones of saturation, that significantly lower the overall shear strength characteristics.

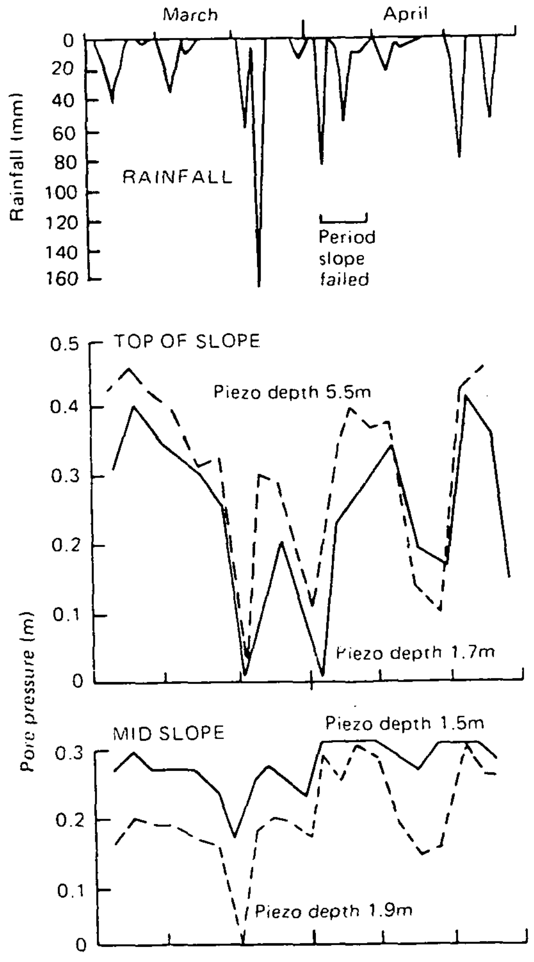


FIGURE 6. Rainfall and pore pressure data from Site 1.

33. Analysing slope conditions even in terms of uniform properties but different depths of saturation, using the Janbu method of interslice forces for translational sliding, indicates a safety factor of less than unity when groundwater reached a depth of 0.5 metres. This conforms to earlier results obtained from planar landslides on clay slopes by Skempton (1964). This safety factor (SF) is dependent upon the difference in depth, above a potential slip surface, of the saturated and unsaturated soil (Z_w and Z) and the soils angle of friction (ψ). When SF equals;

$$SF = \frac{\tan\psi\,[(1 - \frac{\gamma_w}{\gamma}) + \frac{\gamma_w}{\gamma} \times \frac{z_w}{z}}{\tan\beta} \qquad 1.$$

in which γ_w and γ are unit weight of water and soil and β is the angle of the slip surface. As would be anticipated from the equilibrium relationship the depth of sliding is related to shear strength and would be deep for an homogenous soil. In the case of the sites investigated there are localised zones of weak shear strength within the colluvium in which failure inevitably occurs.

34. Soil permeability tests carried out in the laboratory indicated average rates of flow of less than $5x10^{-4}$ mm/sec for the colluvium soils and $1x10^{-7}$ mm/sec for the shale. From observations and the analysis of standpipe data recorded at all sites this was at least an order of magnitude less than the rate groundwater entered the slopes. Dye-tracer tests, using the compound Fluoresceine LT., a yellow dye with the colour index Acid yellow 73, were used on a number of slopes to determine secondary permeability, through fissures and natural pipes, as distinct from the primary intergranular permeability. Recovery of tracer was good and it was possible to determine its presence at dilution levels of $1x10^{-7}$ parts tracer to water. Hydraulic conductivity estimated from such tests was greater than $1x10^{-2}$ mm/sec particularly at the top of the slopes and beneath the road.

35. Observations of groundwater being forced through the bitumen pavement material, when heavy vehicles applied pressure to the road, was common at many landslide sites. Often the large amount of groundwater, and excess hydrostatic pressures, caused considerable pot-holing to occur before the slope commenced to move. It is likely that such hydrostatic pressures are transmitted downslope, through natural pipe networks, and have some influence on the gradual creep movement that occurs on the majority of such slopes. However this effect could not be determined because of the limited response of the piezometers used.

Slope materials.

36. A notable feature of soil formation in most humid-tropical conditions, is that the rapid rates of weathering gives rise to distinct mineralogies which are dependant upon elevation and groundwater conditions. Clay minerals are important indicators of the engineering properties of soils and therefore being able to identify them by the soils position in terms of weathering characteristics is of considerable value.

37. Soil types; The weathering of subsilicic volcanic materials, in humid-tropical conditions, is usually a two stage process involving hydrolysis and the breakdown of silica, alumina and magnesia. On the shallow poorly drained slopes, in Java, where limited groundwater movement allows both silicates and cations to collect, the processes may reverse during each dry season and smectite clay minerals, with a 2:1 lattice structure, are formed. On the colluvium/shale slopes the predominant clays are montmorillonitic and on limestone/shale slopes it is the less common vermiculite which is predominant. The latter reflects a greater abundance of calcite in the mineral forming processes.

38. On more efficiently drained upper sections of slopes the

predominant mineral formed is generally the amorphous-clay allophane which subsequently weathers further to form halloysite, kaolinite and gibbsite in that order of increasing maturity. All of these soils differ significantly from the smectites; possessing greater permeability, lower specific gravity and lower plasticity. Their characteristics in terms of slope stability have been described by Wesley (1977) and Rouse, Reading and Walsh (1986). Table 7. shows the main range of soils on slopes in Java, their properties and the geomorphological relationship of each.

39. Soil mineralogy tests, using x-ray diffraction methods, were carried out on samples of soils from a number of landslide sites. Both orientated air dried and orientated glycolated tests were made and differences in peak refraction values confirmed the presence of considerable amounts of an expansive smectite mineral. The soil characteristics, in relation to its formation and position on slopes, was very similar to that reported by Subagjo and Buurman (1980), for shallow slopes in East Java, and follows the pattern of weathering and mineral formation originally proposed by Lang (1967) for volcanic soils in Dominica.

TABLE 7. Principal soil groups on slopes in Java.

PRINCIPAL MINERAL	SUB-GROUP MINERALS	PARENT MATERIAL	GEOMORPHIC RELATIONSHIP	PEDOLOGICAL TERM	PHYSICAL DESCRIPTION	ENGINEERING ATTRIBUTES
1) SMECTITE GROUP	a) MONTMORILLONITE b) VERMICULITE	a) COLLUVIUM FROM VOLCANIC BRECCIA, SAND STONE & SHALE b) LIMESTONE COLLUVIUM & INTRUSIVE MATERIAL	SLOPE BASINS WITH POOR DRAINAGE. A HIGH pH (REDUCING CONDITIONS) & A DISTINCT WET & DRY SEASON.	VERTISOLS	BROWN-BLACK HIGHLY PLASTIC & EXPANSIVE FEATURES SO THAT THE SOILS CRACK WHEN DRY.	HIGH PLASTICITY; LOW SHEAR STRENGTH; SOILS TEND TO BE VARIABLE IN TERMS OF GRADING.
2) AMORPHOUS GROUP	ALLOPHANE	VOLCANIC ASH (ANDESITIC) MATERIALS	HIGHER SLOPE ABOVE 1,000 METRES	ANDOSOLS	YELLOW/BROWN WITH A HIGH MOISTURE CONTENT	VERY LOW DENSITY; GOOD ENGINEERING SOIL
3) KANDOID GROUP	HALLOYSITE	VOLCANIC ASH SANDSTONE & ANDESITE	FREE DRAINING MID SLOPES IN ACIDIC OXIDISING CONDITIONS.	LATOSOLS	RED COLOUR OPEN TEXTURE MODERATE DENSITY IRON-RICH	LOW DENSITY; WITH A HIGH PERMEABILITY; GOOD PROPERTIES
4) SILICA DEPLETED	GIBBSITE	VERY OLD ANDOSOLS AND LATOSOLS	LOW ELEVATION WELL DRAINED ZONES	NITOSOLS	COMPACT SOILS REDDISH-BROWN DEPLETED IN MINERALS	VERY GOOD STRENGTH; OFTEN OVER-CONSOLIDATED

40. Of further relevance to the behaviour of slopes with a high content of an active clay is the cation association of such clays as, Mitchell (1976) suggests, this may have a considerable influence on the properties of the

clay. However there are no references describing such associations for clays in tropical soils and only a small amount of data was obtained during this recent study. The main cation in samples of the montmorillonite clay was found to be calcium, which is divalent, and therefore relatively more stable than such clays with monovalent ions. However the vermiculite, which is inherently a less expansive clay than montmorillonite, has weak monovalent sodium cations and therefore has a relatively high exchange capacity. Both clays exhibit intra-crystalline and inter-crystalline swelling when saturated, a factor that contributes to the highly expansive nature and activity of these clays. Table 8. shows the mineralogy of samples collected.

41. Despite sample (1) coming from the dryer Central region of Java and appearing to be a less weathered soil than either of samples (2) or (3) the mineralogy tests show it to contain a greater amount of smectite clay. The Subang shale is a fresh sample recovered from a borehole and the Damar series a very weathered sample from the surface. Despite the high amount of clay in the latter it retains the dense characteristics of the original shale possible because of the large amount of Kaolinite. These examples illustrate the inhomogeneous nature of lower slope soils due to different states of weathering.

TABLE 8. Clay mineralogy of samples from unstable slopes.

	COLLUVIUM (1)*	COLLUVIUM (2)*	COLLUVIUM (3)*	DAMAR SERIES SHALE #	SUBANG SERIES SHALE #
MONTMORILLONITE	62%	35%		36%	
VERMICULITE			35%		
KAOLINITE	10%	15%		54%	
MUSCOVITE			10%		40%
FELDSPAR	18%	15%	20%	1%	
QUARTZ		30%	30%	6%	50%
OTHER	10%	5%	5%	3%	10%

Weight % may have a relative error of up to 10%

* (1) Semarang slide (2) Site 1 (3) Site 2

\# The Damar sample is from the ground surface and weathered. The Subang sample is from a depth of 8 m and fresh.

42. Soil tests; Laboratory soil testing was carried out on up to 100 'undisturbed' samples recovered from boreholes at each test site. Soil grading tests, carried out in accordance with BS.1377, and using an accepted dispersing agent, sodium hexametaphosphate, proved to be the most unreliable of tests in terms of the amount of clay sized particles. The results were generally 50% below what was estimated in more reliable, x-ray diffraction clay mineralogy tests, in terms of total clay content.

43. Triaxial shear strength tests, using pre-consolidated undrained methods, also provided a wide range of values and in particular extremely low angles of internal friction. However the creep failure, which occurs on all slopes, may provide sufficient explanation for this in terms of structural anisotrophy providing a distinct angle of weakness. Also a number of recent references on tropical soils have refered to the fragile nature of such materials and indicated that triaxial testing should be carried out on samples much larger than the 37 mm diameter cores used in this study. A brief summary of soil test data from three sites is contained in Table 9.

and shows typical average values.

TABLE 9. Average values for soil test data from three sites.

	LIQUID LIMIT	PLASTICITY	CLAY CONTENT	SHEAR STRENGTH	
(MONTMORILLONITE SOILS)					
ONE	82%	49%	28%	$49kN/m^2$	11^0
	*(67-97%)	*(34-64%)	*(19-37%)		
(VERMICULITE SOILS)					
TWO	50%	30%	30%	$28kN/m^2$	11^0
	*(44-70%)	*(26-40%)	*(20-50%)		
(MONTMORILLONITE; HIGH CLAY CONTENT)					
THREE	75%	45%	29%	$36kN/m^2$	5.5
	*(61-89%)	*(31-60%)			

* Range within which 65% of all tested samples come.

44. The plasticity of almost all soils recovered was above the A-line on the liquid limit/plasticity curve and average activity values were 2.48 for montmorillonite and 0.85 for vermiculite samples. This is shown on the typical Liquid limit/Plasticity and Clay fraction/Plasticity curves for some representative samples of these soils, see Figure 7.

45. Many of the slopes, with angles of between 12 and 20 degrees, are therefore steeper than the soil characteristics suggest they should be. Using a limit equilibrium analysis based on the Janbu method of inter-slice forces, Janbu (1973) it can be shown that for the existing slope angles and depths of failure, for typical soil shear strengths, a Factor of Safety of 1.05 can be assumed for modest pore pressures and the water table at a depth of 1.5 metres. It is known from the rainfall data that much more severe groundwater conditions exist, than have been used in the analysis, for short periods each year. Therefore most slopes are inherently unstable, during such periods, and rapid creep failure occurs as a consequence.

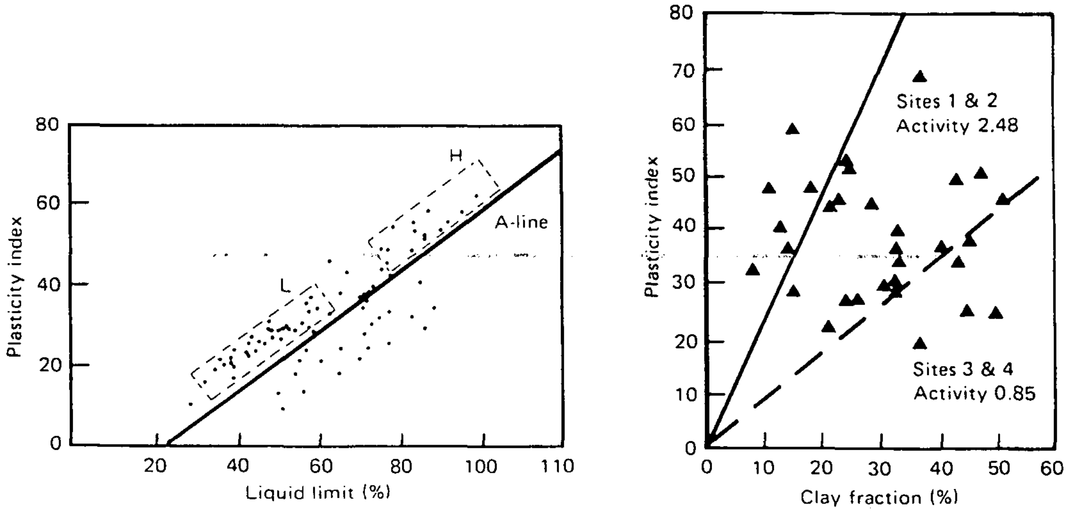


FIGURE 7. Plasticity and activity curves for clay samples.

Rates and depths of slope failure.

46. From an engineering viewpoint the rates at which slopes fail is extremely important both in terms of hazard risk and the choice of methods used to contain such failure. In the majority of cases in Java the problems of rapid catastrophic failures on roads can generally be ignored. The main problems relate to containing vast amounts of slow moving material in terms of protecting roads from damage.

47. Simple methods of determining the depth of failure, which consisted of 19 mm diameter plastic pipes with a method of checking any bending, were installed to depths of 20 m on all of the sites but failed to provide any reliable evidence of failure. Subsequently the 'Soiltest' single-axis servo-accelerometer inclinometer was used to provide information about depth, rate and direction of movement. Locally extruded 53 mm diameter aluminium access tube was installed to depths of 30 m in the slopes.

48. The rates of failure were found to be as much as 15 mm/day during very wet periods, a rate which in terms of creep is exceptionally fast. The inclinometer access tube had a very limited life before bending made it unsafe to use. However the total annual movement was determined by measuring surface reference markers, and subsequently rows of pegs, and found to be approximately 0.75 m/year. This provided an average rate of creep over a year of 2 mm/day and suggests that during the dry season movement ceases. Certainly there was no detectable change from the inclinometers during this period. It also indicates that during the five to ten years that creep occurs, before sufficient loss of support causes a road to fail, the total movement is between 3.75 and 7.5 metres. Whilst this appears excessive it should be considered in terms of the total length of the slope, which can be 500 m, therefore providing a ratio of deformation to length of only about one percent.

49. The depth of failure ranged from 2 m to more than 13 m and related to the depth of colluvium and the shear strength of the soil which increased significantly at the interface with the shale. Therefore the sliding surface was always above this level. From data provided by borehole logs it was apparent that sliding occurred most frequently along horizons were the colluvium was gravelly with a low plasticity. The reasons connected with this were not clear but perhaps these are zones were the natural pipe and fissure network is greatest and therefore the slope is weakest.

CONCLUSION.

50. Within Java there is a range of landslide types, ranging from vast, avalanche type, lahar slides, steep failures in allophanic and halloysitic residual soils and slow translational and creep failures in highly plastic smectite materials. Only the latter significantly affect roads at present causing a considerable amount of damage to the countries highway

network each year.

51. This type of slope failure has a distinct pattern in terms of the characteristics of terrain and groundwater in which it is likely to occur.

a) Failure occurs on shallow slopes with gradients of between 12^0 and 20^0. Such failure is generally so gradual that almost no visible indication exists at the ground surface. However it can usually be recognised on the road surface by a gradual change in camber and cracking of the pavement.

b) Failures occur in areas of colluvium underlain by impermeable shales. Above the failure zones slopes of very porous volcanic breccia are present which supply colluvium with large quantities of groundwater. Drainage within the colluvium is effectively prevented by the shales and as a result highly plastic smectite clays are formed creating a zone of saturated soils with low shear strengths.

c) Slopes assume steeper angles than would otherwise appear to be justified by the weak nature of the soil. Some additional slope support seems to be afforded by terracing for rice cultivation and occasion trains of large boulders aligned down slope.

d) The slopes where failure occurs are generally between 250 to 500 metres in length and usually considerable time needs to elapse before slow movement accumulates sufficiently to a point were highways are damaged. Rough estimations suggest that the period may have an interval of from 5 to 10 years between visible disturbances.

e) In the light of a new understanding about the effects of shallow slopes failures on roads the existing methods of dealing with slope problems could be modified. In this respect recommendations, concerning maintenance, would be to consider the whole slope rather than merely the part containing the road. This would involve the adoption of remedial policies based on sound slope engineering methods.

f) A knowledge of the location of unstable landslide prone ground can be of considerable benefit to the design of new roads and the remedial treatment and maintenance of existing roads. Such knowledge can be achieved by the ground mapping of colluvium/shale sites and the compilation of inventories of recorded data and experience.

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