WAC Bennett Dam - the characterization of a crest sinkhole

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ABSTRACT: In June 1996, a small cavity was discovered on the crest of the 183 m high WAC Bennett Dam in British Columbia, Canada. Subsequent drilling to investigate the condition of the dam core below the cavity resulted in a sinkhole on the dam crest with a surface expression 2.5 m in diameter and 7 m in depth. Following this incident the safety status of this very large dam was uncertain. A comprehensive investigation program was urgently planned and executed to characterize the sinkhole. This paper describes the objectives and criteria developed for the program, the scope of the key activities at the sinkhole, and some important lessons learned during the investigation.

1. INTRODUCTION

Site investigation and characterization are among the first steps in determining a project's feasibility and cost. In areas where the ground conditions and the performance of structures are well known, site characterization may be routine. For greenfield sites with poor ground conditions and sensitive new facilities, foundation design and site development may be a significant factor in the overall project cost and viability. In many cases a significant component of construction risk may be site development itself.

Performance and design requirements are defined by an owner or owner's representative in concert with his engineering team. Site investigation methods are selected to match these requirements, usually in the context of competitive bidding. The objective is to obtain all geotechnical information necessary for design, construction, and dispute resolution.

Due to the inherent variability of ground conditions, the most challenging aspect of site characterization can be determining what constitutes adequate investigation coverage. In effect, the development of the scope of a site investigation is an exercise in risk management, generally done intuitively by suitably experienced practitioners. The scope of the investigation is balanced among existing information, local knowledge, anticipated variation in ground conditions, sensitivity of the structures to variable conditions, the performance requirements, consequences of poor performance, and the expected or available budget. On large projects with considerable risk (probability of failure × consequence), decision analyses and risk management techniques have been applied to site investigation design (Vick & Bromwell 1989).

Another type of site characterization is the post-construction foundation investigation of structures subject to distress. The difficulties of this type of work are often compounded by the spatial and logistical restrictions of working in an operating facility. The case history described in this paper deals with the investigation of a sinkhole in a very large dam under an operating reservoir about 170 m deep. The overriding objective was to determine the safety of the dam.

At the start of the investigation, it was not known whether the disturbed core of the dam was confined to the zone directly below the sinkhole or resulted from a more pervasive mechanism for which the collapse at the surface was but an early warning. In the latter case, drilling to understand the safety of the dam could actually reduce safety through hydraulic fracturing and/or crest collapse. Central to all investigation planning and execution was the minimization of risk due to drilling.

Although the objective was clear, planning was complicated by the necessity to immediately understand the dam safety status, by limitations in the state of practice in drilling technologies able to investigate a dam core under full reservoir, and by an uncertain scope. This paper describes planning issues and lessons learned during this challenging project. There is also limited discussion of the investigation techniques and results.

2. 1996 WAC BENNETT DAM INCIDENT

On June 14, 1996 a passing motorist discovered a 450 mm diameter hole in the asphaltic concrete road surface on the crest of Bennett Dam. Examination of the hole within an hour of its discovery revealed a cavity with a volume of 2 m^3 and a maximum depth of 2 m extending beneath the crest pavement. The top of a vertical steel pipe (later determined to be a construction survey benchmark tube) was barely visible at the base of the cavity. The following day a careful excavation to 5 m using a backhoe confirmed the presence of the survey benchmark tube (see Figure 1), and established that the cavity was not evident below 2 m. The benchmark tube comprised concentric 65 mm inner and 150 mm outer thin walled steel pipes; the outer pipe was designed to act as a sectional sleeve to protect the inner survey pipe.

The existence of the buried benchmark tube was not known to the surveillance engineers who regularly inspected the dam, nor did it appear on any readily available construction drawings. It was later determined that the benchmark tube extended from the rock foundation at a depth of 115 m to the dam crest.

Our immediate assessment speculated that the cavity was likely associated in some as yet undetermined way with the survey benchmark tube. The volume of the surface cavity was similar to the open annular space between the concentric pipes over their 115 m depth to bedrock. This volume balance provided a plausible early working hypothesis for the cavity development. That is, over the 24 years since reservoir filling, core material had slowly migrated into the annular space between the pipes. In an attempt to evaluate this initial hypothesis, it was decided to investigate the condition of the dam core at depth around the benchmark tube using a Becker Penetration Test (BPT).

On June 17, 1996 the first BPT hole was drilled within 1.5 m of the survey benchmark tube, using a close-ended 140 mm OD pipe, driven by a single acting diesel hammer. This pipe advanced to 32 m with virtually no resistance. While drilling was suspended to attach additional pipe at 32 m the dam crest surrounding the survey benchmark suddenly dropped 7 m, leaving a cylindrical, vertical sided hole 2.5 m in diameter (see Figure 2). Coincident with the collapse, the water level in an open "leaky" inclinometer casing (Observation well OW-5) 30 m away rose suddenly by more than 2.5 m. This unexpected local crest collapse constitutes the 1996 incident at Bennett Dam.

In early July a second survey benchmark tube, and an associated second more subtle sinkhole, was discovered in the upstream shell overlying the core just upstream of the dam crest.

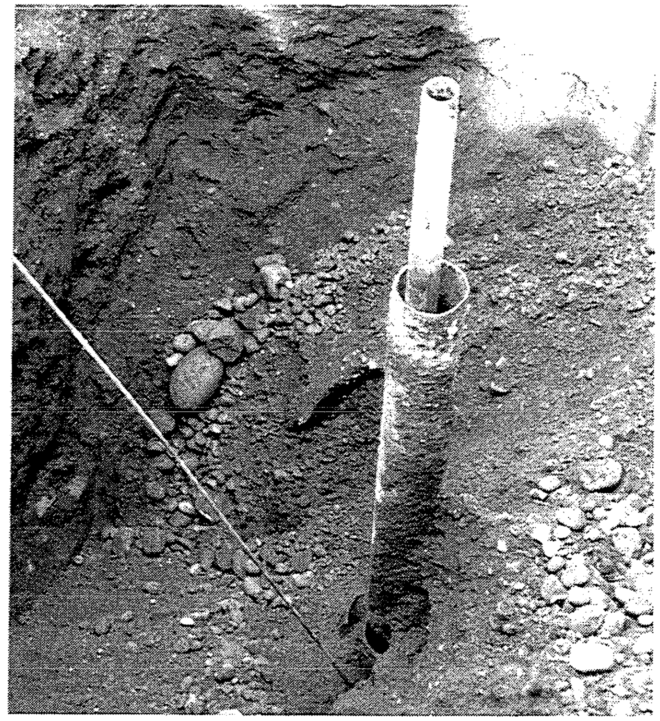

Figure 1. Benchmark tube in Sinkhole No. 1.

Bennett Dam is located on the Peace River near Hudson's Hope in northeastern British Columbia, Canada as shown on Figure 3. The dam is a zoned earthfill embankment 183 m high. In 1967, when construction was completed, Bennett Dam was the highest earthfill embankment in the world. It retains the 360 km long Williston Reservoir, the largest reservoir in North America. The underground powerhouse generates 2730 megawatts, which is 30 percent of the power requirements of British Columbia. A layout of the dam is shown on Figure 4. Also shown are the locations of the two sinkholes.

The core of the dam is a broadly graded, non-plastic silty sand with some gravel which was manufactured from glacial outwash deposits. Downstream of the core are two filter zones and a

Figure 2. Sinkhole No. 1.

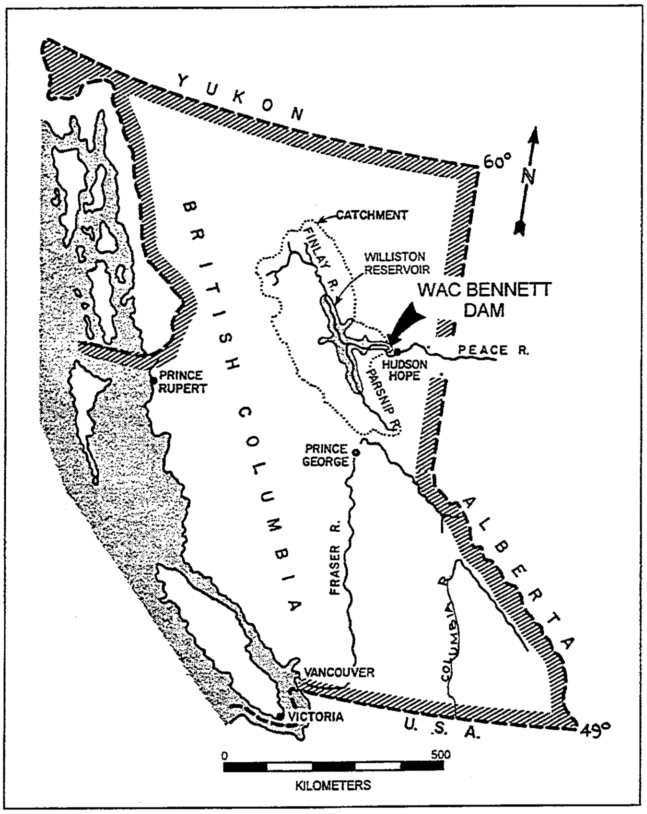

Figure 3. Key plan (after Ripley 1967).

coarse gravel chimney and blanket drain for seepage control. The upstream and downstream shells were constructed with sand and gravel. The dam is founded on Tertiary sandstones and shales which dip 5 to 10 degrees downstream. A typical cross section is shown on Figure 5. Details of the design and construction are given in Ripley (1967) and the 25 year performance of the dam is reviewed by Stewart & Imrie (1993).

Following the dramatic but localized crest collapse, it was clear that significant additional investigations would be required to determine the safety of the dam, to understand the extent of the

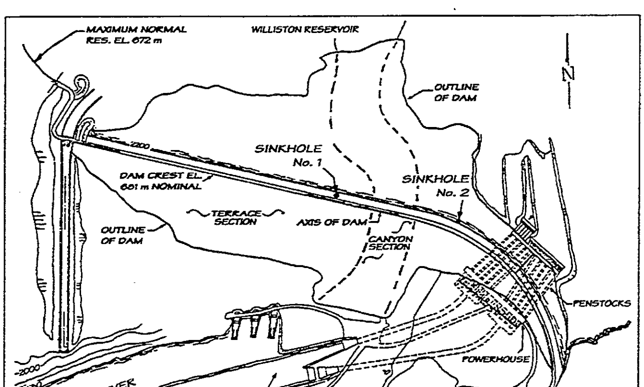

Figure 4. General arrangement (after Ripley 1967).

damage to the core, and to assess alternatives for rehabilitation as required.

The collapse occurred during the spring freshet as the reservoir was rising to its maximum pool elevation. In consultation with the Office of the Comptroller of Water Rights, British Columbia's dam safety regulator, and the Advisory Board (Drs. R.B. Peck and N.R. Morgenstern) the decision was made to lower the reservoir. Intrusive investigations of the core were delayed until freeboard was increased. This would improve the safety margin in the event that another crest collapse occurred. On June 22, BC Hydro opened the spillway gates. Discharges through the spillway and powerhouse, at a maximum rate of 5100 m^3/s, lasted eight weeks. Over this period the reservoir drawdown was less than 2 m.

During reservoir drawdown, various surface geophysical techniques were employed to investigate the condition of the dam beyond the sinkholes. During this time the intrusive investigations at the sinkhole were planned. Part of this planning involved trial drilling and downhole geophysical surveys in intact portions of the core at locations distant from the sinkhole.

During the early investigation stages, the uncertain safety status of the dam drove the urgency to complete the work. As the investigation proceeded, and the safety of the dam was better understood, the need to complete the investigations was driven by the requirement to remediate the dam so that the entire 1997 spring freshet could be captured. The investigations were planned to accommodate these goals, incorporating dam safety risk mitigation measures to the extent possible.

3. INVESTIGATION OBJECTIVES AND CRITERIA

The objectives which formed the cornerstone of the investigation were to:

- characterize the extent and nature of the disturbed core beneath the sinkhole(s);
- establish whether the loose zones and their cause constituted a dam safety hazard;
- gather sufficient information for remediation design and construction; and
- complete the investigations before the harsh winter to permit return of the reservoir to full service.

Although the scope of the work could not be fully defined, the planning was facilitated by the delay needed to meet the requirement for additional freeboard. This investigation delay of 6 weeks was used to develop the criteria and protocols, and to determine the test equipment and techniques. All

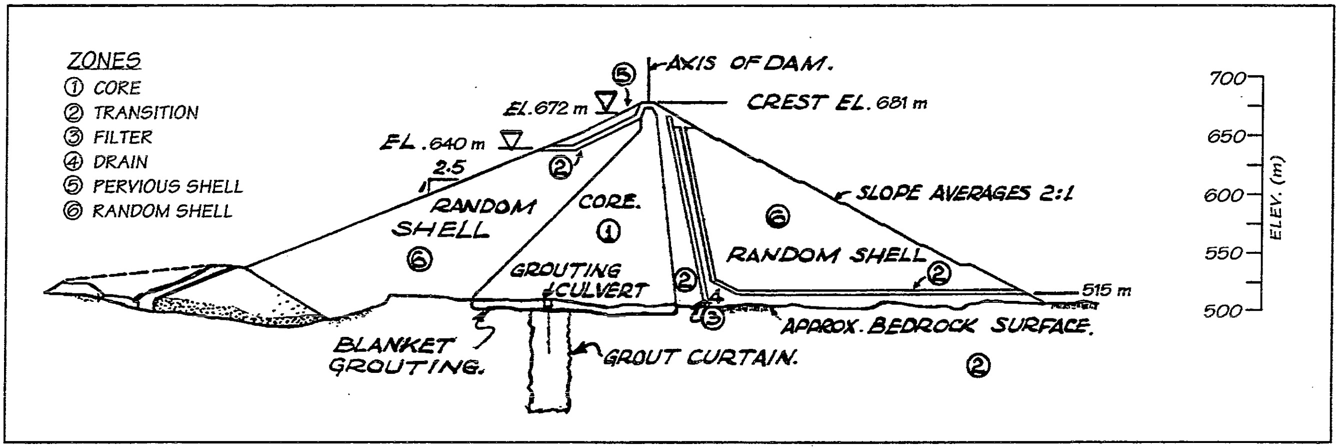

Figure 5. Dam cross section (after Ripley 1967).

planning was done at site by a resident team of senior personnel brought together from BC Hydro and consulting companies across Canada. Experts in specific investigation techniques were retained as needed.

Key investigation criteria were as follows:

- minimize all dam safety risks during drilling;
- maximize the use of surface geophysical (non-intrusive) techniques to examine at least the upper part of the dam;
- use proven technology to drill at the sinkhole, with modifications to minimize core damage;
- use the least intrusive techniques for investigating the sinkholes;
- develop the program incrementally, building on the early results;
- access the global experience of others who have investigated similar problems;
- minimize the number of drill holes, recognizing that the information gathered must be more valuable than the potential for immediate or long term damage to the core;
- maximize the amount of information gathered at each drill hole;
- drill 24 hours/day and use multiple drills where practicable;
- assess drilling data as obtained and adapt the program as conditions become better understood;
- test any unproven methods under conditions similar to those expected at the dam;
- develop safety and surveillance protocols, both for personnel and emergency response (e.g., heavy mechanical equipment and emergency grouting equipment to be in "ready" mode on the dam crest);
- develop detailed drilling procedures, maintain a continuous presence of an experienced senior engineer on crest for "first response", and develop detailed response plans for all foreseeable contingencies.

The investigation plan incorporated all objectives and criteria noted above. The following sections discuss some individual components of the investigation program, particularly identifying planning considerations and lessons learned. This paper describes the investigation at Sinkhole No. 1. Investigations at Sinkhole No. 2 and beyond the sinkholes are not discussed.

4. CONE PENETRATION TESTING

4.1 Selection of Method and Objectives

The seismic piezocone penetration test (SCPTU) was the principal investigation technique used to define the characteristics and extent of the disturbed dam core beneath the sinkhole. The SCPTU was selected because, of all intrusive investigation techniques available, it yields the most information with the least disturbance. It is also a very controlled, sensitive penetration method with real time data output.

While considering the seismic piezocone, we were concerned about whether it could be pushed into the core at all, because of the likely presence of inter-layered loose and dense materials. Piezocones, or for that matter cone penetrometers of any kind, cannot be pushed into well compacted soils.

The basis for believing that the piezocone could penetrate the core came from the minimal resistance experienced by the Becker Penetration Test at the sinkhole. We were also aware of dynamic cone penetration tests of the backfill materials around vertical riser pipes in the glacial till core at the LG4 development in Quebec (Boncompain et al. 1989).

The SCPTU program objectives were to determine the depth and extent of the disturbed zones, and to gather as much data as possible from each SCPTU profile.

4.2 Description of SCPTU Equipment and Procedures

The piezocone included transducers for measuring tip resistance, sleeve friction, pore pressure and temperature. It also included a bi-axial geophone for measuring compression wave/shear wave velocity.

The equipment and penetration procedures followed ISSMFE (1989) standards, except that the tip area was 15 cm^2 instead of 10 cm^2 and the penetration rate was generally slower than 2 cm/s. A larger tip was used because of the potential need for greater sensitivity in very loose core. A slower penetration rate was used because of concern that the cone rods would buckle on dense material before the hydraulic ram could be shut down. Both concerns proved to be valid.

After collaring each SCPTU hole (Sonic, Barber, and mud rotary rigs were used for this purpose) initial drilling was carried out by a Simco 5000 mud rotary drill rig to reach the test level. Procedures for drilling to support the SCPTU tests were similar to those described in Section 6 of this paper.

The piezocone was pushed with a hydraulic ram fitted to the Simco 5000 drill rig. Before cone testing, HWL rods and BWL rods were lowered inside the HW casing to laterally support the cone rods. The piezocone was then lowered to the bottom of the casing and pushed into the soil. Testing continued until:

- the piezocone refused in a stiff zone, or
- bending in the piezocone rods became excessive (due to a long, laterally unsupported section beyond the casing in soft ground).

The piezocone was then removed from the hole, the casing was advanced, the hole cleaned out, and testing continued. Because of friction buildup, the casing had to be nested several times to reach target depths.

Before resumption of SCPTU testing in uncertain ground conditions, a "dummy" cone mounted on BWL rods was quickly lowered to the bottom of the casing and pushed into the soil. On several occasions the dummy cone encountered stiff ground. This trial procedure saved time in lowering and then removing the 1 m threaded SCPTU rods.

Every 1 or 2 metres, piezocone testing was paused to allow pore pressures and temperatures to equilibrate around the tip, and to carry out downhole seismic velocity testing. Seismic "shots" were made by discharging a heavy gauge shotgun into a prepared hole. The shot pattern varied, but generally included locations on four sides of the SCPTU hole at several prescribed offsets.

4.3 SCPTU Test Program and Results

Six SCPTUs were completed at Sinkhole No. 1. Typical results are shown on the following figures:

- Figure 6 shows the location of selected drill holes at Sinkhole No. 1.
- Figure 7 shows the standard test results (tip resistance, shaft friction, friction ratio, and dynamic and equilibrium pore pressures) for the first SCPTU hole in Sinkhole No. 1.
- Figure 8 is a section showing piezocone tip resistance with depth for a number of SCPTUs at varying distances from the centre of Sinkhole No. 1.

Note that in the first SCPTU the tip resistance is remarkably low to a depth of 33.5 m, with values approaching the equilibrium pore water pressures. The cone rods essentially fell under their own weight to 33.5 m. The low tip resistance was first thought to be due to low density but subsequent testing showed that it was primarily a function of very low stresses in the disturbed zone. Below the low tip resistance zone is dam core with rapidly varying density. The characterization of the dam core is described in a later section.

4.4 Lessons Learned

The first SCPTU test was carried out, of course, without knowledge of the general conditions below the sinkhole. There was much debate about whether there would be a repeat of core collapse and/or pore pressure response in adjacent piezometers. Consequently, an attempt was made to anticipate all possible dam responses, and to develop procedures and contingency plans to address them. However, when venturing into unknown ground conditions, there is always much to be learned.

We recognized at the beginning of the program that the piezocone investigation had an inherent limitation. Because the piezocone cannot be pushed through compacted soil, the location of the loose zone must be estimated *a priori*. The piezocone is therefore a characterization tool, not a general investigation tool in this situation.

Normal methods of interpreting SCPTU data (Lunne et al. 1997) are based on measured parameters and some knowledge of in situ stress state. In this case, in situ stresses were extremely low. Since this was not known at the start of the program, interpretations of soil type using SCPTU results were misleading. Fortunately, soil classification was not an issue, as material type was well known. On other projects involving unexpected and unusual stress conditions, this issue could be more important.

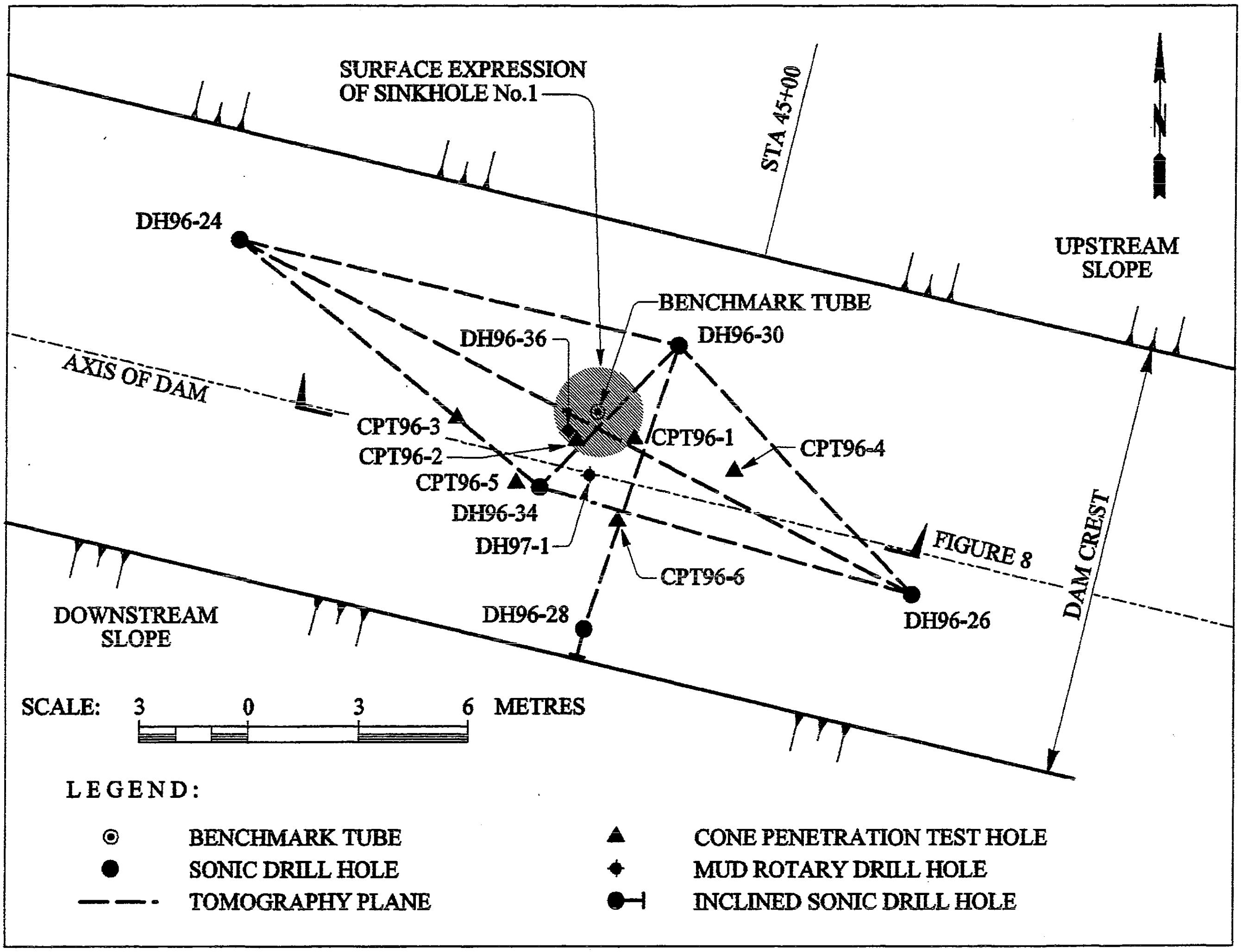

Figure 6. Selected drill holes at Sinkhole No. 1.

The "dummy" cone proved to be a valuable tool for proving out ground after drillouts because drill rods can be lowered much faster than SCPTU rods.

Drilling fluid was routinely lost when cleaning out the inside of the casing, as the drill bit approached the bottom of the casing. This issue is discussed later.

Despite the above shortcomings, the SCPTU exceeded our expectations in providing comprehensive ground information quickly and, most importantly, without reducing the safety of the dam. Indeed, the success of the SCPTU program permitted the use of more intrusive investigation techniques at the sinkhole.

5. SONIC DRILLING

5.1 Objectives

In addition to the SCPTU program, we recognized that it would be necessary to drill holes into the dam to probe the extent of the disturbed core, to characterize the condition of both disturbed and undisturbed core, to define pore pressures, and to install instruments of various types around the sinkhole. However, the spectre of damaging the core by the drilling itself caused great concern, and resulted in a considerable planning effort to select a suitable drill rig and drilling technique. The drilling method would have to be capable of investigating intact core and any zones of intermediate disturbance where the SCPTU could not be pushed.

Listed approximately in order of decreasing priority, the drilling method should:

1. Not damage the dam core in any significant way. In particular, it should not cause hydraulic fracturing under conditions of low total stress and/or low pore pressures which might exist in the dam core.
2. Not trigger collapse of loose zones (as occurred with the Becker rig).
3. Be capable of drilling to depths in excess of 120 m.
4. Allow recovery of soil samples for logging and laboratory tests. As a minimum this should include standard classification tests and preservation

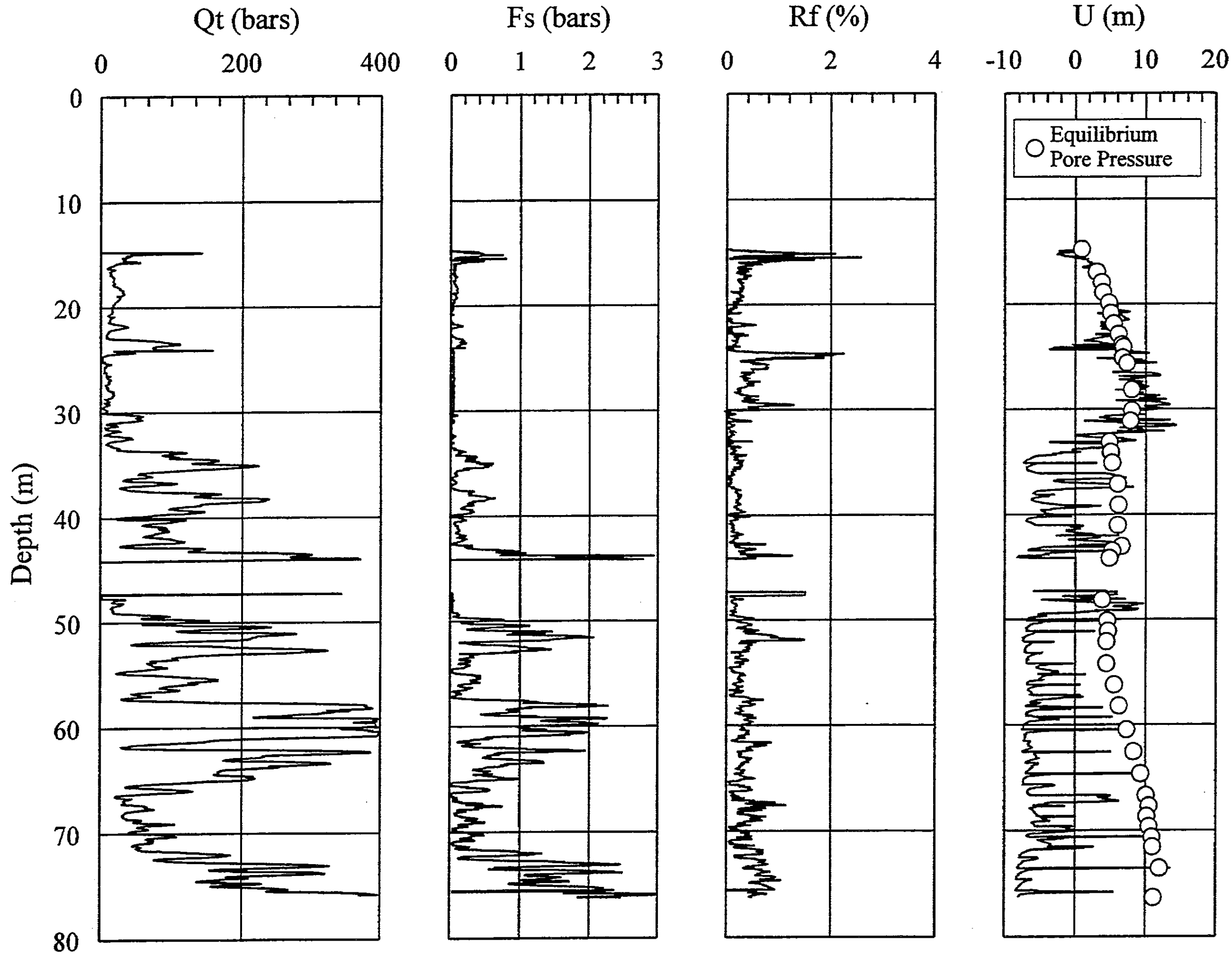

Figure 7. CPT96-1 profile at Sinkhole No. 1.

of soil micro-features such as layering, seams, gradation changes, etc.

5. Allow measurement of in situ density.
6. Permit installation of piezometers and casings (for later geophysical testing).
7. Allow proper completion of the hole, including grouting and sealing to prevent migration of water vertically through the drilled zone.

5.2 Selection of Drilling Method

A drilling method that could meet the above criteria equally well would be a rare find, but the main concern was meeting the foremost criterion, that of not damaging the core. This seemed to rule out standard techniques that employed drilling fluids. Air-drilling methods had the greatest potential to cause hydraulic fracturing, but methods using water and drill mud were also undesirable.

Hydro Quebec was in the process of drilling several relatively shallow experimental holes into dams with similar cores using very heavy drill mud. The benefit of the heavy mud appears to be lack of mobility along fracture planes despite the increased likelihood that heavy mud will cause hydraulic fracturing compared to water or air. However, this technique was in the research stage at shallow depths, and thus not considered suitable for immediate use at Bennett Dam.

Drilling methods that drive a casing into the ground were also considered unsuitable, mainly because of the energy required and because they were too slow or would not reach the necessary depths. This included the Becker hammer drill and cable tool drilling.

One drilling method met most of the criteria given earlier. This method, called "sonic" drilling, had been successfully used to similar large depths in the Fraser River delta. It is used extensively in environmental work and had been used previously by BC Hydro in seismic assessments in granular materials in dams. Reviewing past performance of the sonic drill, it appeared capable of meeting most of the objectives stated earlier. The exceptions:

- The objective of not triggering collapse in a moderate to large loose core zone was probably not achievable with a rig that had sufficient power to drill to the desired depth and that transferred significant vibration into the ground.

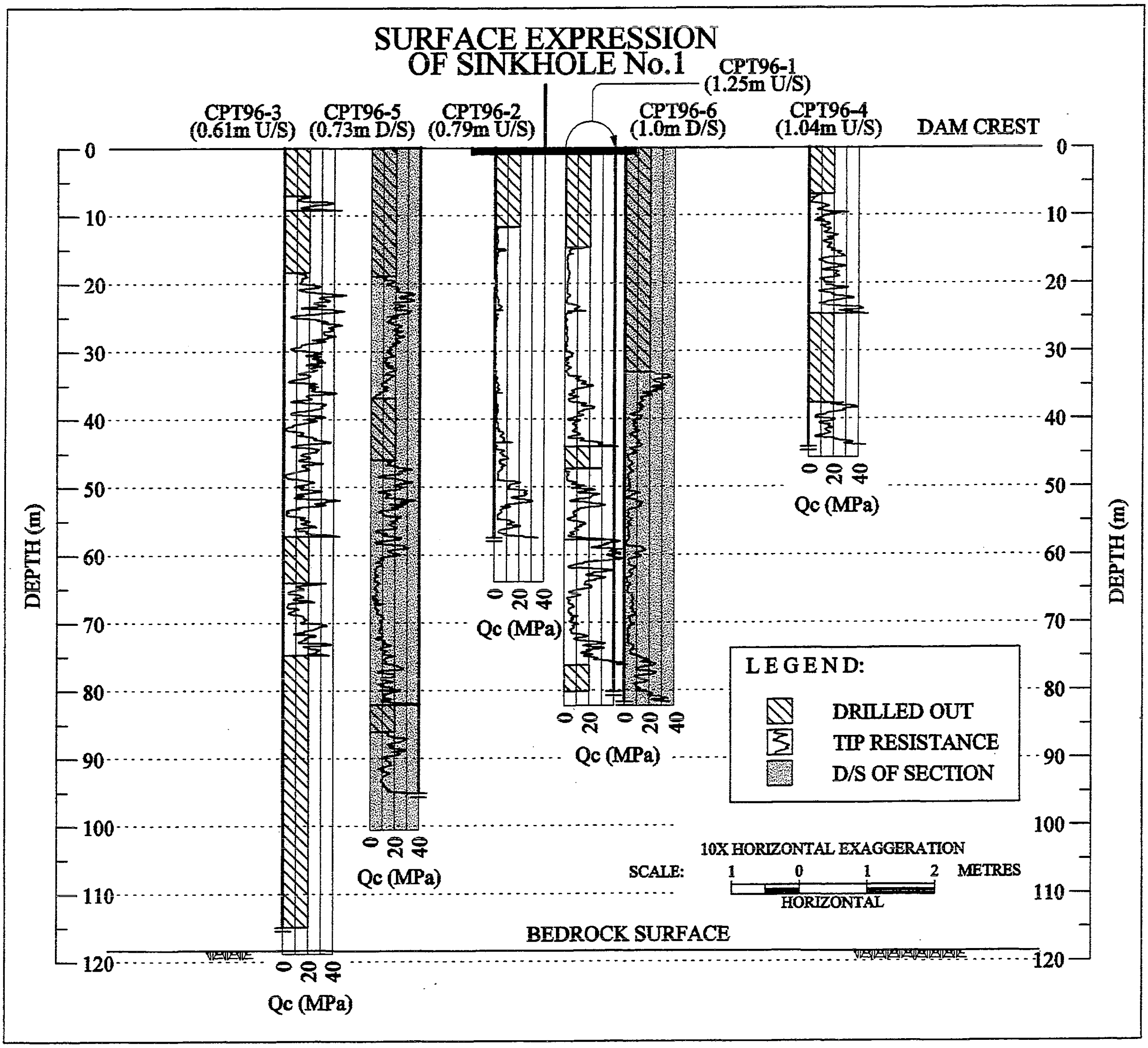

Figure 8: SCPTU profiles at Sinkhole No. 1.

- The continuous sample recovered by a sonic drill is slightly disturbed and thus it is not possible to directly measure density of the core.

5.3 Description of Sonic Drilling

The sonic drill is truck mounted and accompanied by a support truck which carries casing and drill rods (Figure 9). The rig has a hydraulic head with an oscillator that generates and transmits a cyclic axial force down the drill rods to the core barrel and drill bit (Figure 10). The vibrations at the bit loosen moist soil and liquefy saturated soil, allowing the core barrel to penetrate the ground. The sonic drill alternately advances the core barrel and then the casing, normally in 3 or 6 m sections. The equipment is not wireline; consequently the drill rods and core barrel must be removed from the hole to retrieve the sample. Holes are usually started with a large casing and core barrel, and then telescoped down in size as friction builds up on the casing. Table 1 shows typical rod sizes.

Normally the equipment operates dry, but a

Item	Nominal Size (mm)	Inside Diameter, ID (mm)	Outside Diameter, OD (mm)
Core Barrels	115	96.2	114.5
	165	142.4	161.9
Drill Rods	90	76.0	89.8
Drill Casings	140	122.8	140.3
	190	174.6	193.7
	220	201.2	219.1

Table 1. Sonic drill casing, core barrel and rod sizes.

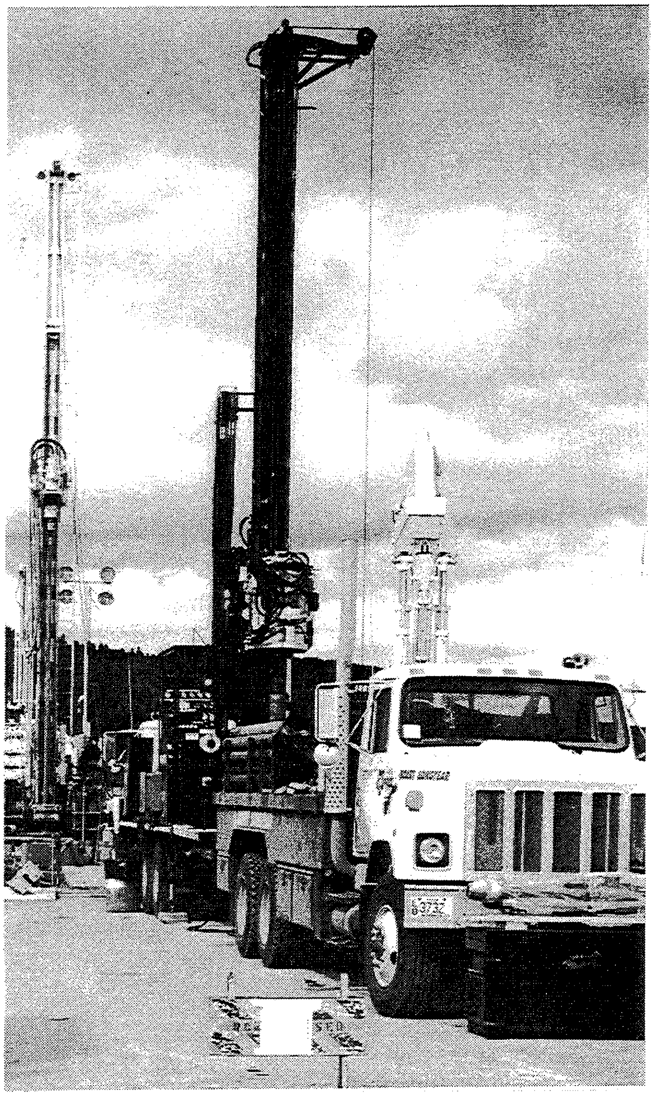

Figure 9. Sonic drill and support truck.

modification on this project was to add only enough water to balance in situ pore pressure. To address the shortcomings of the sonic drill, the following were implemented:

- Investigations with the sonic drill were started at a distance from the sinkholes, with the intention of drilling in ground that was largely undisturbed, to avoid triggering ground collapse.
- The sonic rig was instrumented to measure the following drilling parameters: hydraulic pressure and rate of fluid flow to the vibratory head, vibration frequency and acceleration of the head, hydraulic pressure driving the torque and downward pressure on the drill rods, and drilling advance rate. This had never been done before, and it was hoped that correlations could be developed between these drilling parameters and ground conditions such as density.

5.4 Testing of Sonic Drilling

The capabilities of the sonic rig were tested in sound core before drilling near the sinkholes. The first sonic hole was drilled in early July 1996, on the right abutment of the dam, to a depth of 68 m. No problems were encountered in this hole. The next two sonic holes on the crest were drilled in mid- and late July 1996, in the terrace section (Figure 4), to depths of 120 m and 123 m. In the first of these holes, the 140 mm OD casing stuck at a depth of 117 m but was recovered with a 40 tonne jack. While drilling in the rock foundation, the core barrel stuck and was eventually lost. The second hole was drilled without incident.

Even though problems were encountered, the prototype drilling was successful in that it identified the need to use at least 3 sizes of casing when drilling to 120 m depth, and allowed development of drilling, sample recovery, and hole completion techniques while still drilling in non-critical areas of the dam. It also provided the opportunity to test crosshole tomography techniques.

5.5 Production Drilling

Thirteen additional sonic holes were drilled from the crest of the dam into the core. Most of these were about 120 m deep, but two holes drilled in the canyon section extended deeper, one to a record depth of 140 m. This was considered to be the depth limit in the core using three sets of casing. The depth from the dam crest to base in the deepest part of the canyon is 183 m. To reach this depth with the sonic drill, one would need to telescope an additional casing size, either starting with a larger or finishing with a smaller diameter casing than is commonly available.

As part of the risk mitigation procedures and in anticipation of settlement during drilling close to the sinkholes, all drill rigs were supported on steel beams spanning the dam crest, and the work area was overlaid with geogrid to protect personnel from sudden drops in the ground surface. In addition, surveillance crews monitored surface and subsurface movement while drilling was underway.

After completion of drilling, 70 mm diameter slope inclinometer casing or 76 mm diameter plastic casing was lowered into the hole, then the hole was grouted in stages (to limit grout pressure and thus prevent hydraulic fracturing) while simultaneously removing the steel casing. In areas of very soft and/or collapsing ground, tube-à-manchette sections were included to permit later grouting of the plastic casing.

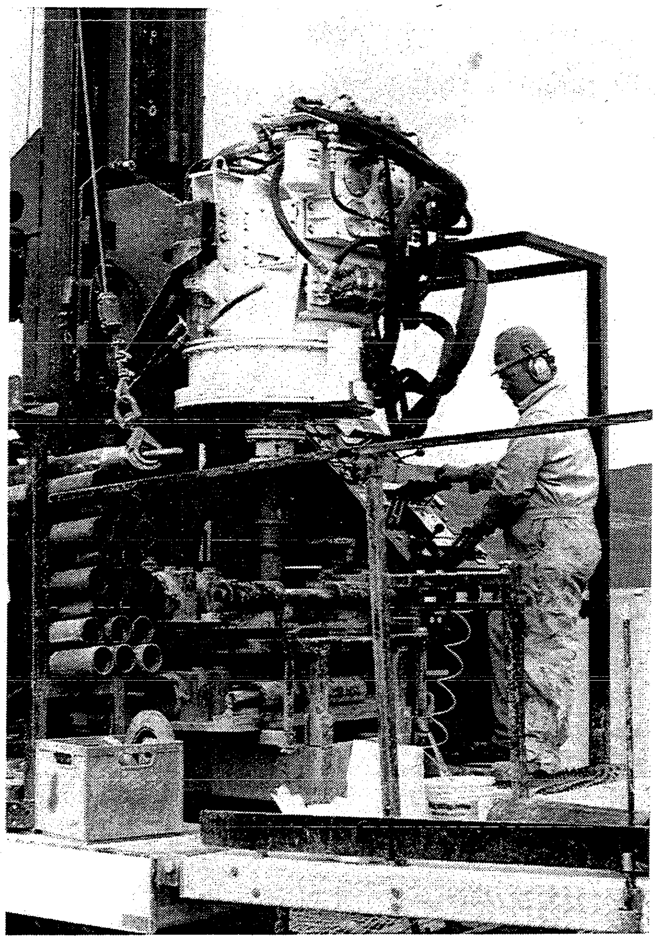

Figure 10. Hydraulic vibratory head on sonic rig.

5.6 Results

Two figures are included which show results from sonic drilling. Figure 11 shows fines content and void ratio (from water content) with distance from the sinkhole. Figure 12 shows a typical plot of drill parameters with depth.

5.7 Lessons Learned

Many lessons were learned throughout the sonic drilling program, first as drilling and sampling procedures were developed, and then later as specific problems were encountered in each hole.

The first lesson was the need to carefully control water level in the drill hole. The water level needed to be sufficiently high to prevent heaving of soil, but also sufficiently low to prevent hydraulic fracturing. Control of water level was even more important when carrying out falling head permeability tests. Proper control in most cases was obtained only where the piezometric pressure was known with a reasonable degree of accuracy before drilling. This information was gathered from previous drilling, adjacent SCPTU testing, seepage analysis and existing piezometers in other parts of the core.

Another lesson was the difficulty of retrieving continuous samples in loose or soft ground. Various types of bits and core catchers were available, but experimentation was necessary to develop a reliable sampling procedure. In some cases, despite these measures, samples in loose ground were repeatedly dropped, causing severe sample disturbance (e.g., mixing, segregation when dropped through water).

The safety precautions taken during the sonic drilling proved to be invaluable. Surface settlements of up to 1.5 m occurred over an area of 2 to 3 m diameter around individual drill holes in or close to the sinkhole.

A group of five field inspectors supervised the drilling on a 24-hour basis (2 rigs), monitored instrument response, and logged all samples. Factors which contributed to the quality of this work were: written drilling, testing, and safety procedures that were updated as knowledge was gained; specific written instructions for each hole; establishment of standards for logging holes; and thorough and frequent communication between senior engineering staff and field staff.

In regards to logging standards, we found that in the early part of the program all staff were consistently underestimating the fines content of the dam core samples. The fines in the samples were almost entirely coarse silt, which was difficult to distinguish visually from fine sand. A set of standard samples was prepared, and all staff were trained in the visual estimation of fines content, after which time the logging became more consistent and accurate. This issue was important, because other field and laboratory testing was triggered by the identification of genuine fines deficient zones in the core.

Drilling parameter data (such as advance rate, head vibration or acceleration, etc.) were collected on most holes. Very extensive and detailed analysis of this data, both on a theoretical basis and looking for trends, provided no correlations with the geotechnical characteristics of the ground. This was a keen disappointment.

Completion grouting of the holes proved to be very difficult. Grout was placed in the hole in controlled lifts to prevent hydraulic fracturing of the core. Typically these lifts were 15 to 20 m thick. Since the grout needed to set up before another lift was placed, it was a time consuming process (even with the use of accelerators), one that ideally should proceed independently of the drilling except for the need to remove casing from the ground. In some holes where a higher permeability zone was present, it was necessary to place the grout in lifts only 2 to 5 m thick, which further slowed the completion process.

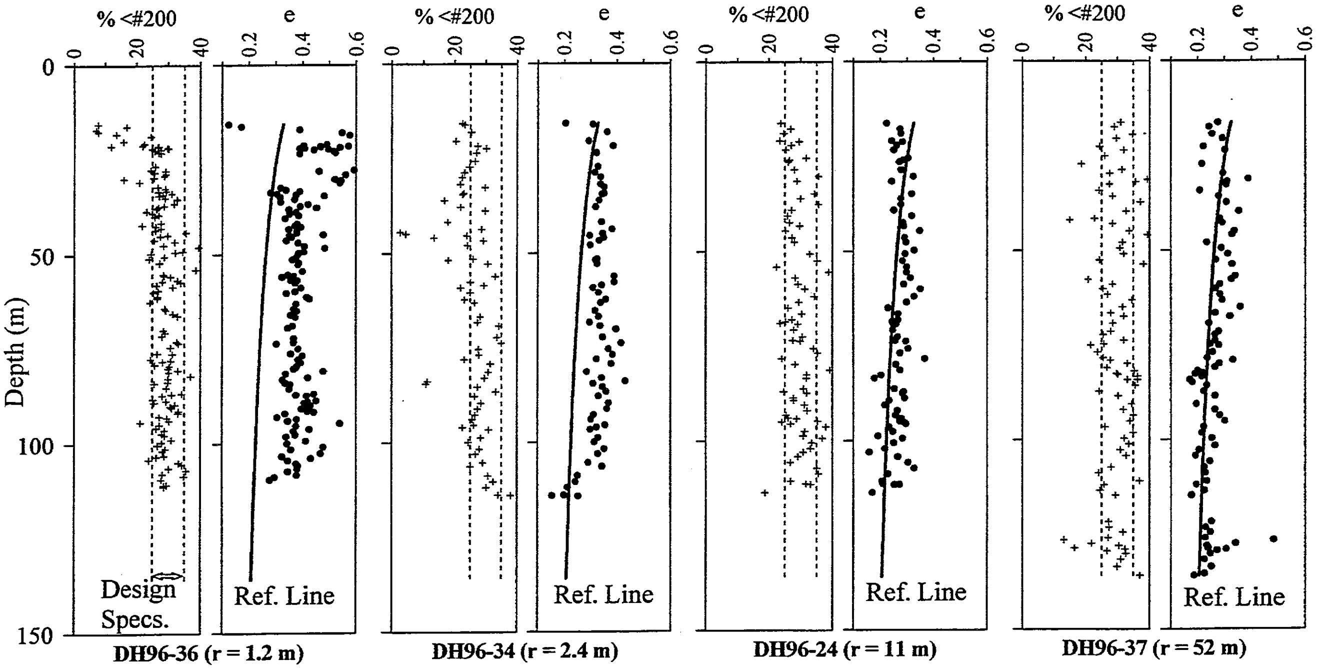

Figure 11. Fines content (passing No. 200 sieve) relative to design specifications, and void ratio for drill holes located at various distances from Sinkhole No. 1.

Mixing and pumping of non-standard grout mixes was also a problem (see Section 7). Keeping sanded grouts in suspension required careful control of water content, which was also necessary in the maintenance of the mixing and pumping equipment. The use of accelerators under variable temperature conditions caused particular challenges.

One behaviour that was not anticipated was the amount of bending and in some cases buckling that occurred in the slope inclinometer and other plastic casing, and which led to problems with insertion of geophysical probes and the tube-à-manchette packer/ grouting unit. The buckling effect was most pronounced close to the sinkholes, but some effect was evident even in holes 10 to 20 m away, from which we concluded that there were at least two causes:

- bending of plastic casing during installation and grouting, and
- lateral ground movement occurring after installation of the casing, due to later drilling or other reasons.

When the problem was recognized, two actions were taken: we switched to a larger plastic casing (to give greater clearance for the probes), and we modified procedures by keeping a string of drill steel inside the plastic casing during grouting, to reduce casing movement and bending during this process.

An important non-technical lesson was the necessity for clearly defined contracts with the drillers, even under near emergency response conditions. Particular challenges on this project included obtaining commitment for rigs when requirements changed daily, scheduling of crews when the drilling extended for long periods of time and/or around the clock, retaining good drilling crews who understood the site, and cost inefficiencies related to use of short term contracts over a long period where production efficiencies should reduce costs.

In retrospect, after an initial period in which the site staff became familiar with the drilling method and the drillers became familiar with the site conditions, the sonic drilling method performed essentially as expected. With care, all objectives except items 2 and 5 (see Section 5.1) were met. Use of the sonic rig to set surface casing for some of the SCPTU holes confirmed the potential of this method to cause ground settlement at the sinkholes, and hence it should not be used where collapse of loose ground is anticipated. Despite our best efforts, the recorded drilling parameter data were not useful in assessing ground conditions. The parameters which can be assessed for this method are very limited, but the technique does provide essentially a continuous relatively undisturbed sample. The vibrations can cause breakdown of coarser particles and this should be evaluated on a material and site basis.

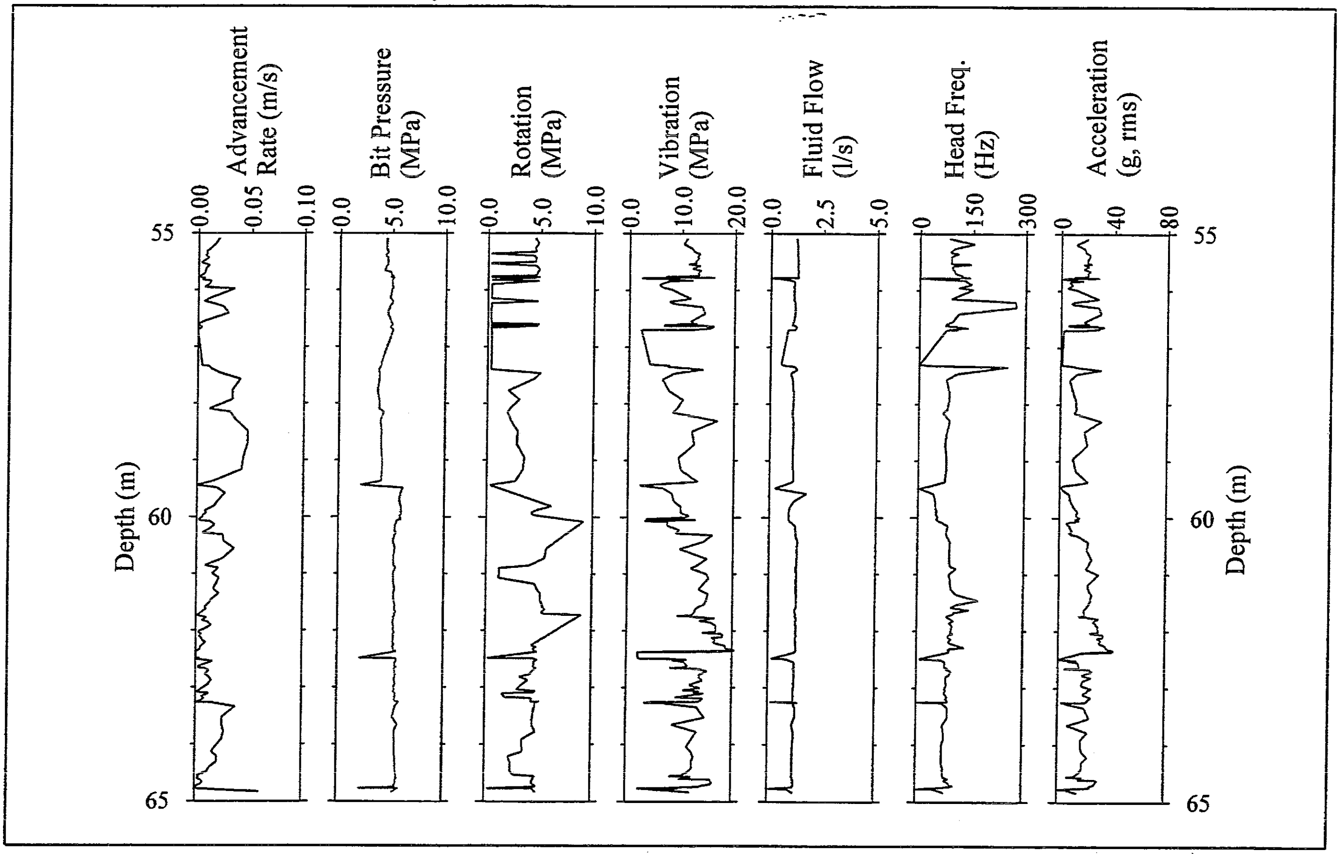

Figure 12. Sonic drill parameters for DH96-22 (55-65m).

6. UNDISTURBED SAMPLING AND PRESSUREMETER TESTING

6.1 Selection of Drilling and Sampling Methods

In assessing the processes responsible for the development of the sinkhole and for remediation design, it was important to obtain samples for gradation analyses and to measure the stress conditions within the sinkhole. Despite its merits, the SCPTU test could not reliably provide this information. Since the sonic drill was also not suitable for this purpose (because of the potential for further ground settlement and also because of poor sampling capabilities in soft ground), alternate methods of obtaining soil samples were considered.

A technique for mud rotary drilling in disturbed core (described below) had been developed during SCPTU testing. At this stage in the investigation, mud loss in the sinkhole was less of a concern because it had been decided to remediate the sinkhole with compaction grouting. Mud rotary drilling was therefore selected for the sampling hole.

Because of the variable ground conditions, several different samplers were tried: fixed piston sampler; heavy wall tube sampler with core catcher; side wall sampler; HQ3 core barrel; and a "slush" sampler which had originally been used in the arctic for sampling soft ice and which was modified for use in soft ground. Of these, the slush sampler was the most successful and is described herein. Two pressuremeters were also brought to site - a standard high pressure "insertion" model, and a low pressure, self-boring model.

6.2 Drilling, Sampling and Pressuremeter Test Procedures

The holes were drilled using a mud rotary rig, but the drilling procedure was unconventional.

- The upper portion of the hole (undisturbed core, above the water table) was collared. For the sampling hole, a sonic rig installed 194 mm OD casing to 15 m depth. For the pressuremeter hole, a Barber rig installed 152 mm OD casing to 18 m depth.
- The sonic (or Barber) rig was moved off the hole and replaced by a Simco 5000 rotary rig.
- PW casing was advanced into the disturbed dam core, ahead of the drill bit, in 3 to 6 m increments, using a combination of down pressure and rotation with no fluid circulation.
- The inside of the casing was then drilled out with a tricone bit and mud circulation. The drill bit was not allowed to extend beyond the bottom of the casing.

- The last two steps were repeated to advance the hole between sampling or pressuremeter test depths.
- When excessive friction developed on the outside of the PW casing, the drillers switched to HW casing and continued with the same procedure.

Test hole DH96-36 was continuously sampled. It was drilled in November 1996 in sub zero conditions. Samples were taken frequently (every 1 to 2 m), mostly with the slush sampler affectionately known as "Frostie". This sampler is similar to a long, very thick wall tube sampler, with an enlarged tip (Figure 13). It was attached to BWL drill rods, lowered to the bottom of the casing, and pushed into the soil. A plug of soil at the bottom of the sampler was then frozen by passing liquid CO_2 from the surface through a 6.4 mm diameter plastic supply line into an expansion chamber at the tip of the sampler, and returning CO_2 gas through a similar line to the ground surface. Freezing of the plug typically required 2 to 4 minutes. Once freezing was complete, the CO_2 supply was shut off, the sampler was withdrawn from the hole, and the bottom of the sampler submerged in hot water to thaw the frozen plug. The sample was then extruded manually, logged, photographed and partitioned for gradation testing and water content determinations.

Pressuremeter testing was carried out at drill hole DH97-1 in early March 1997. A comparatively robust high-pressure pressuremeter was used for the first two tests because the pressuremeter operator was concerned about damage to the membrane from coarse material. The limiting pressure at 10% strain was very low in the first test (less than 50 kPa). Because of its low sensitivity, the high-pressure tool was replaced by the self-boring pressuremeter for the remainder of the tests. A total of 23 pressuremeter tests were completed over a depth range of 28 m to 91 m.

6.3 Results

The dam core was successfully sampled in DH96-36 from a depth of 32 m to the bottom of the disturbed core at 109 m, using the slush sampler. This feat itself was remarkable, and served as an indication of the low stress conditions. The lower, much harder and likely undisturbed dam core was drilled with an HQ3 retractor core barrel from 110 m to bedrock at 115 m.

The disturbed dam core was tested with the pressuremeter in DH97-1. Liftoff pressures were very low, varying from 15 kPa at 28.5 m depth to 220 kPa at 90.7 m depth. The following figures illustrate the sampling and test results:

- plots of void ratio vs. depth and fines content vs. depth (Figure 11) for DH96-36;

Figure 13. "Frostie" sampler.

- a typical pressuremeter plot (Figure 14); and
- a plot of horizontal stress with depth (Figure 15).

6.4 Lessons Learned

As anticipated, mud rotary drilling beneath the sinkhole proved to be difficult. The most important consideration was hydraulic fracturing due to mud pressure. The drilling procedure provided some protection against hydraulic fracturing as long as the drill bit was inside the casing, but in almost every

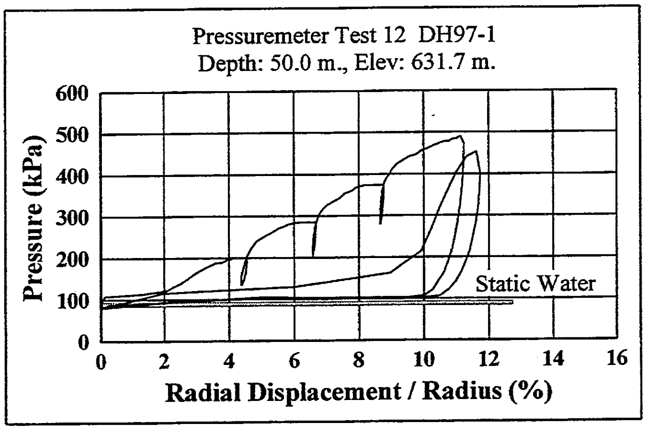

Figure 14. A pressuremeter result at Sinkhole No. 1.

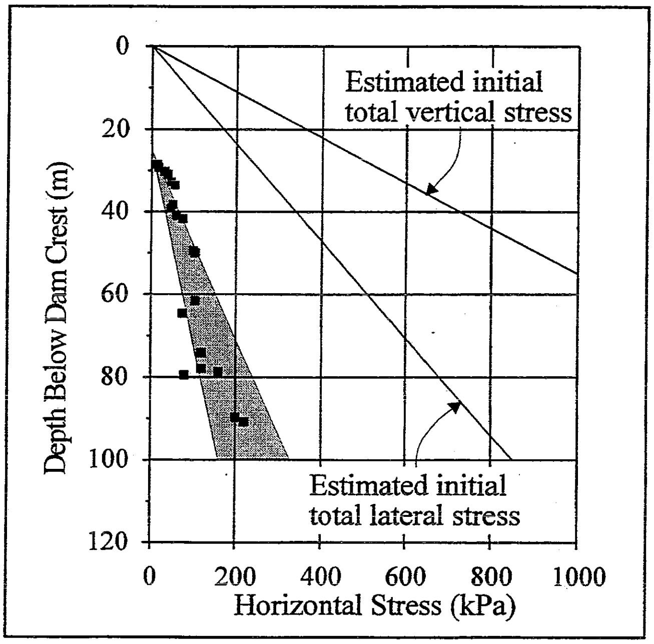

Figure 15. Horizontal stress versus depth from pressuremeter tests at DH97-1.

run, drilling fluid was lost when the bit approached within a few centimeters of the bottom of the casing. On several occasions there were reactions in nearby piezometers, possibly caused by hydraulic fracturing. Loss of mud in loose ground had been anticipated and accepted as an unavoidable consequence of obtaining relatively undisturbed samples.

It is possible to advance a mud rotary hole in soft ground using the above procedure without hydraulically fracturing the ground, as long as a plug of soil is maintained at the bottom of the casing. However, if sampling or in situ testing is desired, it is necessary to clean out the entire casing which inevitably resulted in mud loss possibly due to hydraulic fracturing.

The second lesson learned was also an important one - that loose ground could be effectively and efficiently sampled with the "slush" sampler, permitting recovery of slightly disturbed material. Near continuous samples are possible, although actual sample lengths may vary if ground conditions are variable. Minor problems that occurred when the sampler (designed for soft ice) was used in soil, were overcome with small modifications. This type of sampler has application in many other geotechnical problems involving soils that are too soft for conventional sampling techniques.

Grouting the mud rotary sampling hole was more difficult than the sonic holes. The main problem was high grout loss, despite the use of small lifts, grout accelerators, and even permitting the grout to partially set inside the drill casing. This was due to the extremely loose ground conditions around this hole. Significant time and effort were required to complete the hole.

Some of the performance issues noted above were accepted in this specific application because remediation of the poor ground within the sinkholes was planned. Under other circumstances the performance of the mud rotary drill would not have been tolerable because of the lack of fluid control and the uncertainty of damage to the core.

7. CROSSHOLE TOMOGRAPHY

7.1 Objectives

A variety of geophysical tests were used during the sinkhole investigation. The majority of these were deployed from the surface to search for potential defects in the upper part of the dam. These surface methods met with very limited success.

This section describes two downhole procedures that were used to investigate the dam core around the known sinkholes, over the full depth of the embankment. They are crosshole radar tomography and crosshole seismic tomography, both deployed from within cased drill holes.

Tomography, meaning measurement along a cut or section, is an imaging process originally developed for medical purposes. It allows the spatial distribution of some property within a test zone to be calculated from measurements made at the boundaries of the zone.

Drilling within the confines of the sinkholes was minimized to reduce the risk of precipitating another ground collapse. Tomography, in theory at least, promised the ability to characterize the sinkholes using drill holes that were safely beyond the disturbed zones.

7.2 Basic Principles

In crosshole tomography, a signal source is positioned in one cased drill hole and one or more receivers are located in another drill hole. Transmission of energy from source to receiver defines one ray path. Measurement of ray path travel time usually forms the basis of the procedure although in some cases other parameters may be measured as well. The discussion that follows is restricted to travel time; identical techniques apply for other parameters.

In a typical application, a dense array of overlapping ray paths, with a wide range of orientations, is generated. The travel time for each ray path represents one piece of information. Considered individually, this information allows the average velocity along one ray path to be determined. A collection of arrival times from a large suite of ray paths, however, permits the variation of velocity throughout the measurement plane to be calculated. This is carried out by subdivision of the zone traversed by the rays into N cells. The velocity in each cell is unknown but can be calculated from the data supplied by the N arrival times. Data processing is actually more complicated than this simple example suggests. A more detailed discussion of tomography can be found in Wong (1987).

Output from a typical tomography analysis gives the signal propagation velocity in each of the cells under consideration. These results are contoured to produce a tomogram that shows the distribution of velocity in the test zone. The overall accuracy of a tomogram is a complicated function of many factors:

- drill hole separation;
- number of ray paths;
- number of cells in the tomography model;
- number and accuracy of the boundary conditions;
- number of adjacent and intersecting planes analyzed simultaneously;
- orientation of ray paths with respect to the target;
- wavelength of the energy;
- velocity contrasts;
- error content of the arrival time data; and
- contouring procedures.

Although some guidelines on the influence of these factors are available, their combined effects on the accuracy of the final product cannot be quantified.

7.3 Planning And Implementation

Vattenfall HydroPower Ltd. of Sweden used crosshole radar tomography to image a sinkhole in one of their embankment dams (Carlsten et al. 1995). On the basis of this case history, plans were made, shortly after the discovery of Sinkhole No. 1, to conduct a similar investigation at Bennett Dam. At this stage use of crosshole seismic tomography was not anticipated. Examples documenting the successful use of the seismic technique under conditions similar to Bennett Dam were not known.

Crosshole tomography requires cased drill holes of sufficient size to accommodate the transmitter and receiver tools. For radar measurements, the casing must be non-metallic and held in place with grout transparent to the signal. Standard geotechnical grout used for drill hole backfill typically has a high water content and also some bentonite. Bentonite's low electrical resistivity causes strong attenuation of radar signals. A number of modified grouts, eliminating the bentonite while attempting to maintain appropriate strength, stiffness and shrinkage characteristics, were tested at Bennett Dam. Ultimately, a standard "machine base" cementitious grout was used. This grout had a high resistivity and so did not significantly attenuate the radar signals.

Tomography requires that the start and end coordinates of each ray path be precisely specified. In crosshole applications this requirement can be satisfied by installing grooved casing that can accommodate a slope inclinometer probe. This allows the casing's position to be accurately determined.

Original plans called for a ring of five to eight drill holes to be arrayed around Sinkhole No. 1 on a diameter of about 10 m. Crosshole tomography was to have been conducted between pairs of opposing drill holes. This layout, ideal for imaging the sinkhole, was modified for two reasons - one logistical, the other technical. Sonic drilling in the vicinity of the sinkhole and SCPTU testing directly in the sinkhole had to proceed simultaneously because of schedule constraints. With two and sometimes three rigs working in close proximity it was not possible to position all drill holes according to original plans. Secondly, preliminary testing results suggested that the sinkhole might be surrounded by a zone of intermediate disturbance. This led to a wider distribution of so called "step-out" drill holes. The resulting network of tomogram planes in the Sinkhole No. 1 area is shown on Figure 6.

During the reservoir drawdown period, preliminary crosshole radar measurements were made in two planes to test the feasibility of the procedure. This work involved three drill holes near the west abutment of the dam in an undisturbed part of the core, distant from Sinkhole No. 1 (the prototype test site). However, the decision to proceed with testing in the sinkhole areas was made, by necessity, before the preliminary radar results were available.

In the interim, a limited field trial of crosshole shear wave measurements had been conducted in two of the drill holes at the prototype test site. The small mechanical hammer sized to fit inside the plastic casing was capable of generating good quality signals. This result, together with general seismic velocity testing experience, was considered sufficient to warrant full scale crosshole seismic tomography at the sinkholes to complement the radar testing.

7.4 Crosshole Radar Tomography

The term radar is a mnemonic that refers to the use of reflected electromagnetic energy in the radio frequency band, (used despite the fact that in the crosshole tests the energy is transmitted, not reflected). The propagation of radar waves through soil is a function of dielectric constant, electrical conductivity and magnetic permeability of the material. The dielectric constant of most non-clay minerals is 5 to 7, while it is about 80 for water. As a result, the bulk dielectric constant of soil is strongly affected by its water content. Assuming that other factors remain more or less constant, changes in radar velocity should correlate to variations in water content (Carlsten et al. 1995). If the material is saturated, changes in water content will correspond directly to void ratio.

The fact that radar transmitters generate repeatable signals affords an additional opportunity for tomography. By comparing the amplitude of a signal at its source to its amplitude at the receiver, attenuation can be determined. Thus a ray path, in addition to having an arrival time, will also be tagged with an attenuation value in dB/m. Tomography works on any quantity that has spatial variability, so calculation of radar attenuation tomograms is possible. This may reveal a localized area within the test zone where signal attenuation is very high.

Radar tomography at Bennett Dam was not very successful. Although the sinkholes can be discerned in the tomograms, they are indistinct, largely because the radar velocity contrasts are small. In addition, inconsistencies in the results occur: one sinkhole appears as a lower, and the other as a higher, velocity zone. An identical pattern appears in the attenuation tomograms. The poor quality of the results raised doubts about the usefulness of radar tomography as a diagnostic technique in this case.

The observed deficiencies likely arise from two factors. It appears that the correlation between radar propagation and water content, at least for Bennett Dam core material, is weak. Attempts to correlate radar velocities extracted from the tomograms with measured water contents from similarly located drill holes samples were not successful.

The combination of electrical and magnetic factors that affect radar propagation nevertheless produced tomograms that imaged the sinkholes. That these results contained inconsistencies suggests that no single parameter exerts primary influence. Radar response appears to be a complicated function of poorly understood parameters that may or may not relate to mechanical soil properties.

7.5 Crosshole Seismic Tomography

Crosshole seismic tomography, based on shear wave velocities, successfully imaged the sinkholes. An example tomogram, between DH96-24 and DH96-26 passing directly through Sinkhole No. 1, is given in Figure 16. This shows a narrow vertical zone, with shear wave velocities as low as 150 m/s. Undisturbed core, in areas well removed from the sinkholes, was found to have a typical shear wave velocity of about 550 m/s. The gap in the lower left hand corner of the tomogram is the result of a casing jam that prevented a full sweep of measurements.

The shear wave velocity tomograms correlated reasonably well with available geotechnical information and data obtained during compaction grouting of the sinkholes. In general, however, a

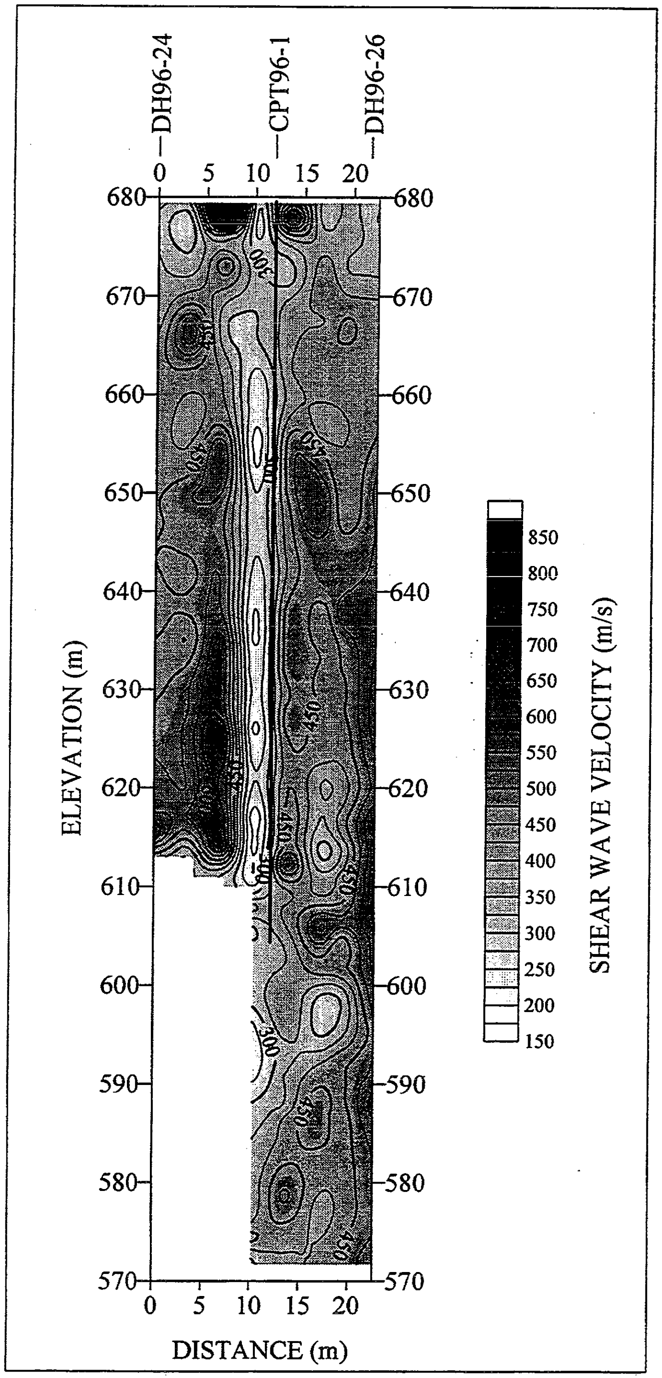

Figure 16. Seismic tomogram at Sinkhole No. 1.

tomogram can easily appear more authoritative than it actually is. We noted, on successive reinterpretations of the data, that the final result could change considerably. It is also possible to skew the results when they are being contoured. This is particularly true if colour contours are used, as visual emphasis can be created at arbitrary velocities. Monochrome shading lessens but does not eliminate this problem.

Areas of unusually low or high velocity in a tomogram often occur in areas where the ray path coverage is sparse. A tomogram should not be interpreted without reference to the ray path pattern upon which it is based. Alternatively, a ray path with an erroneous arrival time or incorrect geometry may be included in the data set inadvertently. This can have a subtle or dramatic effect upon the tomogram. Procedures to quickly assess the quality of the tomography data and allow errors to be corrected are not discussed here. The reader is referred to Wong (1987).

7.6 Lessons Learned

Some of the lessons learned during the course of the geophysical investigations at Bennett Dam are listed below. Several are specific to crosshole tomography; others, while applicable to tomography, relate to geophysical investigations more generally.

- Simultaneous analysis of multiple tomogram planes is essential for success. Drill holes should be located so that a maximum number of adjacent and/or intersecting planes can be included within a single three dimensional tomography model.
- Slight casing bends can cause tools with minimal clearance to jam. Simple procedures to straighten casings prior to and during grouting should not be overlooked.
- Information that can be used as boundary conditions in tomography analysis (e.g. downhole shear wave velocities) should be obtained and applied if practical. This can significantly improve the quality of the results.
- Tomography works best when ray paths parallel to the boundaries of the target zone can be generated.
- Bad data for even a single ray path can have widespread effects on the quality of a tomogram. Rigorous quality control of all data is required.
- Crosshole tomography is slow, complicated and expensive. An experienced contractor is essential for success. Even then, independent review of all aspects of the work is necessary. This should include reproducibility checks of selected results.
- Crosshole tomography makes no direct measurements within the test zone between drill holes. All results are inferred from measurements made at the boundaries of the test zone. A tomogram is best viewed as an approximate representation of actual conditions. Reasonable, but nevertheless non-unique solutions, can be obtained.
- Care should be taken in producing contoured tomograms. Monochrome representations are recommended over colour to minimize opportunities for visually skewing interpretation of the results.
- Interpretation of a tomogram should not be done without reference to the ray path coverage for that plane. Less credence should be given to results in areas where coverage is sparse.
- Analytical modelling of a proposed tomography program can give considerable insight into how successful the procedure may be.
- Attempt to determine if a proposed geophysical technique responds with sufficient sensitivity to variations in the geotechnical parameter(s) of interest.
- Prototype tests are valuable but may not reveal all of the potential problems that can occur in wider application of a technique.
- Geophysics is very data intensive. Rigorous data management procedures should be in place at the start of any investigation if inefficiencies and errors are to be avoided.
- Communication between geophysical and geotechnical practitioners is difficult; considerable effort is required if misunderstandings are to be avoided.
- Clearly defined requirements for data presentation and reporting should be specified in all contracting for geophysics work.
- Like many fields, instructive failures are reported in the geophysics literature less commonly than the success stories. Even these, we suspect, may be coloured by over optimism. At a minimum, recognize that not all experience reported in the literature may be applicable to a new situation.

8. CHARACTERIZATION OF CORE BENEATH SINKHOLE

8.1 Geometry

The sinkhole geometry was interpreted from cross sections of the SCPTU results, primarily the tip resistance and the pore water pressure response. An example cross section is shown on Figure 8. It is not immediately clear what the lateral limits of the sinkhole are, due to the spatial variation of the tip resistance.

Very low tip resistances (less than 1 MPa) were encountered to a depth of 35 m and moderately low values (1 to 10 MPa) to a depth of 95 m. The latter are interlayered with zones of higher tip resistance and zones where the piezocone met refusual. There is a suggestion from the data reviewed in 3D that the most disturbed zone is drifting downstream at depth (reference CPT96-5 and-6).

The SCPTU results a short distance from the sinkhole (reference CPT96-3 and-4) show a variable tip resistance profile, but no significant or vertically continuous zones of low tip resistance. This is interpreted as a transitional disturbed zone between the intact core and the sinkhole.

The results of the sonic drilling were used to extrapolate beyond the SCPTU locations to the intact core. Since the measured drilling parameters could not be correlated with density, the moisture contents from the samples were used to determine void ratio. Figure 11 shows the result for four drill holes at increasing distance from the benchmark tube at Sinkhole No.1. The reference line was calculated assuming an initial void ratio of 0.307, corresponding to the average fill density measured during construction, and using the compressibility of the core material when subjected to overburden stresses.

It is clear from Figure 11 that void ratios decrease with distance from the sinkhole. For example, the average void ratio below a depth of 30 m is 0.38 in DH96-36 (1.2 m from the centre of the sinkhole), 0.33 in DH96-34 (2.4 m away), 0.27 in DH96-24 (11 m away), and 0.26 in DH96-37 (52 m away). The average void ratios obtained in these holes are representative of other holes at similar distances from the sinkhole. A linear interpolation of the results would suggest the edge of the disturbed zone at about 5 m from the benchmark tube. This is consistent with the results of the SCPTU which shows disturbed core at 4 m from the centre of the sinkhole.

Sinkhole No. 1 is a vertical to sub-vertical feature with a downstream drift at depth. The diameter of the most disturbed material is 2 to 3 m to a depth of 90 m. There are some stiffer zones between the loose zones, which may be continuous, or which may reflect a wander in the vertical sinkhole.

Between the inner zone and intact core is a disturbed zone, with an outside diameter greater than 10 m and less than 20 m. The seismic tomography results shown on Figure 16 support these dimensions, with a vertical column showing very low shear wave velocities (less than 200 m/s) to depths in excess of 70 m with a diameter of 2 to 3 m. The tomography also shows a downstream drift to the vertical feature.

8.2 Soil Properties

The SCPTU data (tip resistance, friction ratio, pore pressure response and decay), the 24 pressuremeter test results, and the relatively high quality continuous "frostie" samples were used to assess the geotechnical properties of the sinkhole material.

The following summarizes the main characteristics.

- Very low stress conditions (less than 10% of the estimated initial total vertical stress) exist to 90 m depth (Figure 15).
- The material is very loose, with void ratios of 0.37 compared to intact core with void ratios of 0.25 (Figure 11).
- The fines content is essentially unchanged from the as-placed fines content (Figure 11).
- The samples from the sinkhole showed the existence of "wet seams", similar to those described by Sherard (1973), throughout the full depth. These seams were 25 mm to 50 mm thick, randomly and frequently distributed, and were clearly visible as the samples were extruded from the sample tubes.
- Based on the SCPTU pore pressure response, significant zones of "contractive" material were noted in the sinkhole to a depth of 35 m.

9. CONCLUSIONS

All the objectives of the investigation program were successfully met. The sinkholes were defined and characterized to the extent required to select and design the remediation method. Along the way, and under conditions of severe schedule, technical, political and environmental stress, a great many lessons were learned. Perhaps the most important general lessons are as follows.

- We did not discover any "good" way to drill into the core of this dam, under operating reservoir conditions.
- For a project like this careful planning, meticulous attention to detail, high quality inspection, and detailed safety protocols are critical.
- Prototype testing of new and innovative methods is very helpful, but one must remain vigilant for unforeseen problems which are certain to arise.
- In situ conditions can have dramatic influence on the suitability of various investigation methods. In this case the extremely low stresses in the sinkhole affected the most suitable geophysical tomography methods, permitted pushing the SCPTU (but influenced the interpretation of the SCPTU), and compounded the problems of drilling with fluids.

- Consider all risks with the investigation program and build risk mitigation strategies into all the work.

10. ACKNOWLEDGMENTS

The success of the Bennett Dam sinkhole investigation was due to the dedication of a large number of individuals drawn from companies across Canada. In particular, the exemplary contributions of Mr. David Hill, P.Eng. of Thurber Engineering Ltd. and his drilling investigation team are acknowledged. Likewise, Mr. Dennis Diggle of Foundex Explorations Ltd. warrants special recognition for the innovative drilling and sampling solutions he developed. Mr. David Woeller, P.Eng., and his ConeTec Investigations Ltd. staff are largely responsible for the success of the SCPTU testing. The crosshole seismic tomography would not have succeeded without the dedication and expertise of Mr. Patrick Lapointe, P.Eng. of Geophysics GPR International.

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