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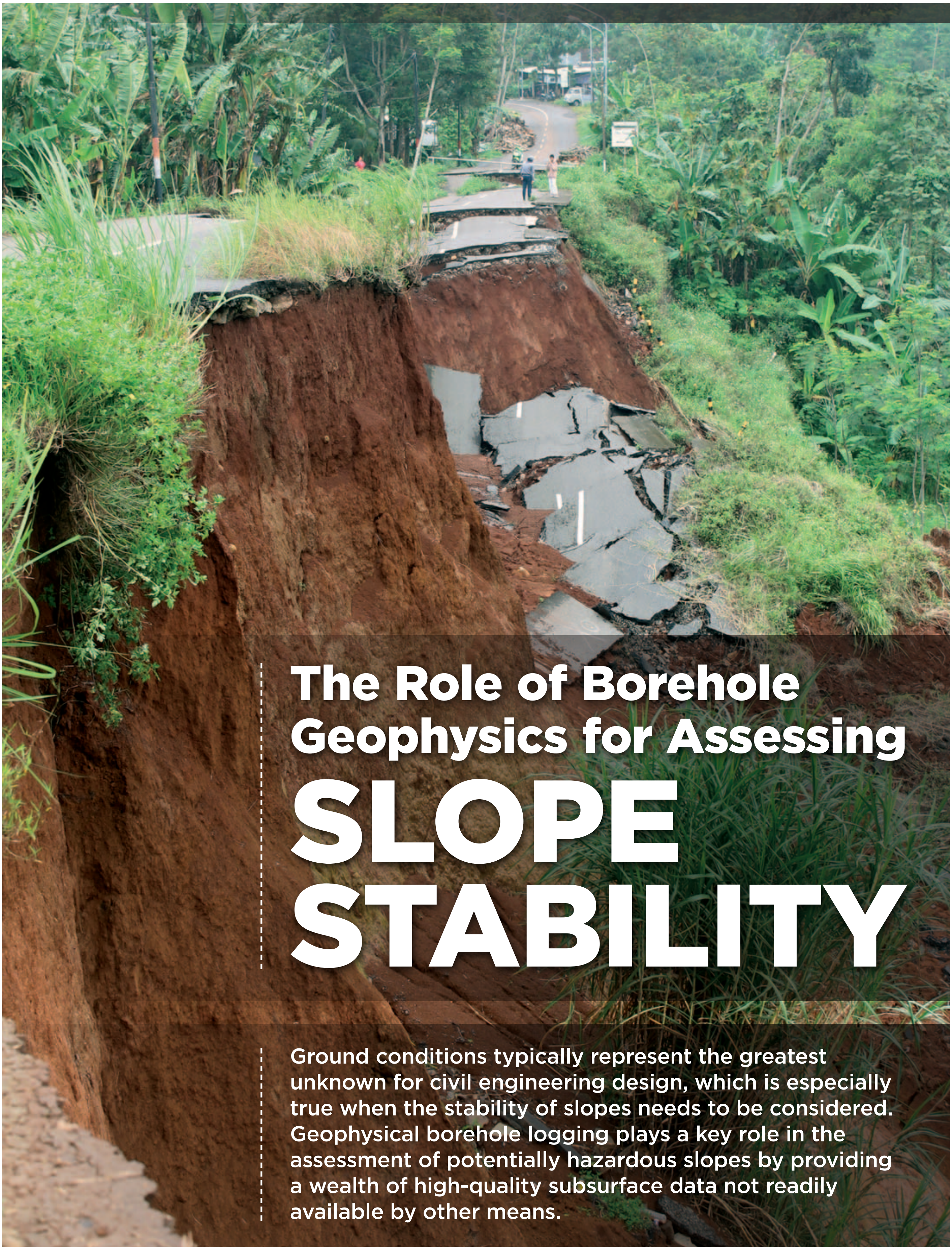

The Role of Borehole Geophysics for Assessing SLOPE STABILITY

Ground conditions typically represent the greatest unknown for civil engineering design, which is especially true when the stability of slopes needs to be considered. Geophysical borehole logging plays a key role in the assessment of potentially hazardous slopes by providing a wealth of high-quality subsurface data not readily available by other means.

Logging at distance for a hazardous slope overlooking a coastal railway.

What is Slope Stability?

A slope is considered stable when it can withstand its own weight and the external forces without displacement occurring. Slopes are analysed by calculating a Factor of Safety (FoS), defined as the ratio of forces resisting shear to those driving it, where a safety factor of less than 1.0 implies that the slope is unstable. In geotechnical design, values for an acceptable FoS may range from 1.1 to 1.4, although the value used will depend on the uncertainty of the modelling parameters and on the slope's risk profile.

The factors that affect slope stability are primarily the angle of the slope and the cohesion of the slope material, where the slope angle dictates the driving force, generally gravity, and the cohesion is the resisting force resulting from the slope material shear strength. In addition, there are many contributing factors which influence whether a slope is stable or not, including fracturing and weathering in hard rocks, and for earthen slopes, height, water table level, drainage, erosion and the presence or otherwise of stabilising vegetation.

Slope failure may occur incrementally, for example, due to erosion or freeze/thaw cycles, or be catastrophically triggered by severe events such as intense rainfall, earthquakes, volcanism or man-made factors such as earthworks and mining.

Over time there may be an accumulation of separate events that contribute to the ultimate failure of a slope. Spatial methods using laser ranging techniques from drones, aircraft and satellites allow slope profiles to be delineated cost effectively. Hazardous features can be identified and changes in profiles over time can identify the precursors of failure which may prompt more detailed investigation.

Where Slope Management is Applicable

Urban development in cities with space limited by mountainous terrain needs careful management to ensure landslide risk is mitigated, as urbanisation expands onto ever steeper slopes. Hong Kong is a good example of where such slope management is key, as buildable land is scarce, the igneous bedrock includes problematic weathered granite and the area is subject to regular typhoons and heavy rainfall. Seismically active urban areas need to take extra precautions as earthquakes notoriously trigger landslides on unstable slopes. Other cities may suffer from unregulated urbanization which can decrease the stability of hillsides by cutting into them to make space for housing development. The ensuing provision of roads, removal of vegetation and additional water from leaks and poor drainage further worsen the situation.

Linear infrastructure, in the form of roads, railways and waterways, may need to cross hilly or mountainous terrain. To achieve the goal of minimising elevation changes cuttings may be needed which need to be carefully designed and maintained to ensure slope stability both above and below the infrastructure.

Mining activities, as they constantly create and change slopes, need to manage their activities to ensure safe operations. For surface or open-cast mines, material overlying the target minerals, the overburden, is removed and deposited in a heap. Pit slope stability can be achieved with higher inter ramp angles of the mined faces by geotechnical investigation (e.g. a televiewer survey) with a significant cost benefit from reduced waste stripping. Management of heaps of overburden and mining tailings is also needed especially where an embankment dam is used to hold back liquified material from ore extraction processes.

Dams and levees in even the flattest terrain also need slope management to protect

Table 1: *Geophysical Probes Used for Slope Stability Assessment (most common first)*

Probe	Outputs	Data Usage
High Resolution Acoustic Televiewer® High Resolution Optical Televiewer®	Unwrapped, oriented borehole wall image	Fracture identification and characterisation Bed boundary delineation Depth and orientation control for core samples
3-Arm Caliper (Gamma)	Diameter, gamma	Bed delineation and weak zone identification Correlation between boreholes
PS Logger®	P-wave velocity S-wave velocity	Poisson's ratio and small strain moduli Shear strength of rock-mass
Formation Density	Bulk density	Density profiles Rock-mass determination (weight)
Nuclear Magnetic Resonance (NMR)	Porosity, permeability	Water distribution profiles Permeability estimation
Electric Log	Resistivity	Hydrogeological characterisation
Focussed Electric Log	Resistivity	Hydrogeological characterisation
High Resolution Flowmeter	Flow rates	Inflow and outflow determination
Temperature Conductivity	Temperature, conductivity	Location of aquifers

against flooding. Earth-fill embankment dams and dykes are routinely constructed to protect against the flooding of areas adjoining rivers or coasts.

The Role of Geophysical Borehole Logging in Slope Stability Assessment

Geophysical borehole logging supplies key in-situ data for slope stability analysis which complements other geotechnical investigative techniques such as spatial mapping, surface seismic and CPT. Borehole logging works equally well in all types of formation, from unconsolidated sediments through to the hardest rocks, producing digital data that can easily be combined into structural databases. The very nature of slopes means that logging crews need to be flexible to successfully log boreholes that may be difficult to access and are often angled or even horizontal. This may require logging from a distance, the use of portable systems and push systems for shallow angled boreholes. Once the logging crew have achieved a safe workable setup a range of geophysical probes can be deployed quickly and cost effectively in a single borehole. ***See Table 1*** for the probes most involved in slope investigation.

Borehole Televiewers, producing unwrapped oriented images of borehole walls, have achieved global acceptance for geotechnical investigations and are the go-to probes for slope stability investigation. Acoustic Televiewers require a fluid filled borehole whilst Optical Televiewers work in dry or clear fluid filled boreholes. When conducting a televiewer survey the logging team should always carry both types. When using Televiewers, it is not imperative that core samples are collected though this is still the normal practice. The digital data derived from processed televiewer logs now routinely enhance or replace costly traditional core logging. ***See Table 2*** for the benefits of using Televiewers versus conventional core logging techniques for slope stability investigation.

In addition to Televiewers, all the probes shown in Table 1 have also been deployed for slope stability assessment. The 3-Arm Caliper produces natural gamma profiles which are useful for bed delineation and for correlating bed boundaries between boreholes. The diameter data can be useful for identifying weak zones and providing QC for other probes affected by washouts from the drilling process.

Table 2: *Advantages of Televiewers versus Conventional Core Logging Techniques for Slope Assessment*

Factor	Benefit
Improved Quality of Data	Conventional core logging requires the logger to individually assess each fracture and may lead to erroneous identification of drill induced fractures. Televiewer data is based on the in-situ borehole wall image, improving rock mass quality estimates. Using structural information from televiewers eliminates human error from manual core measurements.
Accurate Depth Control	Televiewers measure depth with centimetre accuracy while core samples may not match driller depths due to incomplete recovery. The possibility of incorrectly reconstituting a highly fractured core sample is also eliminated. Televiewers show only the in-situ borehole wall, whereas core samples may, in the worst cases, be irrecoverably broken up. ***See Figure 1***
Automatic Orientation	All televiewers record directional information in real time so that borehole data can be automatically converted from apparent to true orientation. Whether the borehole is near vertical, steeply angled or even horizontal the derived structural features can be characterised in true orientation using automated processing software such as GeoCAD®.
Simple Fracture Zone Characterisation	It is difficult to accurately assess the orientation and true thickness of fractures from recovered core. Simple to use processing software (GeoCAD®) allows for accurate determination of the azimuth, dip and fracture thickness. Features can be displayed in a variety of ways including tadpole plots and pseudo core images then analysed statistically. ***See Figure 2***
Slope Design Optimisation	Televiewers provide more accurate structural information for fractures and bedding which improves the quality of structural databases and leads to better slope models. Slope design can then be better optimised as confidence in safety factors is improved.
Time and Cost Benefits	Digital files automatically produced from televiewer surveys reduce the time spent determining the orientation and depth of structures and speeds up input into structural databases. Traditional core logging can be time consuming, is more prone to human error and requires QC vigilance on the measurements.

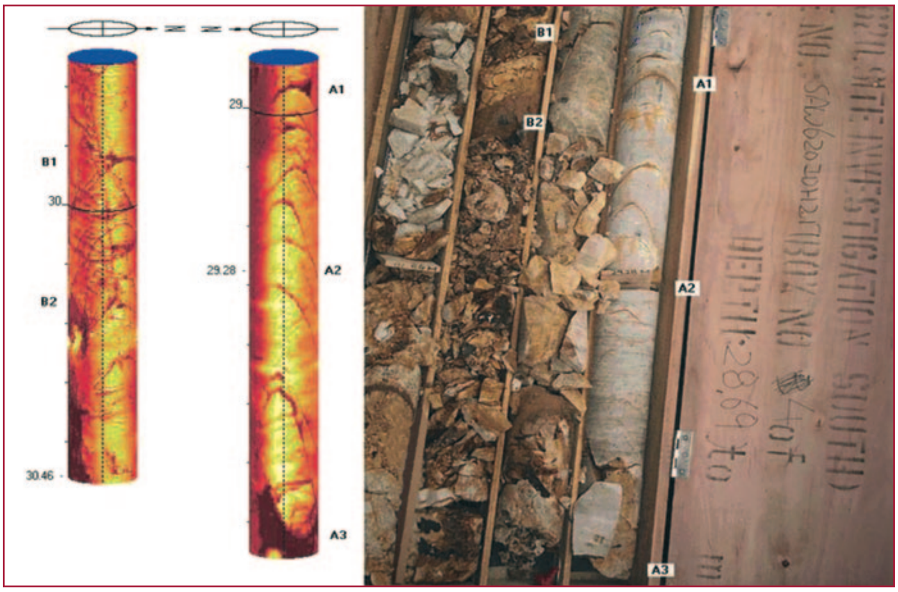

Figure 1: Televiewer generated core where recovery is poor.

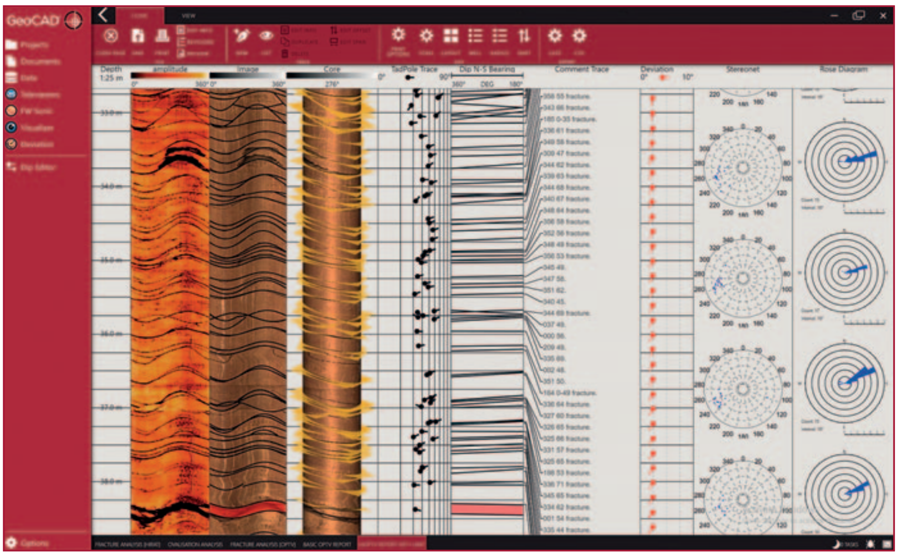

Figure 2: Processed Acoustic and Optical Televiewer data using GeoCAD® software.

The PS Logger® probe measures compressional (P) and shear (S) velocities in hard and soft formations enabling Poisson's ratio to be determined. When combined with bulk density values from the Formation Density probe, small strain moduli profiles can be calculated with the shear modulus being of critical importance when calculating cohesion for slope materials. The bulk density values also enable accurate weight calculation, usually the primary force acting on the slope. Data from the remaining probes are mainly used for determining the groundwater conditions, an important factor in slope stability. The Nuclear Magnetic Resonance (NMR) probe is now gaining popularity for its ability to discriminate between clay-bound, capillary-bound and mobile components of the overall water content when measuring porosity. From this data estimates of permeability and bulk density can be derived. The Focussed Electric and Electric Logs produce resistivity profiles which are routinely used by hydrogeologists analysing groundwater conditions. Finally, the Temperature Conductivity probe and High Resolution Flowmeter are used for identifying and quantifying borehole flows respectively.

How Geophysical Data is Used for Slope Analysis

The task of assessing natural slopes or designing man-made slopes is principally the remit of the geotechnical engineer but may require the input of professionals from engineering geology, structural engineering and hydrogeology. Within their scope will be the identification of hazardous areas, determination of failure mechanisms, sensitivity of the slope to triggers, safe, reliable economic design and the application of mitigation and remedial measures.

Portable logging setup for a hazardous slope overlooking a coastal railway.

This process requires detailed, accurate information regarding slope geometry (spatial methods), geology (trial pits and boreholes) and soil/rock mass properties and groundwater characterisation from geophysical methods including borehole logging.

Historically, limit equilibrium techniques were commonly employed for the analysis of slope stability. With the advent of modern computers and sophisticated software a range of analysis techniques are available including finite element limit analysis, discontinuity layout optimisation and finite difference methods. More recently the risk assessment concept is being used to calculate the consequences of and the probabilities of failures. Digital data from borehole logging simplifies the task of feeding these large computer models.

Engineers have at their disposal a wide range of methods for stabilising slopes including rock anchors and nails, slope drainage enhancement, stabilising facing systems to promote vegetation and protect from weathering and reprofiling and scaling.

The Future

The assessment, analysis and mitigation of potentially hazardous slopes is of increasing importance as society continues to expand its influence geographically. Climatologists predict that, as global temperature rises, there is an increased likelihood of major weather events, which may trigger slope failures, typically through landslides. Prevention and mitigation are always preferable to risking human lives and the costs associated with remedial action after a major slope failure. Borehole geophysics, by providing detailed and accurate subsurface data, will play an increasing role in the investigation of potentially hazardous slopes thereby improving confidence for engineers when calculating safety factors and managing slopes.

Graham Comber

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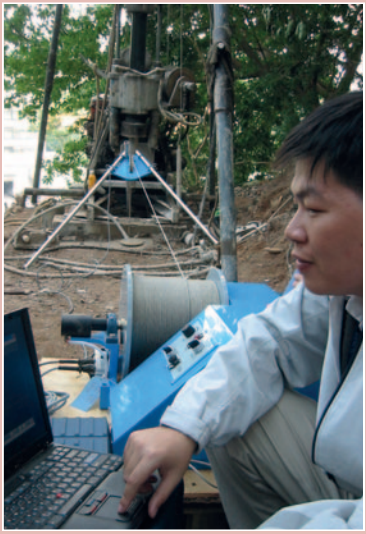
SLOPE STABILITY STUDY IN TAIWAN



The slope had started to fail (as some homes had slid down the hill) and a school was in danger. This is a typical slope issue in Asia. Core samples show the washed-out fracture zone.