Natural slope problems related to roads in Java, Indonesia

W.HEATH, Transport & Road Research Laboratory, Crowthorne, UK
B.S.SAROSO, Transport & Road Research Laboratory, Crowthorne, UK

ABSTRACT

In relation to the high number of landslides which cause serious problems to Indonesia's highway network study was carried out in order to determine common patterns of failure and to establish methods of identifying potential high risk areas of slope instability in Java.

It consisted of a regional appraisal and a detailed study of soil and groundwater conditions at a few selected sites in Central and Western Java. The shallow soil slopes on which such failures often occur generally consist of colluvium resting on a relatively impermeable shale. The high weathered soils have a high clay content which, from mineralogy tests on samples recovered from test sites, proved to have an expansive 2:1 lattice structure and clays were generally montmorillonites and vermiculites. Other soil tests showed these soils to have a high activity value of up to 2.48.

Four modes of failure and associated groundwater conditions, consisting of mass creep, lateral slides, mud flows and a rotational slump of the road section, were identified as being characteristic of most failure sites. The report describes the instrumentation results and observations used in determining these features of slope failure.

1. INTRODUCTION

During 1981 a joint study commenced between the Indonesian Institute of Road Engineering and the Transport and Road Research Laboratories Overseas Unit into the problems of slope instability in Indonesia. The general aim of the study was to seek overall patterns of failure on soil slopes, which were connected with highway problems, and to determine the mechanisms of such failure in order to improve the methods of dealing with landslides. In addition it was anticipated that such a study would provide a means of identifying areas of potential risk and that this would assist in the preparation of hazard maps for highway alignment and maintainence purposes.

The study concentrated on landslide problems in the most developed area of Indonesia, that of Java, and besides examining widespread occurrences of slope failure a number of specific sites were selected for detailed examination.

As is often common with large landslide studies there were difficulties initially in determining which were the most appropriate investigation and testing procedures for use on the sites. In this respect the limited background information relating to slope stability problems in Indonesia proved to be a severe handicap. Consequently the number of slides being investigated grew and a restricted range of investigation procedures appeared to provide advantages in terms of the resources available. These included; mapping, sub-surface soil sampling and testing, the use of instrumentation to determine the rate and depth of failure and an investigation of groundwater conditions including the detailed study of pore water pressures at one test site.

Subsequently a range of groundwater and soil information about different slopes was collected and related to more general observations of slope failure throughout Java. In this respect the empirical records dealing with large scale slope movements, in those other parts of the world where similar slope problems exist, were of value.

2. BACKGROUND TO THE STUDY

The first phase of the study consisted of the selection of four representative sites for investigation, and included the preliminary mapping of these sites and limited sub-surface exploration. Reference to this stage has been made by Saroso B.S. et al (1983). It was planned that the second stage include a more detailed investigation of the sites including the determination of the depth and rate of failure and the groundwater conditions on the slopes. It was also proposed that the shear strength of slope materials should be determined to some degree of precision. Prior to the start of the second stage in 1983 fifteen piezometers were installed at one site in four groups along the slope. The selection of piezometers and their distribution on the slope were determined as part of a joint study involving Bristol University.

During the second stage it was recognised that instrumentation results and observations were more relevant from sites that were failing rather than sites with a past history of failure. This meant the rejection of one previously selected site. Additional sites, where continuous slope movement caused problems to roads, were selected including one at the Puncak, km 88, on the main Jakarta to Bandung road. Table I shows the slides which were instrumented and observed in detail during the second stage of the investigation.

Table I. Slopes included in a detailed study

SITE	ROAD LOCATION	MORPHOLOGY OF SLOPE ABOVE ROAD	UNSTABLE PART OF SLOPE
1) (Km61)	BANDUNG-CIREBON	STEEP SLOPES OF	COLLUVIUM AND SHALE
2) (Km64)	" "	VOLCANIC BRECCIA	
3) (Km21)	BANDUNG-JAKARTA	STEEP ANTICLINE OF	COLLUVIUM AND SHALE
4) (Km24)	" "	REEF LIMESTONE	
5) (Km24)	WELLERI-SUKAREJO	STEEP SLOPES OF VOLCANIC BRECCIA AND SEDIMENTS	COLLUVIUM AND SHALE
6) (Km88)	JAKARTA-BANDUNG	VOLCANIC BRECCIA AND ASH	OLD SLIDE DEBRIS
7) (Km54)	BANDUNG-CIAMIS	ANDESITE BRECCIA	VOLCANIC COLLUVIUM
8) (Km46)	BANJAR-WANGON	VOLCANIC BRECCIA	VOLCANIC COLLUVIUM
9) SEMARANG	KRAPYAK-SEMARANG TOLL RD.	VOLCANIC ASH/SHALE OLD SLIDE MASS	MAINLY SLIDE DEBRIS

Much of the instrumentation and investigation took place at Site 1. Tomo, km 61, and Site 4. Citatah, km 24, two sites close to the Indonesian road research laboratories in Bandung. At Tomo highly porous deposits, composed of volcanic breccia which is generally old lahar, feed groundwater into colluvium which overlies folded beds of shale belonging to the Subang formation. Citatah is different only in that it is a section of a reef limestone anticline which feeds groundwater into a similar sequence of colluvium and shale.

At Tomo the road failed at four locations, within the sector from km 61.7 to 67, during the course of the study. Failures at the instrumented part of the site, km 61, consisted of a 100 m long translational slide, mud slides and continuous periods of slow earch deformation and creep. Within the old lahar deposits above the road failure only occurs when the lower slope becomes oversteepened. No such failures occurred during the period of the study. Figure 1 provides information about this site with details of the main failures and locations of instrumentation.

2.1 Geology and geomorphology:

The island of Java forms part of an active volcanic mountain chain, the Sunda Arc, where diastrophism has resulted in uplifted and folded sequences of Tertiary and more recent sediments to produce a physically rugged and complex landscape. This is modified by an extensive alluvial coastal plain in the north and a series of old alluvial lake basins in the central region. The main geotectonic activity has been in the southern region of Java where the terrain consists of extremely complex morphostructural units within an uplifted sedimentary and frequently active volcanic mountain system.

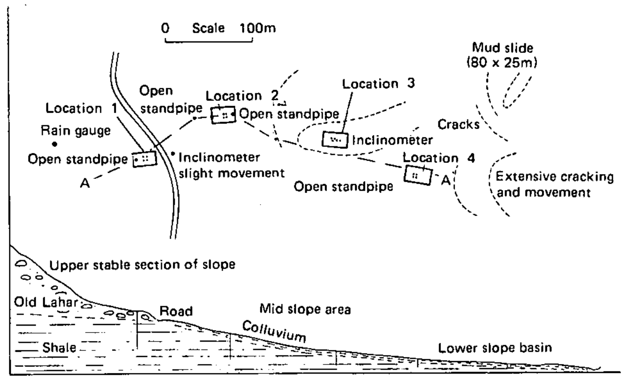

Fig. 1: Details of the slide at site 1; Tomo

The geomorphological features of many slopes in Java are similar in that they consist of folded marls or weathered volcanic deposits overlain by sequences of colluvium derived from volcanic breccia and ash. Massive deposits of these porous breccia and ash materials occur on the steeper sections of slopes to form huge collection areas of groundwater. The contribution of extensive groundwater retention zones, reservoirs, to slope failures has been described by Denness B (1973) in relation to failures in Colombia. In Java the lower areas of such slopes are invariably covered with extensive bodies of weak colluvium, an extremely variable material, consisting of boulders, cobbles and gravel in a sand/silt and clay matrix. Such conditions account for a considerable proportion of the total road network area which includes 3,200 km of main and 9,000 km of secondary roads servicing a population of 90 million. Figure 2 shows the percentage of the road network for West Java within areas of landslide risk.

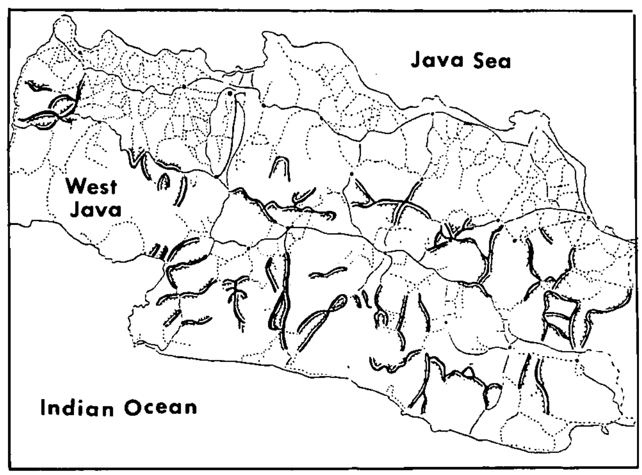

Fig: 2. Road-sector map of slope hazards in West Java

2.2 Characteristics of slope failure:

Within the lower slope regions failure generally follows a predictable pattern and is related to both high rainfall and the excess groundwater released from highly porous deposits on the upper slopes.

In terms of published references, Brand E.W. (1984), has outlined the extent of information for the whole of South-east Asia. The only published reference dealing extensively with slope failures in Indonesia is that by Wesley L.D (1977) and relates to problems in homogeneous soils on steep volcanic residual-soil slopes. Within the typical soils of Indonesia, derived from pyroclastic materials and marl sediments, Mohr E.C.J (1944) has commented on the high shrinkage, to approximately half the wet volume of these materials, and relates this to montmorillonite clays. Such clays, within the phreatic zone of groundwater, tend to form in alkali soil conditions which possibly indicates the influences the high pH calcium carbonate marls have on the weathering of volcanic materials.

Rouse W.C et.al (1986) have published results of a soil study in Dominica, West Indies, in environmental conditions similar to those in Indonesia. In particular the reported distribution of amorphous clay minerals at the higher elevations and 2:1 lattice clays, including smectite, on the lower footslopes, where high levels of groundwater accelerate the weathering process, can also be identified in Indonesia but in much less distinct patterns.

2.3 Rainfall related to slope failure:

The climate of much of Indonesia is quite seasonal being influenced by the equatorial tropical convergence and characterised by a prolonged wet season from September to May. Rainfall records have been collected over a period of sixty years, Berlage Jr.H.P (1949), and indicate that average yearly rainfall varies between 1,500 and 5,000 millimetre. Table II shows the general conditions of rainfall in Java.

Table II. Features of rainfall in Java (Berlage)

GENERAL	ANNUAL RAINFALL	INFIL-TRATION	EVAPO-TRANSPIRATION	PERIOD OF WET=SEASON
WEST JAVA (NORTH)	1,798mm	690mm	980mm	8 MONTHS
WEST JAVA (CENTRAL)	1,966mm	1,360mm	710mm	8 MONTHS
WEST JAVA (SOUTH)	3,454mm	2,820mm	410mm	10 MONTHS
EAST JAVA (NORTH)	1,740mm	830mm	1,340mm	7 MONTHS

In Java the principal influence on the amount of rainfall is the ground elevation and the period of the tropical convergence. Within the lower slope area it is between 1500 mm and 3,000 mm per annum. From the records of Berlage, peak rainfall generally occurs in January and then again between the months of March and May. This corresponds to the periods when the majority of landslides are reported. In terms of the effects of rainfall infiltration, and longer term groundwater conditions, such failures appear to have two distinct components.

General observations, Newspaper reports and inclinometer results support the view that most slides occur during or immediately after a period of exceptionally heavy rain. Both Brand E.W (1984), in terms of Hong Kong slides, and van Bemmelen R.W. (1949), in terms of lahar slides in Indonesia, have reported upon precipitation threshold levels of 70mm within an hour or less to initiate serious landsliding. Levels of rainfall exceeding these values are not uncommon in Java.

In contrast vast quantities of groundwater are retained within the highly porous upper slope deposits of breccia and ash throughout the wet season. This is dissipated onto the lower slope deposits maintaining a saturated condition and promoting creep failure. It is this, the least spectacular and difficult to observe aspect of slope failure, which is the fundamental factor of all slope instability affecting roads in Java.

3. GROUNDWATER AND INSTRUMENTATION

A difficult aspect of the study was the measurement of groundwater pore pressure and permeabilities within the restricted horizon of unstable colluvium. At the main instrumented slope, site one, groundwater levels measured from open standpipes at five positions on the slope were collected for a period of two years, see Figure 3. These indicated a high build up in the level of groundwater at the start of each wet season with the exception of an area of slope above the road. The most notable variation in groundwater level occurs at the mid-slope positions where an increase of more than 5 metres in the phreatic level was recorded. Similar patterns of groundwater build-up were also observed at sites three and five where open standpipe levels were also monitored.

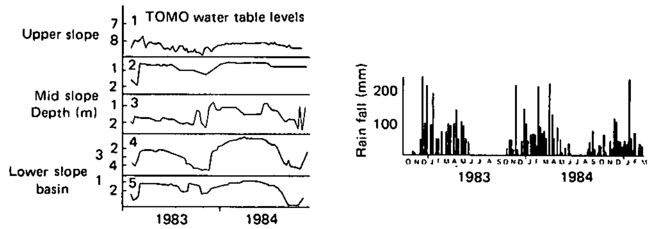

Fig. 3: Standpipe groundwater levels

3.1 Groundwater flow and pore pressure:

Groundwater flow conditions and the build up of pore pressure in the colluvium are relevant to slope failure investigations particularly in the design of drainage as a means of controlling movement. In this respect the model developed by Whipkey J.F and Kirkby M.J (1978), of the build up of a saturation front appears particularly relevant to slopes in Java. it presupposes that subsurface flow conditions generally require an impeding layer or a progressive decrease in permeability with depth before any appreciable flow occurs. A horizon of weathered shale meets such conditions on the majority of unstable slopes in Java. Figure 4 shows what are essentially the conditions during a period of steady long-duration rainfall. As the precipitation continues a zone of saturation within the impeding layer gradually increases and consequently reduces the diffusing gradient or rate of percolation into the layer. This causes a saturated layer to back-up within the upper more permeable colluvial zone and progressively extend upslope. However it does not extend uniformly because of differences in hydraulic conductivity.

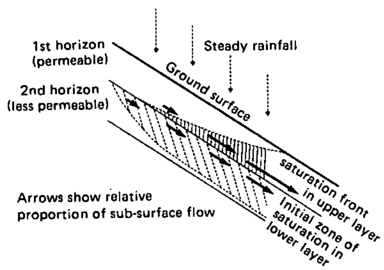

Fig 4: Slope saturation model. (Whipkey et.al)

The characteristic variations in patterns of instability on a given slope in Java may perhaps be explained in terms of the spatial distribution of this pattern of saturation across a slope, perpendicular to the forward movement of the saturation advance. This is likely to vary considerably, over periods of years, and may be influenced significantly by disturbances to the slopes groundwater such as deforestation and land development. Such models, in terms of Java's slope failure problems, appear to be extremely relevant but are particualrly complex to develop and prove.

3.2 Piezometers:

The piezometers used to determine groundwater pore pressure were the standard coarse ceramic filter (250mm x 50mm) Casagrande type, Casagrande A. (1949), fitted to 19 millimetre PVC open standpipes. Installation was in the prescribed manner with bentonite end seals and a 200 millimetre filter of coarse sand. It provided a hydrostatic piezometric response, to reach an 90% equalised hydraulic pressure, of approximately 10 hours. This was a serious disadvantage resulting in the loss of data relating to the transient groundwater response to storm events.

3.2.1 Recording piezometric levels: In general the instrumentation of unstable slopes is made difficult by the inaccessibility of the sites and therefore methods of recording the data from instruments are necessary. In Java a recently developed acoustic method was used to measure and record the level of piezometric water in the standpipes. For depths up to 10 m it was claimed to measure water levels to an accuracy of 5 mm under constant conditions. However assumptions made in the design of this technique, and referred to by Anderson M.G and Kneale P.E (1987), regarding the type of standpipe and influence of temperature led to practical difficulties and serious errors. Fortunately additional pore pressure data was obtained by taking manual readings at three day intervals and this proved to be more reliable.

3.3 Dye tracer:

Investigations were made using the dye fluoresceine LT, a yellow dye with the colour index; Acid yellow 73, constitution reference 45350 and a chemical base of the sodium salt of hydro-o-carboxy phenyl fluorine. The purpose was to determine permeabilities and groundwater flow paths across the slides.

4. SOIL PROPERTIES

4.1 Clay mineralogy:

X-ray diffraction examination was used to determine the clay mineralogy of soils on a number of failing slopes in Java. For each test three samples were prepared, one randomly orientated, and the second and third with the minerals orientated and glycolated and orientated. These allow the principal clay phases and the presence of swelling sheet silicates to be identified. The tests indicated relatively low levels of amorphous minerals and little Halloysite as being a characteristic of these lower slope materials. Table 3 shows the mineralogy of samples which have been examined. It also includes details of the shale at two sites.

Table III. Mineralogy of soil samples from colluvium within the slope failure zone.

SITE:	COLLUVIUM SOIL TYPE	MAXIMUM AMOUNT CLAY MINERAL	SECONDARY CLAY	QUARTZ %	ASSOCIATED CATION
1&2	BRECCIA/SHALE	SMECTITE 35%	KAOLINITE 15%	30%	Ca
3&4	L/STONE/SHALE	VERMICULITE 40%	MUSCOVITE 5%	20%-40%	Na
6	VOLCANIC ASH	GIBBSITE 20%	ATTAPULGITE 10% SMECTITE 5%	40%	Mg
7	ASH/SHALE	SMECTITE 60%+	KAOLINITE 10%	1%	
1TO4	SHALE	MUSCOVITE 40%	MIXED 10%	50%	
7	SHALE	KAOLINITE 54%	SMECTITE 34%	6%	

Similar clay mineralogies have been reported in East Java, Subardja and Buurman P (1980). Gibbsite was related to mid slope weathering profiles and the smectites to basin positions. The landslide slopes on which smectite clays are prevalent can be readily identified by the high rate of shrinkage and cracking of the soil that occurs during the dry season.

Vermiculite was also found on shallow lower slope positions, in East Java, and defined as a pre-smectite stage of mineralogy. Unlike smectite clays which are widely associated with low values of shear strength and consequently slope failures, the vermiculites have received considerably less attention. However the clay structure, whilst not as active, is similar to montmorillonite in having a weak expanding 2:1 lattice and a high cation exchange capacity.

Gibbsite was found to be associated with old volcanic ash soils at one landslide site. The presence of gibbsite in such soils has been attributed to the severe tropical weathering of igneous basic rocks with the rapid removal of silicates, Harrison J.B (1934). Collapse, by saturation, and a weakening of cementation has been reported by Brink A.B.A and Kantley B.A (1961) and Vargus M (1973) for lateritic soils and Foss I (1973) for andosols. However there is still no direct test evidence of soil collapse to support field observations in Java.

4.2 Soil tests:

Soil samples were collected from a range of depths, up to 20 metres, including those positively correlated with slickenslides or planes of failure determined from inclinometers. Table 4 shows a range of soil test results.

Table IV. Soil test data from slopes

SOIL TYPE	DEPTH FEATURE	CLAY %	MINERALOGY OF MAIN CLAY		w%	LL	PI	c′ kN/m	φ Angle
** JAVA: (Main Test Site. 'Tomo' Site 1)									
Colluvium	2m Gravelly	22	Smectoid	30%	45	81	46	57	8
"	3m Clayey	47	"	35%	40	83	49	84	4
"	5m W/shale	43			30	81	46	45	14
Shale	11m	20	Muscovite	40%	28	110	75	58	23
**JAVA: (Other Test Site. 'Citatah' Site 3)									
Colluvium	2m Gravelly	48	Vermic-	30%	30	50	26	22	14
"	5m Gravelly	56	ulite	40%	18	46	27		
			Site 4						
Colluvium	1m	31	Vermic-			71	40	24	10
"	4.5m	31	ulite			70	27	10.5	13
"	8.5m	32	"			51	29	28	4.
	10m	25	"			49	27	33	4.5
"	13.5m	23	"			44	27	29	7.5

It is noticeable from these results that the smectites are not always associated with the highest values for either the liquid limit or plasticity Index. However in terms of activity, Figure 5 such soils have a high average value of 2.48, which is within the range of 1-7 for a calcium-cation associated montmorillonite. In this respect the soil test and x-ray diffraction results support the conclusion of a soil with a high smectite clay content. The less active clays including the vermiculite samples have an average activity of 0.87.

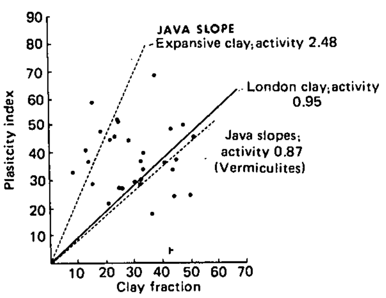

Fig 5: Activity value of soils

Laboratory soil grading tests were considered to be unrepresentative in terms of the clay-size proportion of the colluvium from failing slopes. From tests performed on a much greater sample than that shown in Table 4 an average clay-size content of 26% was determined. This had a standard deviation of 12% implying that few samples had clay contents greater than 40%. Other evidence including x-ray mineralogy examination, the high activity values of the soil and its physical properties all indicate a considerably higher amount of clay.

In this respect the fines in the soils appear to form clumped particles, larger than 0.002 mm, which resist breakdown during normal grading tests. Terzaghi K (1958) noted that Javanese volcanic residual soils had characteristics very similar to Kenya soils in terms of the clays forming aggregated particles that distorted the value of the soils liquid limit and were difficult to break down. Whilst it is difficult to draw parallels between the colluviums and the residual soils this ability of such soils to behave similar to soils with a large granular fraction, and consequently high cohesion, but readily break down under specific conditions should be considered in any future research into slope stability problems in Java.

The values obtained from pre-consolidated drained triaxial tests included low angles of shear resistance within the range 5° to 15°, and relatively high values of soil cohesion. They may reflect an orientation of the soil structure from the effects of the slow creep. The angle of internal friction is clearly related to the soils cohesion, see Figure 6. This shows the intercept between shear angle and cohesion for what are considered to be samples of colluvial near planes of failure. Figure 6 shows the increased range of plasticity for samples recovered from shallow depths and this is reflected in the range of soil moisture values. A correlation also exists between the soils liquidity index and horizons of failure within the soil profile.

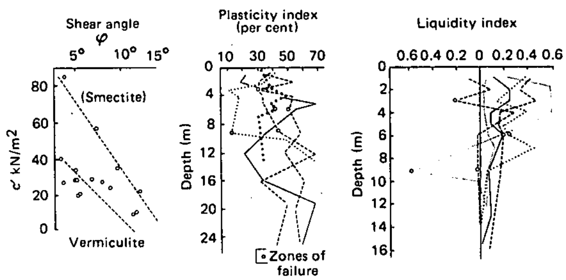

Fig 6: Range of soil properties

5. GROUNDWATER INFLUENCE ON SLOPE FAILURE

Rainfall conditions at a number of slopes are shown in Table 5. The information suggests that the total amount of annual rainfall had some influence on the number of slides. Also it was established that at least 50% of reported slides occurred during or after periods of heavy rain when daily rates exceeded 100mm. The rate of infiltration of such rain into the slopes is also relevant to slope stability. This together with groundwater flow conditions were determined from dye tracer tests. Such tests at four sites, within the upper slope area, provided samples of the dye, at dilution levels of between 0.3 and 2.3 parts-per-million recovered in bore holes placed up to 200 metres down slope. Intrinsic permeability, estimated from the dye tracer recovery, was as high as 5,000 m/hour in some tests indicating that fissure and natural pipe flow was a significant factor in groundwater movement. The distribution of dye concentration on an unstable slope is shown in Figure 7a and provides a basis for estimating groundwater flow with depth. The relative position of the spring line agrees with observations made at the surface. In hydro-morphological terms it is also significant that, as previously identified by Deere D.U and Patton F.D (1971), failures are generally within such groundwater discharge zones.

Table V. Features of rainfall at specific sites

SPECIFIC LANDSLIDE SITES			
	ANNUAL RAINFALL	SEASONAL RAINFALL	NUMBER OF LANDSLIDES
SITE ONE	1983. 2,329mm	1982/83. 2,644mm	NONE
	1984. 2,753mm	1983/84. 1,815mm	TWO
		1984/85. 3,222mm	NONE
SITE THREE	1983. 2,390mm	1982/83. 2,353mm	NONE
	1984. 2,340mm	1983/84. 2,280mm	THREE
		1984/85. 2,017mm	NONE
SITE FIVE	1982. 1,643mm	1982/83. 1,388mm	NONE
	1983. 1,862mm	1983/84. 2,513mm	SIX
DAILY RAINFALL RATES			
	DAYS EXCEEDING 50mm/24 HOURS	DAYS EXCEEDING 100mm/24 HOURS	PEAK RAINFALL PERIODS
SITE ONE	THIRTEEN	SEVEN	246mm/2 DAYS
SITE THREE	TWENTY FOUR	FIVE	168mm/1 DAY

The recovery of dye from an apparent slip plane was also achieved at one site, Figure 7b, indicating the preferential movement of groundwater along failure planes. The soil samples, of what was a coarse gravelly material, showed a high concentration of the tracer. Subsequently an inclinometer in the same borehole confirmed movement at the depth the tracer had been recovered.

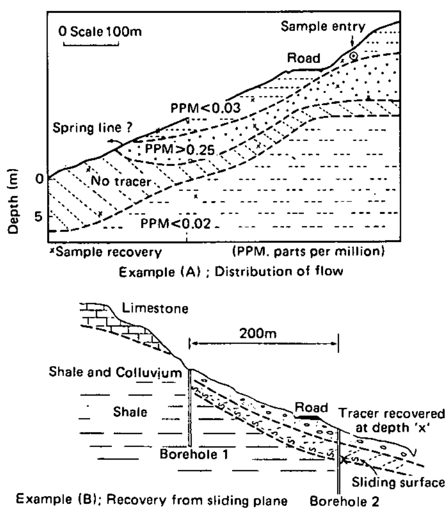

Fig 7: Results from dye tracer tests

5.1 Pore pressure and groundwater at Tomo site:

The hydrological pattern affecting slope behaviour has been determined from three instrumented sites on a failing slope at Tomo, see Figure 1. Fluctuations in pore pressure over a period of one year are shown in Figure 8. Within the mid-slope zone rapid transients in piezometric levels, at the beginning of the wet season, (about November, see Figure 8) are noticed and attributed to the priming of permeability in the soils. An explanation by Bouwer H (1978), is that entrapped air in the soil mass blocks conductivity paths and causes permeability to be less than when the soil is fully saturated. Consequently an initial build up of pressure or head of water is needed to overcome this.

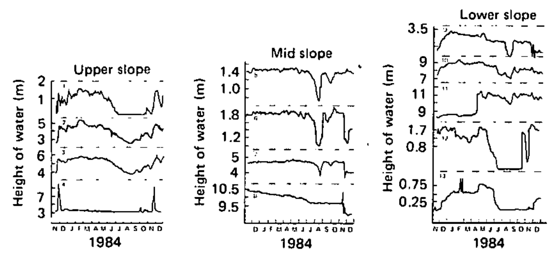

Fig 8: Piezometer levels at one site

5.1.1 Upper stable slope area: This zone is above the road on an area of steep volcanic breccia which overlies shale at a depth of 8.75m. Within this area there were considerable fluctuations in pore water pressure at depths up to seven metres.

Infiltration peaks were recorded on at least three occasions during storms, when open standpipe piezometer water reached to almost the maximum levels indicating pore water pressures in excess of 15 kN/m^2 at a depth of 1.7 metres, 50 kN/m^2 at 5.5 metres, and 60 kN/m^2 at 7.15 metres. In the shale there is little response and its not normally associated with the infiltration wetting front.

5.1.2 Mid-slope area: Within this area of the slope the phreatic level generally remained high for most of the year and piezometric levels rise above the tops of the standpipes frequently during the wet season. Figure 9 the left hand side, shows the variation in piezometric pressure and rainfall together with transient increases in groundwater pore pressure for three piezometers. The right hand side of Figure 9 illustrates increases in pore pressure and a five day pattern of rainfall. Piezometers in the shale showed little response in what is obviously a relatively impervious horizon. The uppermost 300 mm of colluvium, within the A horizon of the soil mass is also relatively impervious as is evident from the flooded paddy conditions on this and similar slopes. Hydraulic conductivity is therefore mainly confined to a narrow horizon which extends to a depth of 5 metres. In this respect the limited depth of the soil profile is probably more relevant than the basin morphometry in determining groundwater movement on this part of the slope.

Soil void ratios are in the range of 0.8 and 1.2 and therefore with natural moisture totally different and occurs as a rotational slump.

ACKNOWLEDGEMENTS

This report describes research that is part of a joint cooperation programme between the Transport and Road Research Laboratory (TRRL) and the Institute of Road Engineering, Indonesia (IRE). The paper is published by permission of the Directors of TRRL and IRE.

The authors wish to express their gratitude to the former Director of IRE, Ir HAB Hasibuan, without whose generous cooperation and assistance the work would not have been possible. Also to colleagues in the geotechnical unit of IRE. Soil mineralogy testing was carried out at Queen Mary's College, London.

REFERENCES

Anderson M.G and Kneale P.E (1987). Instrumentation of Pore Pressure and Soil Water Suction. Slope Stability. (Ed.) Anderson M.G and Richards K.S John Wiley and Sons Ltd. London. P 77-112.

Bemmelen R.W. van (1949). The Geology of Indonesia. The Gov. Printing Office, The Hague, Netherlands. 3 Vols. 1027pp. plus 16 plates and 47 maps.

Berlage Jr. H.P (1949). Rainfall in Indonesia. Verhandelingen No 37. Department van Verkeer, Energie en Mijnwezen Meteorologische en Geophysische Dienst Koninklijk Magnetisch en Meteorologisch Observatorium. Netherlands.

Bouwer H. (1978). Groundwater Hydrology. Pub. McGraw-Hill, London. p43-45.

Brand E.W. (1984). Landslides in Southeast Asia; A State of the Art Report. Fourth Int. Symp. on Landslides. Toronto.

Brink A.B.A and Kantley A.B (1961). Collapsible Grain Structure in Residual Granite Soils in South Africa. Proc. 5th Intern. Conf. Soil Mechanics and Foundation Engineering, Paris, 1961. p611/614.

Brunsden D. (1984). Mudslides. Slope Instability; Ed. Brunsden D and Prior D.B Pub. John Wiley and Sons, London. p.363-418.

Deere D.U and Patton F.D (1971) Slope Stability in Residual Soils. Fourth Panamerican Conference on Tropical Soils, San Juan, Puerto Rico. p87-170.

Denness B (1973). Landslip Problems in Relation to Roads and other Route Planning. Institute of Geological Science, London. IGS.547 100 11/72. pp.70.

Hanna T.H (1985). Field Instrumentation for Geotechnical Engineering. Series on Soils and Rock Mechanics, Vol. 10. pp843. Trans Tech Publications. Germany.

Harrison J.B (1934). The Katamorphism of Igneous Rocks under Tropical Conditions. Imperial Bureau of Sciences, Harpenden. England. 1934.

Mohr E.C.J (1944). The Soils of Equatorial Regions Pub. J.W. Edwards, Ann Arbor, Michigan, USA.

Rouse W.C., Reading A.J and Walsh R.P.D (1986). Volcanic Soil Properties in Dominica, West Indies. Engineering Geology, 23. Elsevier Science Pubs. Amsterdam. p1-28.

Saroso B.S., Dowling J.W.F. and Heath W. (1983). Terrain Evaluation for Road Engineering in Indonesia. 4th Conf. of the Road Eng. Ass. of Asia and Australia. Aug. 1983. Jakarta, Indonesia. Vol. 5 p575-599.

Skempton A.W and DeLory F.A (1957). Stability of Natural Slopes in London Clay. Proc. 4th Int. Conf. Soil Mech. London, 2, 378-381.

Subardja and Buurman P. Soil Catenas on the West and North-east Slopes of the Lawu Volcano in East Java. Buurman P. (Ed.) (1980) Red Soils in Indonesia. Agricultural Research Reports 889. Bulletin No 5. Soil Research Institute, Bogor, Indonesia. p49-67.

Tavenas F. and Leroueil S. (1981). Creep and Failure of Slopes in Clay. Canadian Geotechnical Journal. 1981-02 v18 (1) p106-120.

Terzarghi K (1958). Design and Performance of the Sasumua Dam. Proc. Inst. Civ. Eng. London. No. 9 p369-393.

Vargas M (1974). Structurally Unstable Soils in Southern Brazil. Proc. 8th Intern. Conf. on Soil and Foundation Engineering, Moscow, Vol. 2 p239-246.

Wesley L.D (1977). Shear Strength Properties of Halloysite and Allophane clays in Java, Indonesia. Geotechnique 27 No 2. p125-136.

Whipkey R.Z and Kirkby M.J (1978). Flow Within Soil. Hillslope Hydrology. Ed. Kirkby M.J. Pub. John Wiley and Sons. Chapter 4. p121-145.

contents of up to 40% the soil is saturated. In this condition slow deformation and creep occurs. Whether it is further increases in pore pressure which causes the translational slides to develop was never determined because of the poor response of the piezometers.

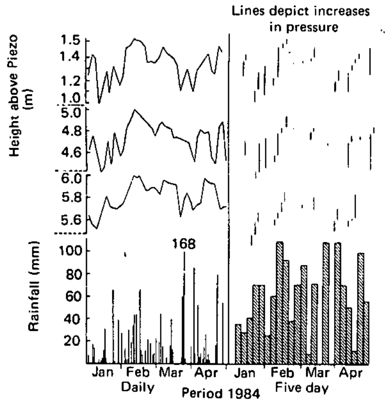

Fig 9: Response of pore pressure to rainfall

However such slides can be modelled in terms of shear stress/strain forces acting on the slope. The piezometer data indicates that the pore pressure at a depth of two metres could be equivalent to or exceed a 2.5 metre head of water, equal to a gauge pressure of 25 kN/m², during heavy rain. Based on an infinite slope analysis (Skempton and DeLory 1957) a calculation of the slope safety factor for a 2 metre deep translational slide shows a factor of safety well below unity for such piezometric pressures. A factor of safety of one occurs when the depth of water is at 0.2 metres. This is based on a 4.5:1 slope gradient and soil parameters of c' equal to 9.8 kN/m² and φ equal to 13°. These soil shear strength values were obtained from drained triaxial tests of samples recovered from just below the failure plane.

Mudslides occur further down such slopes and moisture levels of 59% have been determined from saturated samples. The liquid limit of these soils, determined from laboratory tests, was 78%. The difference possibly relates to the clumping of relatively dry soil particles within a very saturated matrix. The soils recovered from mudslides have a liquidity index of about 0.58 per cent which corresponds with that of a larger sample reported by Brunsden D (1984), in which the majority had a liquidity index of 0.4 per cent or more.

5.1.3 Lower slope basin: Less reliability could be placed on long term pore pressure data from this location because of a translational slide which occurred in the area. In 1985 it was found that the piezometer pipes had sheared at a depth of two metres. From the data it appeared that failure occurred during April 1984. New ceramic piezometer tips, connected to metal pipes, were installed in March 1985. In March 1986 the pipes attached to piezometers at depths greater than two metres had disappeared and were eventually located, folded and horizontal, at a depth of two metres. The sliding mass had pushed these pipes over. Piezometers above the two metre level were not damaged and indicated no abnormal groundwater conditions. Slope movement was calculated to be 1.8 metres over a period of twelve months of which approximately half a metre was attributed to the translational slide and the rest to rapid creep. Surprisingly there were no other signs on the slope to indicate that such a large amount of movement had occurred.

5.2 Hydrological patterns of slope failure

The basin morphometry and colluvium/shale soil conditions, as described, are widespread and relate to the described mechanisms of failure on all similar slopes. The hydrological aspects of what appears to be a common pattern of groundwater movement in permeable soils is relevant to slope stability conditions in Java. This pattern can be summarised as follows:

1) All failing slopes are in areas where groundwater is retained in highly porous deposits and supplied to the slopes continuously.

2) The groundwater on such slopes is confined to narrow layers of colluvium by impervious sediments and clays. Measurements show that a high pore water pressure and soil saturation occurs within these layers.

3) Any disruption to flow caused by the collapse of fissures or natural soil pipes, etc leads to rapid translational sliding.

4) At the toe of such slopes groundwater flow is disrupted by collapse and the resultant ponding causes mud-flows to develop.

5) On the road section of the slopes there is a loss of support and the road-fill fails in a circular slump. The moment of rotation is generally through the centre section of the road pavement.

6. CONCLUSION

The present study has provided results which indicate that the mechanism of slope failure affecting much of the road network in Java is related to a saturation of the soil mass promoting slope creep. This is induced by upslope deposits which have a rechargeable high storage capacity and provide a considerable hydraulic yield to the unstable slopes. Slopes in general are sensitive to such saturated conditions because of the high percentage of active clays that the soils contain.

The instrumentation results generally support the view of a high infiltration and discharge capacity in the breccia and a confined high yield aquifer developing in the colluvium. The test data has therefore helped to conform the mechanism of failure although the slow piezometric response resulted in a loss of some data relating to sudden transient changes in storm induced groundwater surges. These conditions appear to result in translation failures and mudslides. On the road section of such slopes, where landslides are most easily observed, the failure mechanism is