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THE METHODOLOGY AND RESULTS OF SLOPE STABILITY STUDIES IN INDONESIA

SUMMARY

Java is characterised by a central hilly to mountainous volcanic belt comprised of deeply weathered Tertiary ashes and tuffs resting on a relatively weak and unstable sedimentary sequence dominated by mudstones. The region is one of the most tectonically active in the world.

The paper describes research undertaken to develop a methodology to study existing road slopes and to recommend guidelines to promote safe slope construction. The research was co-funded by the International Bank for Reconstruction and Development (IBRD) and the Department for International Development (DfID) and carried out by staff of the Transport Research Laboratory (TRL) collaborating with staff of the Institute of Road Engineering (IRE) in Bandung, Indonesia.

Existing slope data were reviewed but since they were so diverse it was necessary to devise a new data system. This is described in the paper and consisted of about 150 fields grouped into 5 database files. Selected road sections in Java were then chosen on the basis of geology and terrain. About 40, totalling 1100km of road, were investigated and detailed measurements made on 500 individual slopes, mostly cuts. Road sections where failures had occurred and others where no failures had occurred were compared. The data were analysed empirically to derive correlations between slope height and angle and the likelihood of failure for the range of materials occurring in Java. The paper discusses these results.

The knowledge gained can be used to improve the design procedures for new road projects: for existing roads it can be used to improve maintenance treatments.

1 Introduction

The paper outlines the development of a database system for the collection, collation, analysis and reporting of slope stability information in Indonesia. This research was a collaborative venture between the British Transport Research Laboratory (TRL) and the Indonesian Institute of Road Engineering (IRE), the research body of the Department of Public Works. The research was initiated in 1988 and was aimed firstly at determining the extent of the slope problem and secondly at obtaining an insight into possible mechanisms of slope failure. These are identified generically in Table 1. Although a considerable amount of information had accumulated no systematic collation and analytical review of it had been done. During 1991-93, as part of an IBRD-funded research and training project, the Indonesian Slope Information System (ISIS) was developed. A later (1995-7) study used ISIS to survey roads in Java and, later, in Maluku (Cook & Woodbridge, 1997). This report concerns the results of the work in Java.

2 Background

Indonesia is a developing country with an increasing road network. The majority of the roads have up till now not involved the construction of major earthworks. Roads in hilly terrain have been designed to suit the constraints of topography. The future highway network, including the upgrade of existing roads, will increasingly conform to international designs. The result will be that roads within hilly and mountainous terrain will have to be built with larger earthwork components. Because of this it is necessary to make a closer examination of the principles concerned with the adequate performance of highway slopes and to develop a design strategy that serves the Indonesian geotechnical environment. The climate is predominantly wet tropical and has had profound effects on rock weathering. The Indonesian islands, influenced by three major plate tectonic units, have a very diverse geological make up. The region is one of the most earthquake-prone in the world (Sukamto & Pubo-Hadiwijayo, 1997).

The initial objective of the ISIS was the creation of a database of slope information concerning the road network in Indonesia. Allied to the setting-up of this database was the formation and training of a team of IRE geologists, engineers and computer operators practised in its design and operation (Cook et al , 1992).

3 Development

The guidelines for setting up ISIS were as follows:

- a microcomputer database system was used, capable of accommodating differing levels of information from a variety of sources, and with different reliabilities
- Field collection of data was based on the completion of straightforward, standard sheets designed to minimise operator bias
- Data collection from the existing roads would include information on both stable and unstable slopes, and
- Terrain and geological bedrock information in the ISIS database would be included for the purposes of future research. The Indonesian Land System maps were utilised to identify terrain types in conjunction with field data on slopes.

Four phases of activity were planned: data collection, data storage and collation, data analysis and data dissemination. Data collection procedures were designed to suit the input of large amounts of numerical and non-numerical data into a commercial database package. Use was made of coded options under the general headings of location; setting; slope shape; slope condition and slope failures. Table 2 lists the principal data sets in the central database. Data storage and collation, data analysis and data dissemination are based on the effective utilisation of software complying with the following specification:

- Capable of handling large amounts of data in DBF data file format allowing the design of relational tables
- having powerful command language for manipulating data and probably too powerful and extensive for the novice user; hence the need to design an interface between the user and the complex data file structure, so that
- data integrity is not compromised during its entry into the system
- a structured approach to maintaining and updating information is achieved
- a simplified data query and retrieval system is made available to the researcher.

4.0 The Java Survey

4.1 Data Collection Methodology

A standard procedure was adopted for data collection. First, ‘quick’ surveys were carried out on road routes with potential interest, for instance if they traversed key geological formations or major terrain types. If the ‘quick’ survey was successful, a detailed survey was done. Each individual survey is specified as a Site. A Site, generally a specific road section, was divided into a number of Locations; at each Location, data were systematically measured and entered onto a number of standard forms The Natural Slope form contained data relating to the general morphologic and geologic features of the terrain which the road traversed. The Earthwork Slope form contained specific details relating to the slope; if the slope showed a slope failure, then specific measurements were entered onto a Failure Slope form. Serious failures were more closely examined and estimates made of the material volumes involved in the failure: data were entered onto a Special Failure Slope form. Natural Slope and Failure Slope details were taken for only a few locations. Examples of the field forms used for the Earthwork Slope are presented in Figure 1.

Certain exclusion criteria were applied to data collection. If slope heights were less than 5m they were generally not evaluated. Obviously it was not possible to examine all the slopes fulfilling the criteria. The fieldwork was undertaken by IRE engineering staff under the supervision of senior IRE staff.

The field data were entered into the databases by the field teams and checked by the supervisor. Subsequently analysis of these data was carried out by local, computer-literate staff according to a recommended pro-forma.

Altogether 37 Sites, totalling 1200 km of road were surveyed. 207 Natural slope locations were described, 138 in volcanics, 41 in mudstones and 28 in limestone. 468 separate Earthwork slopes, comprising 379 in volcanic material, 74 mudstone/siltstone and 28 in limestone were examined, totalling 60 km, or 5% of the roads surveyed. Of these 188 had Failure slopes, 157 in volcanics, 25 in mudstone and 14 in limestone. There were about 10 Special Failure locations.

4.2 Java: general comments on geology, climate and terrain

The engineering geological environment in Java in relation to geology and climate can be summarised as follows:

- Recent intense volcanic activity with an abundance of tuffs, ashes and lahars.
- Soil profiles derived from the weathering of the volcanic materials having geotechnical characteristics significantly different from comparable temperate soils.
- The occurrence of a hydrogeological unconformity between the relatively highly permeable volcanic materials and underlying relatively low permeable sedimentary rocks: this unconformity is a plane of potential failure.
- Ongoing volcanic and earthquake activity in Java constituting an ongoing serious potential slope hazard.

The Indonesian land-system mapping indicated over 100 separate land systems within Java (RePPProT, 1990), combined into 5 groups:

A: Mountainous and steep hill slopes
B: Dissected plains and moderate hills
C: Rolling hills and plains
D: Low and degraded hill slopes
E: Low-lying alluvial, lacustrine and coastal plains.

The bulk of the earthwork information came from groups A and B.

Material has a significant impact on slope stability in Java (Wesley, 1973, Cook and Younger, 1994). Five main tropically weathered soil-rock mass types are identified:

A: Volcanic masses
B: Clastic sedimentary masses
C: Bioclastic (limestone) sedimentary masses
D: Combined volcanic and clastic sedimentary masses
E: Combined volcanic and limestone masses.

The combination of geology with terrain provides a significant indication of zones of potential natural slope hazard in Java. Table 3 lists land systems that have the highest percentage of failures and confirms that the occurrence of sedimentary sequences in combination with volcanic profiles are the most hazardous. The interaction of geology and terrain at the macro-scale level is indicated by Figure 2, which illustrates hazards associated with various land facets within the volcanic-sedimentary systems.

The variable impacts of geological structure on Java slope hazard are largely a function of the contrasting volcanic and sedimentary soil-rock masses, of which the following are of particular significance:

- an irregular discontinuity between Tertiary argillaceous sedimentary rocks and overlying Recent volcanic materials
- occurrence of weak layers within bedded pyroclastic deposits
- relict fabric within pyroclastic and reworked pyroclastic materials
- occurrence of large fault patterns: Saroso (1984) reports on some natural failures in Java initiated at the intersection of East-West and North North East - South South West regional joint sets.

Hydrology has a major influence on slope hazard in Java (Wesley, 1973, Saroso, 1984; Heath et al 1990). High permeability limestone and volcanics overlying low permeability argillaceous materials are identified as a potentially major hazard and the main cause of many failures.

4.3 Java: results from ISIS analysis

The principal conclusions are:

1. In the Recent volcanic tropically weathered residual soils, slopes up to 12m maximum height can be safely cut at about 60° (3V:1H), see Figure 3. Failure hazard can be further reduced by regularly maintained drainage and erosion protection enabling even steeper slope angles to be cut in some circumstances.

2. In the Tertiary sedimentary sequence contrastingly, particularly in argillaceous materials, slope must be cut at flatter angles of 10° to 12° (1V:4H), see Figure 4.

3. Where argillaceous material underlies the volcanics, the interface is a major, unpredictable geotechnical weakness. Excavations where this interface is exposed, or is close to exposure, require special design with particular attention being paid to face drainage.

4. Most earthwork slopes in Java lack proper provision for drainage and minimal maintenance is carried out. This has a significant impact on the incidence of slope failure.

5. Rainfall patterns for most of Java involve distinct drier and wetter periods. Intense or prolonged periods of rainfall following the drier months are often likely to trigger natural and earthwork instability.

6. The establishment of a protective vegetation cover on earthwork slopes is not usually

programmed. Only 17% of the slopes studied had a substantial vegetation cover. Where natural growth is slow to develop, weathered volcanic soils can develop a loose fabric that quickly deteriorates to scree, inhibiting the development of vegetation.

7. A limited range of remedial works is currently employed on earthwork slopes. Research is being carried to indicate more appropriate cost-effective methods suitable for Java.

8. In the road surveys where the quantity of fill materials in cut-fill situations is significant, the fill fails prematurely owing to inadequate engineering. This may be due to a combination of the interaction of the imposed road on a natural slope and uncontrolled spoil dumping from cut excavations. The latter is still common on Java road projects and leads to down-slope failure, and can be a significant factor in earthwork slope deterioration.

9. There is some evidence for an age-related degradation of slopes back to natural slope angles unless arrested by timely maintenance and remedial programmes, see Figure 5. Erosion of earthwork slopes can be shown to have a definite impact on overall condition, although most volcanic soils are not highly erodible and gradual increase of erosion with time may be a significant factor in the age-deterioration of slopes.

10. Either civil engineering projects or agricultural development may cause changes in vegetation. The development of irrigated rice padi up-slope of earthworks could cause significant increase in potential slope hazard. Some control on agricultural use is necessary adjacent to large highway earthworks. Leakage from irrigation pipes and channels has been noted as a frequent triggering mechanism.

5 Future ISIS Development

ISIS is a data collection and collation system concerned largely with the location, size, geometry and condition of earthwork and natural slopes. Its usefulness has been demonstrated in support of hazard assessment research and road betterment and design projects. There is, however, considerable scope for increasing its breadth and usefulness, as itemised below:

1. The inclusion of data files on the geotechnical and hydrological characteristics of slopes could enhance the technical scope of ISIS. In combination with the detailed failure information and the application of back-analysis techniques, more numerate-based information on slopes could be made available.

2. ISIS could be expanded into an Indonesian-wide database of basic slope location by utilising provincial engineers available in the provincial offices.

3. Integration of elements of the TRL Earthwork Condition Assessment Technique (ECAT) into ISIS could prove most beneficial. The ECAT system employs a low-level oblique photographic technique to assess the condition of earthworks and the combination of this with the ground-proved data from standard ISIS procedures would prove a powerful, and cost beneficial, tool for the systematic monitoring and maintenance of slopes throughout Indonesia.

4. ISIS knowledge on scope failure has clear links with GIS research into slope hazard and the development of slope stabilisation techniques. ISIS data has recently been utilised in the production of research reports on Indonesian slopes (Cook, 1998; Cook and Woodbridge,1998).

5. ISIS could be applied to the development of a more systematic approach to the design, construction and maintenance of the Indonesian road network. This can be achieved by the direct supply of relevant data to Public Works' databases or by being

part of the framework for a knowledge-based approach to road construction. ISIS could be integrated into an overall geotechnical database able to support information-based decisions at key levels in a highway project.

6 CONCLUSIONS

1. A computerised database system has been developed for the collection and collation of road slope information.

2. The data collection is straightforward, once the road traverses have been selected, and can be carried out without specialist knowledge. Data entry is standardised and can be protected against error.

3. Data analysis has resulted in the derivation of a large series of empirical relationships.

4. The system was tested by undertaking selected traverses on 1100km of roads in Java and detailed measurements made on 500 individual slopes. Analysis of the data indicated that the present system of Indonesian slope design maintenance is poor and requires reassessment.

5. An ISIS scheme should be initiated for every new road project. Timely application of the ISIS results and conclusions could result in reduced slope maintenance costs.

6. The system could be modified to suit the requirements of other countries. In particular it could be expanded by incorporating GIS techniques.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Cook J.R.(1997). Guidelines on Indonesian Slope Design. IBRD Road Research Development Project, Bandung. TRL Report to Ministry of Works, Indonesia.
Cook J. R. and Woodbridge M.E. (1997). Highway Slopes in Java. IBRD Road Research Development Project, Bandung. TRL Report to Ministry of Works, Indonesia.
Cook J.R. and Younger J.S. (1994). The impact of the characteristics of Indonesian soils on construction. Proc. 13th Int. Conf. SMFE, New Delhi.
Cook J.R. , Beaven P.J & Rachlan A.(1992). Indonesian slope inventory studies. Proc. 7th Conf. REAAA, Singapore
RePPProT (1990). The Land Resources of Indonesia: A National Overview. Land Resources Dept (Indonesia), ODA. 281 pp.
Sukamto K and Pubo-Hadiwidjoyo M M (1997). Indonesia: In Encyclopedia of European and Asian Regional Geology, Moores E. and Fairbridge R. (eds). Chapman Hall, 376-384.
Wesley L.D.(1973) Some basic engineering properties of halloysite and allophane clays in Java, Indonesia. Geotechnique, 23, 471-494.

Keywords: roads; slope stability; Indonesia; Java; inventory; database; analysis

Slope Hazard Type	Description
Volcanic Hazards	Landslide hazards primarily associated with contemporary volcanic activity, these may be lava and pyroclastic flows; caldera-collapse avalanches; and hot or cold laharic flows.
Natural Landslides	Failures on natural slopes, usually associated with young developing terrain. In Java for example this may involve the re-activation of marginally stable laharic slopes.
Cut-slope Failure	Failure of man-made excavation faces
Embankment Failure.	Failures of man-made embankments. These may be sub-divided in to those associated with failure of the fill material and those associated with the failure of the foundation material.
Combined Cut-Embankment Failure	This form of failure is associated with the reasonably common road-section situation in hilly terrain where material has been excavated up-slope and placed down-slope to form a carriageway partly in cut and partly on fill.
Combined Earthwork and Landslide Failure	These failures occur where either natural instability has caused earthwork failure or where the impact of excavation or fill placement has resulted in the failure of natural slopes.

Table 1 Slope Hazards in Indonesia

General Site	Natural Slope Location	Earthwork Slope Location	Slope Failure Location
Province Site Reference no. Site type Location by road link Location by map reference Topographic maps Geology maps Land system maps General terrain Rainfall conditions	Site reference no. Location reference no. Slope type Location by chainage General geology Land system Slope height & angle Slope profile Terrain setting Slope material Land use Vegetation cover Hydrological conditions Recent weather Slope condition Photograph	Site reference no. Location reference no. Slope type Location by chainage General geology Land system Overall slope height & angle Slope geometry (profile/plan/shape) Slope length Road section & profile Berm numbers & width Bench heights & angles Slope material Geological structure Slope condition Drainage Remedial/stability works Vegetation cover Hydrological conditions Recent weather Upslope height, angle & condition Downslope height, angle and condition Natural slope sheets ? Failure sheets ?	Site reference no. Location reference no. Failure reference no. Location by chainage Failure type Failure size Failure location on slope Failure profile Back-scar height & angle Failure angle Failure condition Failure causes Failure material Actual & potential damage Remedial works & effectiveness Failure date Photograph references Sketches

Table 2 ISIS Inventory Data Sets

Land System Units	
Geomorphology	Bedreock Geology
Strongly dissected tilted plateaus on tuff sediments	Tuff; lahar;sandstone;mudstone
Very steep ridges on tuff sediments	Lahar; mudstone
Hillocky plains on mixed sediments	Sandstone; mudstone; conglomerate
Hillocky plains on directed crystalline tuff sheets	Lahar; mudstone
Irregular mt. ridges on intermediate andesitic volcanoes	Andesite, basalt; breccia
Irregular mt. ridges on intermediate andesitic volcanoes	Marl; andesite; basalt; breccia
Asymmetric broadly dissected ridges on sst and mdst	Sandstone; mudstone
Young intermediate strata volcanoes	Andesite/basalt;lahar
Parallel ridges on volcanic tuffs in dry areas	Lahar; ash
Flat to undulating volcanic plains	Alluvium; recent volcanics;lahar
Undulating to rolling sedimentary plains	Tuff; conglomerate; mudstone
Moderately dissected lava flows	Andesite; breccia; lahar
Moderately steep and dissected lahar slopes	Alluvium - recent volcanics
Hillocky plains on lava flows in dry areas	Andesite; breccia;lahar
Steep hills on marls with rock outcrop	Limestone; sandstone; mark

Notes: Decreasing hazard from top to bottom
Listing based on ISIS data for cut-slopes and natural slopes

Table 3 Land System Units In Java Listed in Terms of Slope Hazard

SHEET 3: EARTHWORK SLOPE

1. Province		2. Site No.	
3. Location No.		4. Slope type	

5. Chainage			
6. Geology		7 .Land system	

8. Overall angle		9. Overall height	
10. Slope profile		11. Slope plan	
12. Slope shape		13. Slope length	
14. Road section		15. Road profile	
16. Berm Nos.		17. Berm widths	
18. Bench heights		19. Bench angles	
20. Material			
21. Structure		22. Favourability	

23. Upslope H		24. Upslope angle	
25. D/slope H		26. D/slope angle	
27. U/slope erosion		28. U/slope stblty	
29. D/slope erosion		30. D/slope stblty	

31. Drainage		32. Engineering	
33. Vegetat'n type		34. Vegetation %	
35. Hydrology		36. Weather	

37. Slope erosion		38. Slope stblty	
39. Slope sheets		40. Failure sheets	

41. Photos		42. Sketches	
43. Inspectors		44. Date	

45. Comments

SHEET 4: FAILURE DETAILS

1. Province		2. Site No.	
3. Location No.		4. Failure No.	

5. Chainage		

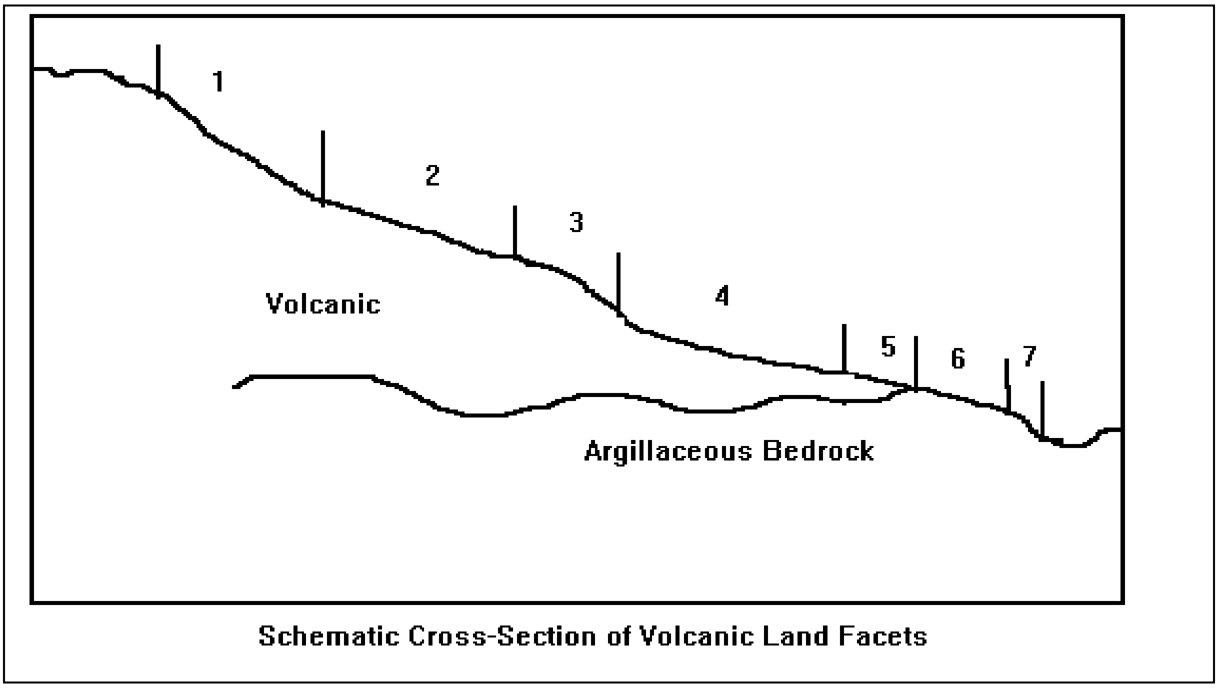
6. Fail type		7. Fail size	
8. Fail location		9. Fail profile	
10. B/scar H		11. B/scar angle	
12. Fail angle		13. Fail condition	
14. Fail causes			
15. Fail materials			

16. Damage caused		17. Potential	
18. Remedials		19. Effectiveness	
20. Fail date			

21. Photos		22. Sketches	
23. Inspectors		24. Date	

25. Comments

Figure 1 Typical ISIS Field Data Collection Sheets



|__________| Approx. 50m

Facet	Description	Slope Hazard
1	Steep Upper Volcanic Slopes	Lava/laharic flow; non-geotechnical hazard
2	Older Laharic Slopes	Reactivation by erosion - debris slide
3	Older Laharic Scarp	Back-sapping/erosion of slopes above
4	Volcanic/Shale Slope	"Reservoir" translational slide or creep
5	Volcanic/Shale Unconformity	Spring-line erosion influencing Facet 5
6	Shale Slope	Shallow translational failure, especially if debris covered.
7	Alluvial Terrace	Toe erosion leading to activation of slopes above .

Figure 2 **Land Facet Hazard in Volcanic-Argillaceous Bedrock Terrain**
(Modified from Sarosso 1984)

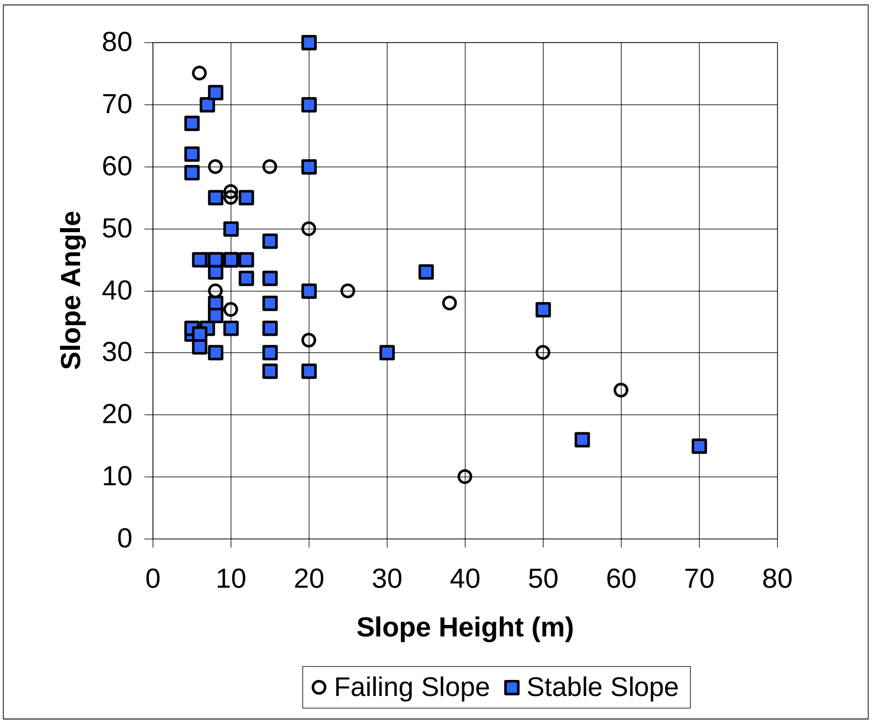


Figure 3 **Slope Height-Angle Relationships for Volcanic Cut-Slopes in a Single Land System**

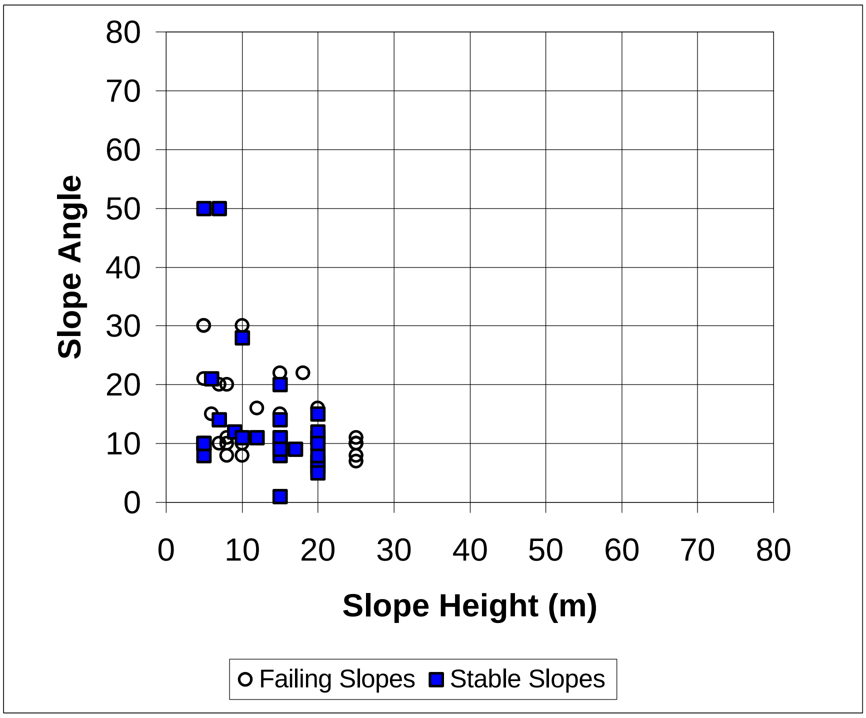


Figure 4 **Slope Height-Angle Relationships for Mudstone Influenced Cut-Slopes in a Single Land System**

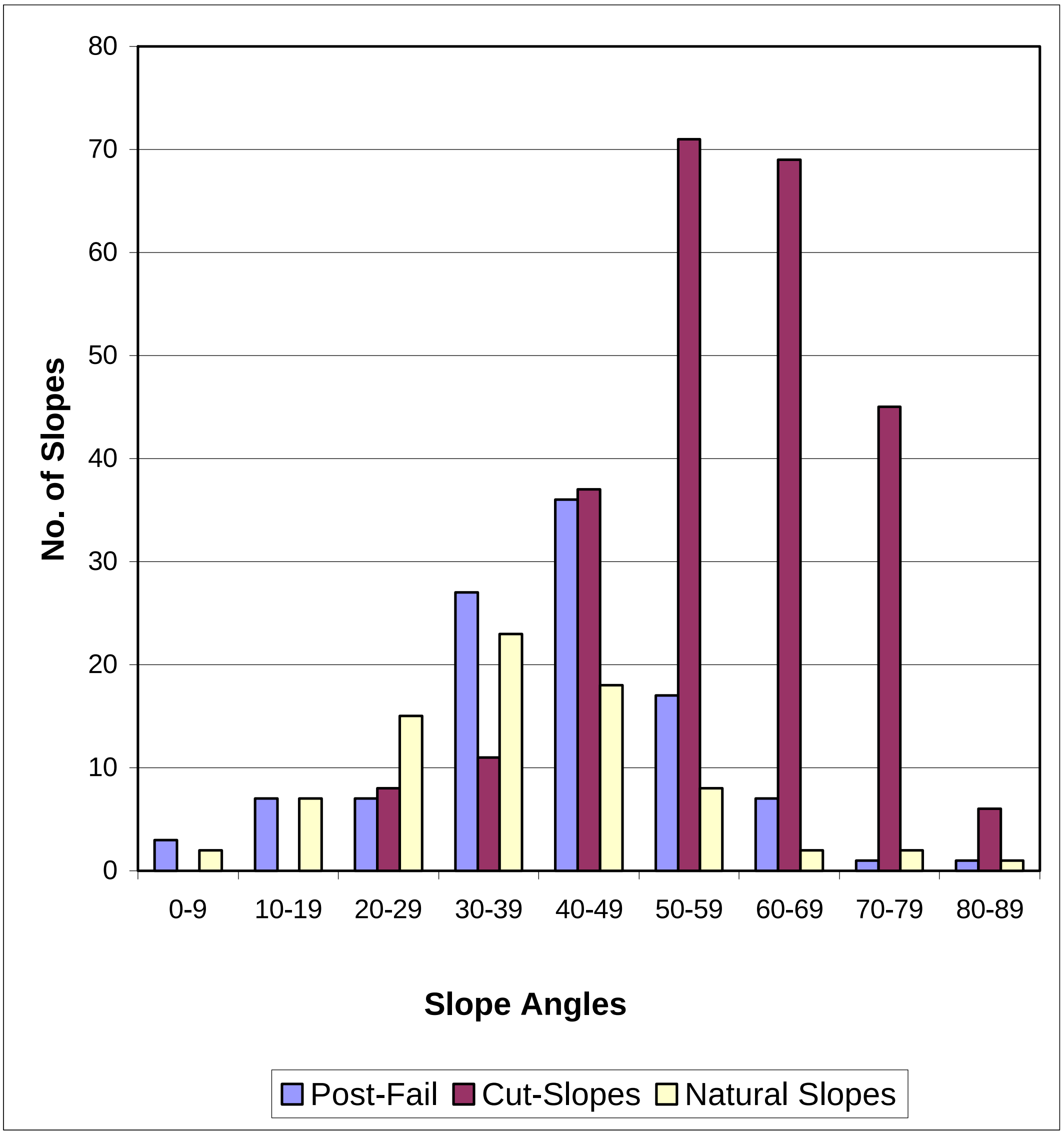


Figure 5 Comparison of Natural, Cut-Slope and Post-Fail Angles in Java Volcanic Materials