Slope failure in surficial weathered tuff induced by the regional drainage system

Rupture de talus en tuf effrité en surface, induite par le système régional de drainage

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SYNOPSIS The failure of a slope cut in the Upper Canal of the Kalayaan Project (Philippines) was originated by large fluctuations of the water table. Despite the project morphology,modelled in weathered tuff, could not evidenciate any important phreatic level for the design of slope cuts, the underlying volcanic agglomerate resulted, as a regional water bearing formation, the cause of the oscillating water table in the upper formations, thus triggering the instability of the slopes already cut. The strength parameters of the weathered rocks involved in the failures were evaluated from back analysis and they may be of interest to other geologists and engineers, since their determination with standard methods is practically impossible.

THE PROJECT

The Kalayaan Pumped Storage Plant, at about 60 km southeast of Manila (Philippines), exploits the head between the Laguna de Bay and the existing Caliraya reservoir. The plant is to be developed in six stages up to the final installed capacity of 1800 MW, with stepping installments of 300 MW at each stage.
The project consists of:

(i) an upper canal,connecting the Caliraya lake to the intake, with capacity for 360 m^3/s.

(ii) the intake, a 25 m high concrete gravity structure.

(iii) the penstock, 6 m diameter and 1340 m long.

(iv) the powerhouse, an elliptical shaft with 38 m maximum inner diameter, 40 m deep.

(v) a switchyard, a dock and a lower canal.

The upper canal is the prolongation of the existing intake canal for Caliraya hydroplant. Its total length is 1500 meters, of which 1100 m represent the new excavated canal. The canal and the intake are underlain by tuff and basalt flows. The depth of weathering is about 15 meters and interests the total thickness of the tuff, below which the basalt, even weathered, is more compact and massive. The entire length of the upper canal has been cut in soft weathered rocks.

GEOLOGY

Rocks and Stratigraphy

The project area is part of the eastern Sierra Madre range,along the eastern part of the island of Luzon and is underlain by a sequence of volcanic rocks with intercalated sedimentary beds. The volcanic sequence include:

- basalt or andesite flows
- agglomerate of fragmental basalt-andesite cobbles and boulders
- tuffs

The basalt or andesite are found as lava flows from fissure and vent eruptions. The development of agglomerates is mainly due to some solidified blocks from the explosive activity, while the tuffs, with fairly regular and uniform stratification, seem to have been deposited in a large standing body water.
Rock weathering is strongly developed and in general the local rocks, both agglomeratic or lava flows, are altered and sometime totally argillized for several meters from the surface. The soil from rock decaying is formed by a highly plastic clay with a percentage of fine sand. Gravel and sand are scarse but coarse detrital masses are thick under the lacustrine surficial deposits.

Structure and Tectonics

Ground evidences and geomorphologic features confirm the presence of a N-S trending normal fault, consequent to which are tension faults and fractures on a WNW-ESE orientation. Jointing patterns are either parallel or transversal to the orientation of the main geological structures.

Geomorphology

The land east of the Laguna de Bay is a broad plateau, broken by east-west trending drainage channels following the soft spots of the underlying formations.
Further east the broad rolling landscape changes to a moderately rugged terrain without any set orientation of mountain peaks and lowlands.
The land, in general, gently slopes to the Pacific; the nearly flat disposition of the plateau helped in the development of a deep zone of weathering with meager erosion.

ENGINEERING GEOLOGY

Andesite-Basalt

Except where it is highly altered by surficial weathering, the fine-grained basalt and the andesite respond as a tough material. In the case of the porphyritic varieties, however, the engineering properties of the rock are very heterogeneous, depending on the degree of alteration.
The glassy matrix of the vesicular basalt responds as a brittle material and tends to become fragmental even under a light pressure.

Agglomerate

The agglomeratic rocks in the project area are fairly thick and gradational into conglomerate. The lithic inclusions consist primarily of angular cobbles to boulders of basalt and tuff in a groundmass consisting primarily of volcanic ash and glass shards. Pumiceous materials have been noted.

Tuff

The term "tuff" is applied to all rocks in the project area consisting primarily of pumice, volcanic ash, and glass shards.
The degree of induration varies from slight to moderate with some indications of stratification, in thicknesses of approximately 10 cms. Spherulites and the presence of vesicules, pumice and some other smaller volcanic ejecta lead to the non-uniform texture of most of the tuff strata.

UPPER CANAL: The Slopes Problem

For the design of the cut slope through the weathered layers of tuff and basalt the basic parameters were obtained during the site investigation.

Shear Strength of the Materials

Weathered materials are difficult to sample and laboratory tests can be misleading due to the true nature of these particular soils.
It was felt that a large scale test would better answer to the question. A trial cut,rectangular in shape, was cut along the alignment of the future canal. The height and slopes were those of the future work.
It was under observation for almost two years and no signs of instability were observed to have developed.
From back analysis the resistance of the soil was determined and the canal slopes designed with a factor of safety against sliding well above 1.5. The design slope was then 1.75 in 1.

Ground Water

No piezometers had been installed in the boreholes, therefore the occurrence of any ground water was derived from surface observation and the trial cut. It was concluded that the acquifer was very deep,discharging into the Laguna through the base rock formations.
Water percolating through fissures was only present in the upper surface layers, related to the rainy season. It was assumed therefore that water was not so abundant in the upper formations as to form an acquifer with a continuous piezometric surface.

The Slope Failure at the Intake

The intake slopes have been excavated from March to middle of May, 1978.
At the end of May the rainy season started and soon after a small slide occurred at the right bank, nearby the intake, involving the upper part of the slope. This happened at the beginning of June 1978 while another major slide occurred the 12th of August 1978, in the middle of the rainy season.

The Site and the Stratigraphy

The area, where the intake has been located, is the beginning of a gentle slope that from the high plane reaches the steep slope above the Laguna. The general stratigraphy of the area is made of an upper surface tuff layer followed by a more consistent volcanic rock, either agglomerate or basalt. The tuff, generally highly weathered, has the consistency and mechanical behaviour of an overconsolidated clay, at the least in the upper part of the deposit.
For this reason, as part of the valley forming process, small slope failures can be detected in the area, due to the combination of the erosion and the progressive loss of strength as a consequence of weathering of the surface soil.
The site investigation carried out in the slide area has shown the presence of two formation:

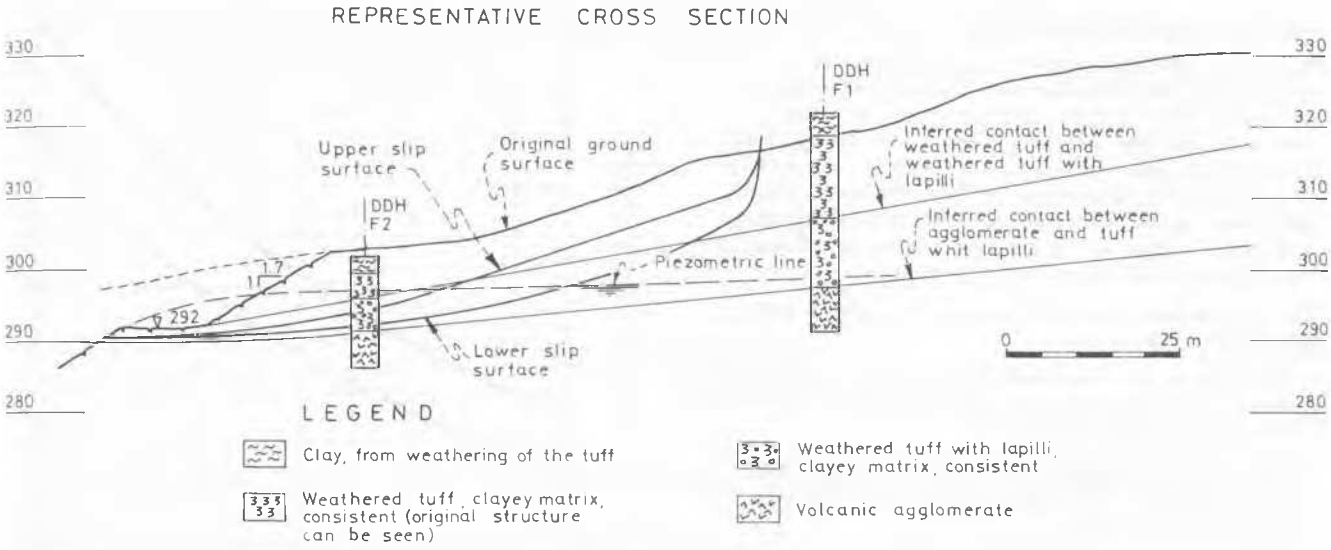


Fig. 1 - Intake - Slope Failure in the Right Bank - Representative Cross Section and Critical Slip Surfaces

- upper formation: tuff,highly weathered. The surface layers can be defined just as clay
- lower formation: volcanic agglomerate.

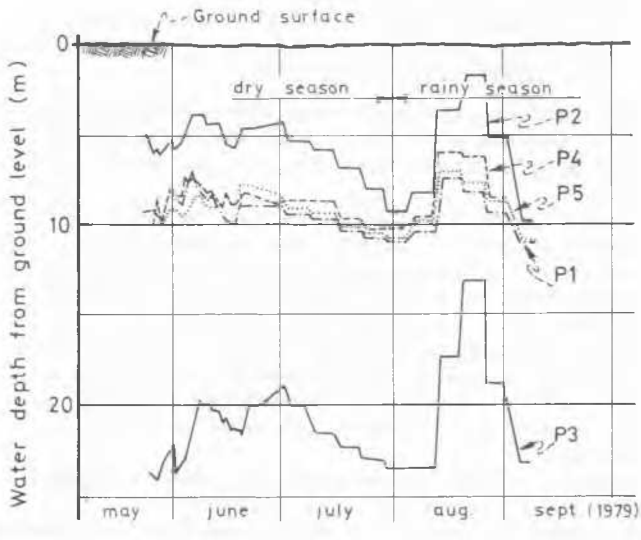
Within the upper formation it has been possible to distinguish between two types of tuff: yellow and rather sandy with a fine matrix and tuff with lapilli.
On Fig.1 the inferred correlation among these materials, based on the boreholes and test pits, is shown on the representative cross section of the slide, while Fig.2 reports the fluctuations of the water table levels during dry and rainy season as measured in the eventually installed piezometers.

It can be seen that:

- the contact surface tuff-agglomerate gently raise uphill
- the thickness of the tuff with lapilli decreases from uphill to downhill. It is sloping toward the cut.

Water has been observed coming out at the contact more or less along the whole front of the slide. In the piezometers ground water has been measured and based on these data a piezometric line has been traced.
In addition it was observed from the recovered samples that the tuff with lapilli has in general a high water content.
The following can be said in conclusion:

- the layer of weathered tuff with lapilli has to be considered pervious with respect to the other present formations.
  A fluctuating water table, recharged by the agglomerate below, builds up pressure at the toe of the slope, where its thickness decreases
- the volcanic agglomerate shall be regarded as the water bearing rock formation. Its extension below the entire plateau is such that water will flow through it regardless of the local morphology.



Piezometer installed in the upper weathered tuff layers

'ig. 2 - Intake - Fluctuations of Water Table Levels as Measured in the Piezometers

Back Analysis of the Slide

Based on the geometry of the slide, the geological survey carried out and the data gathered during the site inspection, the location of the sliding plane was tentatively plotted on the representative cross section. The stability analysis of the enclosed soil body has permitted the determination of the possible range of the shear strength along that plane for the slide to occur.

The principal factors determined after the investigation are:

- the slide is translational, with a sliding plane surface that is approximately paralled to the ground surface
- movement has taken place along the contact between tuff and agglomerate and through the tuff with lapilli
- the layer of tuff with lapilli and the volcanic agglomerate are water bearing. Water was actually seeping out along the contact exposed in the canal cut. The piezometric line in the soil mass has been tentatively located as in Fig.1
- contact surface is locally irregular, but has a general trend, established on the boreholes results: its dip is approximately 10° toward the canal
- catchment area relative to slope where the slide occurred should be much larger than that inferred from the topography. This hypothesis is based on an approximate proportion between amount of water actually seeping and topographic catchment area. As discussed before, the volcanic agglomerate with its lateral extension shall be considered responsible for this unbalanced proportion.

Several slip surfaces have been studied within the boundaries of the actual slide, until the two more critical were located, as shown in Fig. 1.
Stability analysis were carried out with the Janbu method. It has been assumed that cohesion is zero along the failure plane, in consideration of the large movement occurred, estimated in the order of 1 to 2 m.
The procedure ha been as follow: F_s was set equal to 1 and φ' determined as a function of pore water pressure u, introduced through $r_u = \Delta u / \sigma_v$, with σ_v = total vertical stress.
Results of the calculation are shown in Fig.3 for the two critical slip surfaces.
In practice $r_u = 0.2 \div 0.3$ has been considered as the possible range. In the present case, the upper bound for the piezometric surface was suppose to coincide with the contact between tuff and tuff with lapilli, therefore:

- $r_u = 0.15$ for the upper sliding plane
- $r_u = 0.23$ for the lower sliding plane

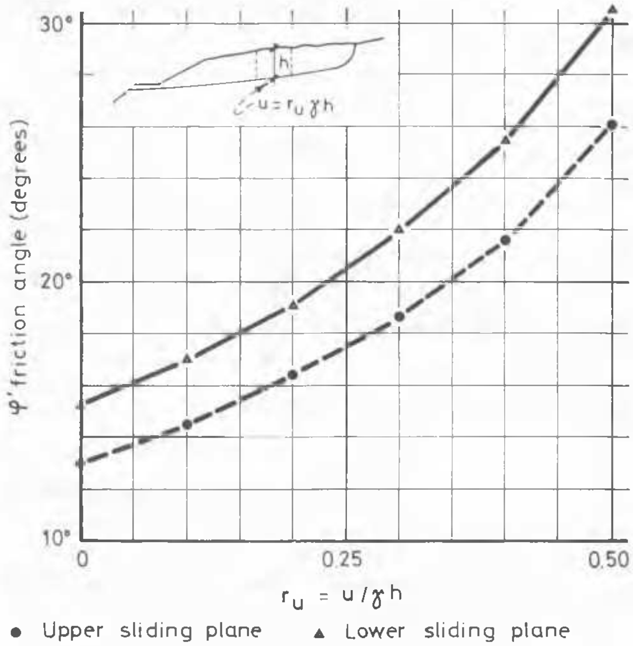


Fig. 3 - Intake - Slope Failure in the Right Bank - Stability Analysis Results

The shear strength of the weathered tuff in this case is conveniently given by:

- $c' = 0$ $\varphi' = 20°$

With respect to the upper surface a more appropriate value of the friction angle would have been $\varphi' = 16°$.

Remedial Measures

A new slope was then designed and its stability checked along the previous established sliding surfaces and new potential ones.
The shear strength parameters were obviously those determined before. Fig. 4 shows the geometry of the new slope and the different slip surfaces analyzed.
A drainage system has been designed to control permanently the pressure of the water seeping through the slope, the major factor to increase the stability.
The system is made of trenches, excavated with a backhoe and filled with sand and gravel.
It is properly working over the last years and the slope has proved to be stable.

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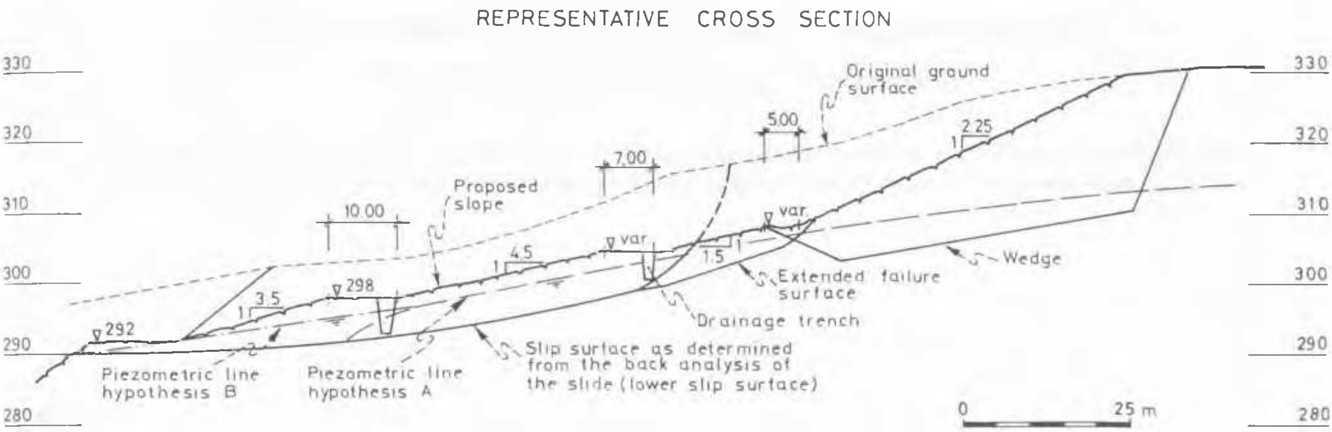

Fig. 4 - Intake - Slope Failure in the Right Bank - New Slope Profile and Remedial Measures

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