THE ROLE OF THE DOWNIE SLIDE IN THE DEVELOPMENT OF 3D GROUNDWATER INSTRUMENTATION
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ABSTRACT
A coincidence of events occurred in 1973 when B.C. Hydro initiated the Revelstoke Dam Project. These events included: recognition of a significant technical problem – the presence of the Downie Slide within the proposed reservoir, the precedent of the 1963 Vaiont Slide, and changes to our understanding of fluid flow within rock masses. These events influenced the development of a modular groundwater instrumentation system operable in adverse geologic conditions.

RÉSUMÉ

1. BACKGROUND
There was an extraordinary coincidence of events in 1973 with B.C. Hydro’s initiation of the Revelstoke Dam Project. These events included: 1) the recognition of a significant technical problem, the Downie Slide, along the side of the proposed reservoir, 2) the precedent set by the 1963 Vaiont Slide, 3) the management, experience and organization of B.C. Hydro, 4) the increased understanding of the influence of fluid flow and fluid pressures within rock masses on the stability of slides, and 5) the evolving state-of-the-art of groundwater and geotechnical instrumentation. This paper describes the interrelationships among these events and how they led to the conception of an idealized, modular, 3D groundwater instrumentation system for the study of landslides. The paper shows how the idealized concept for instrumentation was modified by the constraints imposed by practical instrumentation requirements and the difficult field conditions of the Downie Slide. Finally, examples are given of several landslides where the monitoring systems that were developed were installed.

1.1 Downie Slide Studies
The Revelstoke project had two alternatives: a high dam at the Revelstoke site or two lower dams - one at the Revelstoke site and another just upstream of the Downie Slide. The toe of the Downie Slide would be flooded by the reservoir of the high dam but this alternative would save from CAD $40 to $100 million. Thus, there was strong economic as well as technical interest in understanding the behavior of the Downie Slide.

B.C. Hydro was moderately familiar with the Downie Slide, as they had been studying a dam site in this general area since 1958. However, it was considered important to conduct further studies of the Downie Slide. The primary phase of the Downie Slide studies took place in the period 1973 to 1976. Construction of the drainage system occurred between 1977 and 1983. Monitoring of the slide continues today.

1.2 Vaiont Slide Comparison
Although the 1963 Vaiont Slide in Italy had occurred some ten years prior to the Downie Slide investigations, the Italian slide was still in the minds of the public and technical investigators. Some 2000 persons had perished due to the Vaiont Slide and the generation of hydroelectric power at the Vaiont Dam was abandoned. The Vancouver Province newspaper (1976) published an article comparing the Vaiont Slide to the Downie Slide. Both slides were moving slowly before they were flooded by reservoirs and the depth of flooding of the toes of the two slides was roughly the same (70 to 140m for Vaiont and 70 to 77m for Downie). Many technical papers had been published on the Vaiont Slide, but there was no agreement on the cause of the slide and, in particular, the basic parameters affecting its instability.

Perhaps the most disconcerting thought was the realization that the Vaiont slide was associated with a precedent setting dam and hence the project involved experienced geologists and engineers who would be expected to have used the best available methods of investigation and stability analysis. Because the Vaiont Slide occurred, one could conclude that perhaps the methods generally in use to investigate large slides were inappropriate or the theories and methods used to predict their behavior were faulty. The Vaiont Slide served to impress B. C. Hydro and its consultants with the need to thoroughly investigate the Downie Slide so as to be confident of predictions of its behavior.

B.C. Hydro supported a comparison of the Vaiont and Downie Slides undertaken by Hendron and Patton in
1975 and 1976. Later, Hendron and Patton undertook a separate in-depth review of the Vaiont Slide to better document the comparison. By that time more data was available for the Downie Slide than for the Vaiont Slide. This additional review was supported and published in 1985 by the U.S. Army Corps of Engineers, Waterways Experiment Station (Hendron and Patton, 1985). The studies showed that the base of the Vaiont Slide had formed along a material much weaker than the gouge layers at the base of the Downie Slide. The accumulated evidence suggested that high fluid pressures were present beneath Vaiont Slide and that the slide could have been prevented by drainage. There was also disappointment that so little groundwater data was available for the Vaiont Slide.

1.3 B.C. Hydro’s Project Management

The project management of B. C. Hydro (Hydro) was critical to the successful outcome of the slide investigation. Hydro ensured that the Downie Slide investigation proceeded using the best available techniques while encouraging and funding potential improvements in exploration, instrumentation and analysis wherever these could be justified. Hydro was accustomed to managing large and complex field investigations, could critically analyze the results, and had funds for any studies that were deemed necessary.

Hydro used a group of consultants to advise their technical management team on the direction and scope of the studies. From 1973 to 1985 Hydro’s Downie Slide Review Panel consisted of Dr. William Gardner, Dr. Donald MacDonald and the writer. In 1981 Dr. Ralph B. Peck was added to the Review Panel when decisions were made on the final extent of the drainage measures. At an early stage in the studies the Panel felt the need for additional expertise on the static and dynamic stability of the slide and Dr. Alfred J. Hendron was asked to join the team as a consultant to the Review Panel. He actively participated in a broad range of studies and, together with the Panel and staff of Hydro, took part in the public hearings in 1976 that covered the investigation, stability analyses and proposed remedial drainage measures. There were many other consultants that undertook specialized tasks under the technical direction of the Review Panel. Dr. D. L. Anderson had a significant role in the development of the unique computer program used for stability analysis and undertook calculations of potential slide velocities. Dr. Kam W. Wong provided key assistance with his analysis of slide displacement data.

2. FLOW OF GROUNDWATER WITHIN ROCK MASSES

In the study of a slope’s stability, knowledge of the magnitude of the fluid pressure, its distribution and changes with time are an essential set of field data. These data are typically much more difficult and costly to obtain than are data for other key parameters, for example, the shear strength along the failure plane and the deformation of the slide. In addition, the fluid-pressure distribution is typically the only factor that undergoes significant changes with time thereby triggering slide movements (Patton, 1984). In large slides, fluid pressure is usually the only factor influencing the slide’s stability that can be improved with a reasonable expenditure of funds.

2.1 Fluid Pressure Distributions in Mountain Slopes

M. K. Hubbert (1940) provided a framework for anticipating the flow of fluids and pressure distributions within rock slopes in his seminal paper on the theory of ground-water motion. By assuming that fractured rock masses have relatively homogeneous and isotropic hydraulic conductivity, it is possible to make estimates of fluid flow conditions in mountain slopes by simply increasing the vertical scale of the topography and flow lines on Hubbert’s figures.

In slides one frequently encounters significant differential fluid pressures acting across the gouge and clay seams along the surface of sliding. Also, the differential movements tend to create a variety of flow conditions within the disturbed slide debris. Fluid-pressure distributions in the slide debris can be either more compartmentalized or more homogeneous than they would be in the underlying in-situ bedrock. When gouge is present along the base of a slide, it tends to retard the outward flow of groundwater from upland regions and, as a result, zones of higher fluid pressures are common beneath the slide. These factors led to the development of a stability analysis for the Downie Slide wherein the fluid pressure acting on the base of the failure plane could be different from the fluid pressure distribution used on surfaces within the slide debris. This capability also turned out to be important for the stability analyses of the Vaiont Slide.

One can speculate on how Hubbert’s fluid-pressure distributions would be influenced by the presence of major discontinuities such as bedding, faults and zones of disturbed and undisturbed rock. The resulting general case for mountain slopes is to expect rather uniform 3D flow and pressure distributions when the data is viewed from a distance. However, pronounced and significant variations in these parameters can occur as the area of interest becomes smaller and the effects of local discontinuities exert themselves.

Hubbert’s work was later extended to regions with irregular topography and geologic units having different conductivities by Toth (1962), Freeze and Witherspoon (1967), Hodge and Freeze (1977), and others. Deere and Patton (1967), Patton and Deere (1971a, 1971b) and Patton and Hendron (1974) showed sketches of hypothetical flow systems in fractured rock masses formed in different geologic environments. However, in the period 1940 to 1976 there were relatively few papers published showing applications of Hubbert’s flow systems to rock slopes. Certainly there was no detailed 3D data available from landslide investigations.
2.2 Quality Assurance in Hydrogeologic Studies

In the last 50 years there has been a gradual, but often reluctant, acceptance of increased and formalized quality assurance (QA) in geotechnical and hydrogeologic field investigations. The basic tenant of any QA program is to collect the required data for a technical problem and then to obtain enough additional data that it is possible to prove that the required data is both correct and sufficient. This means that, in hydrogeologic practice, it is not possible to determine in advance how many monitoring zones are enough until the minimum number has been exceeded (Patton, 1990). Also, data from a number of short monitoring zones placed in a borehole are more representative than data from a few long monitoring zones. This is because long zones of open borehole will not only lead to false measurements of the groundwater table but will “average” the pressure data within each zone and the result will mask the true pressures in the zone - - especially when the pressure distribution is not hydrostatic (Patton and Smith 1987).

The approach of using a high “density” of monitoring zones has been hard for many geotechnical engineers to accept especially if they took pride in spending no more money and in obtaining no more information than was necessary. On sites where the geology is simple, the additional data needed for QA purposes can be minimal. However, when the hydrogeologic conditions are complex, as they were at the Downie Slide, substantial additional field data is needed to meet reasonable QA requirements for stability analysis. In QA circles redundancy of field data is a good and necessary accomplishment and this term does not have the unfavorable connotations often attributed to the word “redundant”.

2.3 Discrepancies in the Geotechnical Literature

In view of the importance of understanding the distribution of fluid pressures within and adjacent to a slide, it is surprising to find that significant discrepancies frequently arise in the geotechnical literature between the type and quantity of data needed for a reasonable characterization of the field conditions and those commonly obtained. Many slopes are analyzed using data from a few depths and at a few locations so that fluid-pressure data is poorly defined. Unfortunately, the problem of inadequate groundwater data for slope stability analysis is still with us today.

3. AN IDEALIZED MODULAR GROUNDWATER MONITORING SYSTEM

The significant problems that had to be faced in trying to collect sufficient fluid-pressure data to investigate the Downie Slide during the period from 1973 to 1976 led the writer to consider what an idealized 3D monitoring system would be. When considering such an ideal system one should be free of all constraints imposed by geology, hydrology, existing technology and cost. These “real world” constraints should come into play to modify the idealized system once it has been conceived. This is, in fact, what happened once the idealized system described below met up with the constraints imposed by the field conditions of the Downie Slide.

3.1 The Ideal System

The basic ideal system was quite simple. It had to meet three conditions: 1) it should be a semi-infinite 3D array of nodes comprised of sensor modules, 2) each sensor module should obtain data from an adjacent representative monitoring zone, and 3) the components should be modular and compatible with other components.

“Modular” is a key word. A critical test for true modularity is to ask if additional sensing modules can be added to a monitoring array without reaching any limit to the number of modules or monitoring zones that can be measured. Using this strict definition of modularity, systems with components that have individual wires or tubes leading to each sensing module, monitoring zone or to individual packers would not be considered modular as the wires and tubes needed result in practical limits to the number of units that can be placed in a borehole.

The ideal modular monitoring array probably needs to be made up of two or more compatible modular subsystems:

- Firstly, a modular borehole completion casing system that can be used to hydraulically isolate monitoring zones by means of seals placed between adjacent zones. The tubular casing provides access to a series of monitoring zones located at different depths along the axis of the borehole, while valved ports in the casing couplings provide access to individual monitoring zones.
- Secondly, a modular data acquisition and control system that can be used inside the casing system for data collection. This system consists of a series of probes located along a single data and support line. This second system must be completely compatible with the casing system.

3.2 Calibration and Maintenance Requirements

The ideal borehole monitoring system should have the capability for essential QA tests to be conducted on all components immediately after installation and at any time thereafter. For purposes of repair and maintenance or for calibration and QA testing, the data acquisition system should be removable and, if necessary, replaceable. When these activities occur, it is desirable to eliminate any influence on the fluid-pressures in the monitoring zones. Having two compatible subsystems permits the natural fluid
pressures to be maintained in the monitoring zones outside the casing during probe removal. Pressure stability during calibration is particularly important where low conductivity units are present.

3.3 Requirements for Multilevel Borehole Seals

It is obvious that the quality of hydrogeologic data from any monitoring zone is no better than the quality of the seals that define the zone. Thus, there need to be good and demonstrable seals between monitoring zones. Mechanical or inflatable packers are perhaps best for developing hydraulic seals in boreholes where strong flows and/or significant differential fluid pressures occur. External inflatable casing packers can be modular and provide the means for sealing irregular borehole walls. Having packer inflation valves in each packer permits the packer pressure to be checked after inflation. The individual valves also permit a series of packers to be hydraulically separate and avoids the inflation line transmitting pressure changes from one packer to the next. Clearly chemical stability of packer valves and elastomer glands is also important for long-term performance (borehole sealing problems are discussed in Patton and Smith, 1987).

3.4 Dimensional Requirements

A geotechnical instrumentation system should be capable of being installed in small-diameter boreholes in adverse borehole conditions. Such adverse conditions include poor-quality soils and rocks, irregular borehole diameters and situations where high differential fluid pressures occur at different depths.

The selection of the outside dimensions of the modular components contemplated for the ideal system were strongly influenced by the experience gained using hard-rock drilling equipment on the Downie Slide. Thus, when difficult drilling conditions are encountered, all dimensions of components of the idealized system should be compatible with the inside diameters of the drill rods and the outside diameters of the drill bits.

3.5 Other Useful Capabilities

Although fluid pressure is the key parameter in any slide study, it would be helpful in other geotechnical and hydrogeologic studies for the monitoring system to have hydraulic conductivity testing and fluid/gas sampling capabilities. In addition, because soil or rock in a slide has a tendency to be continually expanding or contracting along the axis of boreholes, monitoring systems should have the ability to accommodate such movements to extend the lifetime of the instrumentation. Problems with displacements are described further in Patton (1983).

4. CONSTRAINTS IMPOSED BY FIELD CONDITIONS

The Downie Slide, with a volume of approximately $1.5 \times 10^9$ cu m, an area of 6.5 sq km, and depths of 200 to 280 m, was larger, deeper and appeared to have more difficult borehole conditions than any slide that had previously been subjected to a detailed geotechnical investigation. Thus, little or no precedence was available and that offered by the Vaiont Slide was disconcerting. In particular, existing geotechnical instruments had not been designed to work at the depths and fluid pressures present at the Downie Slide. Also, the cost of drilling individual exploration holes was an order-of-magnitude greater than was typical in geotechnical projects and many drill holes were required to provide representative coverage of the different regions of the slide.

4.1 Relationships Among Slide Geology, Displacements and Hydrogeologic Measurements

The Downie Slide is composed of a series of interbedded layers of schist and gneiss that dip at 17 to 19 degrees toward the river. Layers of a clayey micaceous silt gouge of tectonic origin were commonly found in the schist - both within the slide and below it. It was not unusual to find 10 to 20 layers of schist and gouge in a single borehole. The slide had utilized several of these gouge layers as its basal surface of sliding. During drilling operations it was frequently difficult to recognize any differences between the rock above and below the basal surface of sliding.

Overall movement of the surface of the slide in the period 1973 to 1976 was found to be about 2 to 3 cm per year. This was so slow that it took two years of measurements in borehole inclinometers together with surface displacement measurements to determine that slide movements had occurred. In developing an understanding of the behavior of the slide, it was necessary to know the range of fluid pressures that occurred from season to season and, in particular, the magnitude of the fluid pressures along the basal surface of sliding that had triggered slide movements. Therefore, there was a need to measure fluid pressures for several years at a number of gouge zones at different depths in each borehole to obtain the data needed for stability analyses made for a particular gouge layer.

The problem of identifying the base of the slide as early as possible was solved in part through the use of borehole geophysical logging combined with surface refraction surveys to distinguish the base of the disturbed, lower-velocity slide debris from the underlying higher-velocity in-situ bedrock.

4.2. Adverse Drilling Conditions

Drilling conditions were extremely adverse in comparison with typical geotechnical environments. Boreholes were lost or unable to reach their target...
depth by the tendency for the drill bit to “rundown” the inclined gouge and hard rock layers or to turn into the inclined contact of hard rock layer at the base of a gouge layer. Also, the problems of drilling through hard broken rock and gouge layers within the slide debris were very difficult to overcome and unsupported drill holes would frequently collapse when the drill rods were withdrawn. Sometimes the soft layers of gouge and schist or blocks of hard rock would squeeze in and grip the drill rods. The combination of the very poor-quality rock and the choice of borehole diameters meant that any instrumentation for the Downie Slide had to be sized to be compatible with the most desirable borehole and drill rod diameters.

4.3. Large Non-Hydrostatic Variations in Fluid Pressure Within and Below the Slide

Variations in piezometric levels were found to exceed 100 m within a single borehole (Patton 1983, 1984). The resulting fluid pressure variations placed enormous forces on the borehole sealing devices. In addition, highly conductive zones were present where the borehole intersected regions with large open fractures. Thus, large fluid flows were possible within a borehole where two such highly conductive zones were encountered that had different piezometric levels. Construction of a reliable seal using grout is very difficult under these conditions.

4.4. Drilling Cost and Accessibility

Before the work started drilling costs were estimated to be in the range of $150,000 to $300,000 per drill hole at a time when the cost of a geotechnical boring was typically $5,000 to $30,000. A significant factor in drilling costs and later in data collection cost was the need to use helicopters to bring in and supply all goods and services. Helicopters had to be used because the nearest road was located at the base of the mountain on the other side of the Columbia River.

4.5. Need to Minimize Drill-Hole Diameters

The cost of a drill hole increases rapidly with the increasing diameter of the drill hole. For the Downie Slide studies, it was decided that HQ (96mm) holes would be the standard size. This would allow the driller to “drop down” to a NQ size drill hole (76mm) when trouble developed in extending the HQ borehole. Thus, any instrumentation placed in the drill hole had to be sized for installation through HQ drill rods and for sealing against the walls of an HQ or NQ borehole. HQ and NQ diamond drilling equipment had been developed by the mining industry for hard rock exploration. While techniques for handling the fluid pressures and rock conditions present at the Downie Slide were in part available in the oil industry, the oil field equipment was generally made for considerably larger boreholes than the hard-rock borehole sizes. The use of oilfield drilling equipment would have increased costs to levels several times those noted above.

5. INSTRUMENTATION SOLUTIONS ADOPTED

It was recognized that no geotechnical instruments were available to handle the combination of depth, fluid pressure, placement and operation in the small-diameter boreholes used in hard rock mineral exploration. In view of this situation B.C. Hydro proceeded with a variety of solutions to meet its immediate needs for detailed groundwater data of the Downie Slide.

5.1. First Solution – Multiple Standpipes

Hydro had previous experience placing small-diameter standpipes inside HQ and NQ sized boreholes. They continued to develop this technique and were able to place seven, 12.5 mm diameter copper tubes into a 100 to 115 mm diameter borehole. The various monitoring zones were separated by cement grout. However, problems arose as the number of standpipes placed in the same borehole increased.

The fluid levels in the standpipes were monitored for piezometric level fluctuations. Frequently, in any one borehole there would be 5 to 20 candidates for completion as monitoring zones. Thus, the need arose for a tool to measure the magnitude of the fluid pressure in small zones throughout the borehole before selecting the most informative zones to be completed as standpipes. The profiling tool described below, was developed as a solution to fill this need.

5.2 Second Solution – The Profiling Tool

While it was desirable to measure the piezometric level at frequent depth intervals during pauses in the drilling, the use of bentonite mud would interfere with such testing activities. Bentonitic drilling mud was needed to control the borehole walls and drill rods. When changes were noted in the geology or drilling conditions, drilling would be stopped and the fluid level in the borehole recorded. Highly conductive zones would tend to eliminate the influence of the drilling mud. However, to obtain higher quality results in all zones tested, it was desirable to isolate the zone being monitored at the base of the drill rods from conditions related to other zones higher in the borehole and from the influence of the column of drilling mud.

An instrument company with knowledge of B.C. Hydro’s project and the challenges it was facing proposed a borehole profiling tool to B.C. Hydro. Hydro agreed to the proposal and the tool was developed for use inside HQ and NQ drill rods. The profiling tool replaced an earlier, more costly and less versatile testing tool that had been used to determine the downhole fluid pressures.

The profiling tool was a type of wireline-testing tool that was lowered inside HQ or NQ drill rods after the core barrel was removed and after the drill rods had been
lifted several meters off the bottom of the hole. When
the tool was in place two packers were inflated to seal
the test zone below from the fluid inside the drill rods
and the fluids/mud outside the drill rods. By operating a
valve after the pressure had stabilized in the test
section, a falling-head or rising-head conductivity test
could be performed. In practice, the use of bentonitic
drilling mud tended to interfere with results of the
conductivity testing. As a consequence of this, results
from these tests were only considered to be indicative
of the zone’s relative conductivity in comparison to the
results from other tests.

Most of the fluid–pressure data for the Downie Slide
was obtained from the multiple standpipes completed at
depths chosen from profiling tool data. This data was
also used for analytical purposes but it was only
available for the short duration of the test. The profiling
tool is described in Black et al (1983).

5.3 Third Solution – The Modular Multilevel Pressure
Monitoring System

Most of the field investigations of the Downie Slide were
over before the third solution became available. This
solution was a modular multilevel array of sensing
elements for installation inside a modular multilevel
borehole completion casing. However, the Downie Slide
provided the impetus to move from the conception of
an idealized 3D groundwater monitoring system to the
step-by-step development of such instrumentation.

6. MODULAR MULTILEVEL PIEZOMETERS

Following its experience on the Downie Slide with the
profiling tool and with a knowledge of the data
requirements for stability analysis of slides, Westbay
Instruments proceeded to develop a series of
groundwater monitoring systems for slide investigations
that would meet as closely as possible the criteria for
an idealized monitoring system as modified by the
constraints of technology, geology and drilling
conditions. As development of the system progressed,
it became apparent that such instruments could be
applied in other types of hydrogeologic studies and so
modifications were made to accommodate additional
constraints imposed by other uses.

Three systems were designed and produced and two
have relevance here: these are 1) a modular system
that combines multilevel piezometers with inclinometer
casing, and 2) a modular system of multilevel
piezometers. Compatible with the two borehole
completion systems is an electronic data acquisition
and control system of probes that contain pressure and
temperature transducers, motorized controls and data
transmission devices.

6.1 The Borehole Completion System

The multilevel piezometer system is a borehole
completion casing that has a number of components
including external casing packers, couplings with
valves, magnetic collars, and plain casing sections. As
developed for use in landslides, the multilevel
piezometer system consists of plastic PVC casing with
and without external packers and couplings of various
types. Borehole seals are produced by means of water-
filled external casing packers. A specific urethane
elastomer that had the required properties with regard
to strength, elongation, permeability and chemical
stability was found for the packer gland. These
components are described in Black et al (1986).

Because slide movements can deform the borehole, the
instrument system had to be flexible. As a result,
telescopic casing segments were devised which can be
installed at those depths in a borehole where
deformations are anticipated.

6.2 The Data Acquisition and Control System

The multiple piezometer casing is compatible with
removable probes that are operated inside the casing.
A single probe can be manually moved up and down
the casing for a set of multilevel pressure measurements. Alternatively, a series of probes can be
connected along a single-conductor cable permitting
them to communicate with a surface memory, control,
and communication unit. The data sensors are housed
in the probes. A surface unit can communicate with all
of the probes in a borehole and with a computer. One
can program the surface unit to have the probes take
readings at some prearranged schedule or when a
pressure threshold is exceeded. Thus, with a series of
probes activated in a number of boreholes, 3D fluid
pressure distributions may be obtained.

In-situ calibration checks of the downhole probes can
be undertaken by independently measuring the
piezometric head inside the casing after deactivating
the probes to record the equivalent inside fluid
pressure. By repeating these two measurements
periodically, drift or other errors can be detected. The
result is a QA program that can be initiated from a
remote location. While some of these procedures were
originally developed for other applications, they could
also be used on landslides. The modular data
acquisition system is described in Patton et al (1991).

7. FIELD APPLICATIONS

7.1 Downie Slide

Development of the system that combines multilevel
piezometers with inclinometer casing was completed
near the end of the drainage activities at the Downie Slide. Hydro installed two such systems in boreholes
drilled near the toe of the slide adjacent to a portal of a
drainage adit. One of these boreholes was 274m in
depth and 58 packers were installed in the lower 200m.
Only 12 of a potential 58 monitoring zones were utilized
as fluid-pressure monitoring zones. Most of the installation was below the established base of the slide. Significant movements associated with erosion and sloughing of the toe of the slide eventually deformed the upper portion of the borehole and prevented access to the lower part of the hole and the installation was abandoned. There was good agreement between the profiling tool data obtained during drilling and the early data from the combined multilevel system. This comparison and other piezometric data gathered on the slide can be found in Patton (1984). The geology, drainage, monitoring and related studies of the Downie Slide are described by Imrie and Bourne (1981), Lewis and Moore (1989), and Imrie et al (1992).

7.2 Pillar Mountain Slide

Another early application of a modular groundwater monitoring system for landslides was the use in 1980 of the system that combined multilevel piezometers with inclinometer casing for an investigation of the Pillar Mountain Slide near Kodiak City, Alaska. In this case, the instrument system was installed in an HQ borehole, 274 m deep. Ninety packers were used to provide borehole seals for 20 fluid–pressure monitoring zones. By simply adding to the number of ported couplings used, 90 fluid-pressure monitoring zones could have been installed. This installation is described in Patton (1983). Both inclinometer measurements and multiple piezometer measurements were obtained in the same borehole. However, with time it became increasingly more difficult to distinguish changes in the inclinometer measurements due to creep in the packers from deformations of the borehole walls. Finally, Inclinometer readings had to be discontinued due to casing deformation. Piezometer measurements continued and provided data for considering various remedial measures. Following this experience, this combined system was discontinued except where the casing could be stabilized by backfill.

7.2 Dutchman’s Ridge Slope Stability Study

In the period 1986 to 1988, B. C. Hydro undertook the first full deployment of the multilevel piezometer system for the slope stability investigations at Dutchman’s Ridge. The site is located on the side of the reservoir behind Mica Dam in central British Columbia. The geologic setting of this slope was similar to that of the Downie Slide with dipping interbedded layers of gneiss and schist that are inclined at about 30 degrees toward the reservoir that covers the toe of the slide. The schist layers contain zones of gouge. Thus, much of the experience gained on the Downie Slide investigations was directly applicable to the Dutchman’s Ridge Slope. The field instrumentation included 15 boreholes with 17 standpipe piezometers, 10 boreholes that had inclinometer casing installed, and 12 boreholes with 250 multiple piezometer monitoring zones. The use of the multiple piezometers permitted detailed 3D fluid-pressure distributions to be obtained for stability analyses. Also, the data was used during construction of the remedial drainage system to control the extent of the drainage system. Further information on this site can be found in Moore and Lewis (1988), Lewis and Moore (1989), Moore (1990), Patton (1990), Tatchell (1991) and Imrie et al (1992).

7.3 Panama Canal Slope Studies

In the 1990s a new phase of stability investigations began for the slopes along the Panama Canal. This investigation was associated with excavation activities for a canal-widening project. Since 1994 multilevel piezometer systems have been placed in more than 50 boreholes along the canal slopes to obtain detailed fluid-pressure data on the complex hydrogeologic conditions. Engineers are now able to examine pore-pressure profiles at a given location rather than having data from a single point. Another significant advance, available to those studying the Canal is that they have the capability to install strings of pressure monitoring probes in one or more boreholes. Should the strings be installed in an array of boreholes, the result will be continuous 3D pressure monitoring. For example, with a 3D monitoring array installed they would be able to examine the influence of tropical storms on the stability of the slopes. These studies are currently under the direction of Maximiliano De Puy, manager of the geotechnical branch of the Autoridad del Canal de Panama (Panama Canal Authority).

8. CONCLUSIONS

The serious engineering problem posed by the existence of the Downie Slide along the side of the proposed Revelstoke Dam reservoir and the magnitude of the financial decisions that rested on the outcome of studies of the slide led directly to conditions that encouraged creative solutions to problems associated with field investigations and data analysis.

While the fluid–pressure data utilized for the Downie Slide studies were largely provided by the use of multiple standpipe piezometers in combination with the results from a profiling tool, one concept that arose from this environment was that of an idealized modular groundwater monitoring system – a system conceived without considering constraints. This idealized concept was then modified in steps to meet quality assurance requirements and the constraints of field conditions, cost and technology.

An early version of the resulting system was installed late in the Downie Slide investigations. But, it was not until after the Downie Slide work had been completed, that a full deployment was made at Dutchman’s Ridge of the detailed 3D groundwater monitoring system envisioned for landslides.

Without the stimulus provided by the Downie Slide investigations and the creative environment associated with the project, these particular advances in
groundwater instrumentation would have been delayed or perhaps never attempted.

9. ACKNOWLEDGEMENTS

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The profiler tool (Profiler), the combined piezometer-inclinometer system (CPI System), the multilevel piezometer groundwater monitoring system (MP System®) and the modular subsurface data acquisition (MOSDAX®) probes described in this paper were developed by Westbay Instruments Inc. which is a part of the Water Services Division of Schlumberger Ltd. Although the writer was involved with the development of these products, he has been retired since 2003 and no longer has any connection with the company or its products.

10. REFERENCES


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