GEOTECHNICAL ADVANCES IN BC HYDRO'S DAM SAFETY PROGRAM

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ABSTRACT
BC Hydro has 74 dams at 41 sites throughout British Columbia and provides benefits that include hydroelectric power, domestic and irrigation water, recreational use and flood control. Dam safety challenges, particularly in the fields of liquefaction, piping and risk assessment, have provided BC Hydro and its consultants with the opportunity to participate and contribute to the development of geotechnical engineering practices in the local, national and international arenas.

This paper discusses BC Hydro's contributions to the advancement of geotechnical engineering through its Dam Safety Program. Included in the list of contributions are advances in: the development of the Becker Penetration Test; liquefaction analyses; the remediation of earthfill dams; the understanding of piping and internal instability; the field of risk and uncertainty in dam safety; and monitoring and assessing the performances of earthfill dams.

Future challenges include the need to better understand and manage the potential ramifications of the recent trends in escalating earthquake criteria and continued improvements in managing internal erosion risks for dam safety.

RÉSUMÉ
BC Hydro possède 74 barrages sur 41 sites à travers la Colombie-Britannique et procure des avantages tels que l'énergie hydroélectrique, l'eau domestique et d'irrigation, l'usage récréatif et le contrôle des inondations. Les défis que face la sécurité des barrages, particulièrement dans le champ de la liquéfaction, la formation de renard et l'appréciation des risques, ont procuré à BC Hydro et à ses conseillers l'opportunité de développer des pratiques en génie géotechnique dans les arènes locales, nationales et internationales.

Cet article discute de la contribution de BC Hydro à l'avancement du génie géotechnique à travers son programme de sécurité des barrages. Les avancements suivant sont inclus dans la liste des contributions : le développement du test de pénétration Becker; l'application d'analyses de liquéfaction; la remédiation des ouvrages remblayés; la compréhension de la formation de renard et d'instabilité interne; le champ de risque et d'incertitude dans la sécurité des barrages; et la surveillance et l'évaluation des performances des ouvrages remblayés.

Les défis futurs incluent un besoin de mieux comprendre et de mieux gérer les ramifications potentielles des tendances récentes de l'augmentation des critères sismiques et de continuer d'améliorer la gérance des risques d'érosion interne pour la sécurité des barrages.

1. INTRODUCTION

BC Hydro owns, operates and maintains 74 dams at 41 facilities throughout British Columbia, as a major part of its generating system. The age of the dams ranges from 1902 to 1984. BC Hydro's dam safety program was formally initiated in 1984 following the era of major dam construction and has evolved over the years.

The present Dam Safety Program includes surveillance, periodic comprehensive dam safety reviews, identification and prioritization of dam safety issues, dam safety investigations and capital improvements when required.

Surveillance of the dams is a continual process involving periodic inspections, and monitoring of instruments in the dams. Instrumentation and Automated Data Acquisition Systems (ADAS) for surveillance is an integral part of the Dam Safety Program (Stewart et al, 2000; Baker & Stewart, 2000). In the mid-1980's there were almost no instruments in BC Hydro's older dams. Today, there are more than 6,000 instrument measuring points and more than a dozen sites are equipped with Automatic Data Acquisition Systems.

Dam issues and risks are generally identified through surveillance activities, or periodic comprehensive dam safety reviews, for each dam. Once a potential or actual deficiency is identified, it is prioritized and tracked in the management system until resolution. Where actual deficiencies are confirmed, appropriate risk mitigation actions are taken and this often results in physical improvements.

Since the early 1980's, during the course of dam safety surveillance, investigations and capital upgrades, BC Hydro has had the opportunity to participate in the advancement of geotechnical engineering and its application to dam safety.

The list of contributions includes advances in the development of the Becker Penetration Test; advances in liquefaction analyses; advances in the remediation of earthfill dams; advances in the understanding of piping and internal instability; advances in the field of risk and uncertainty in dam safety; and advances in monitoring and assessing the performances of earthfill dams.

This paper highlights some of the geotechnical advances in liquefaction and piping/internal erosion in BC Hydro's Dam Safety Program over the last 20+ years and provides references for those seeking further details. Three case histories are presented to illustrate some project driven developments.

Advances within BC Hydro on risk analysis and its application have been presented elsewhere (Hartford, 2001; Hartford and Baecher, 2004) and are not the subject of this paper.

BC Hydro has undertaken large and important dam safety projects where the potential benefits justified the costs. The benefits gained from such studies and projects have provided knowledge and procedures that can apply to many geotechnical projects, large and small, including projects outside of BC Hydro's Dam Safety Program.

2. ADVANCES IN LIQUEFACTION

The damage due to soil liquefaction at Anchorage, Alaska and at Niigata, Japan following the Alaska and Niigata earthquakes in 1964 stimulated geotechnical engineering studies of earthquake-induced liquefaction. Subsequently, the near failure of Lower San Fernando Dam in 1971 due to liquefaction of dam fills prompted a greater interest and highlighted the need to develop a better understanding of liquefaction and its implications on dam structures.

In 1979, BC Hydro started to reassess the safety of its dams constructed prior to 1961. A high level review of these older dams was completed in 1981 and this resulted in the immediately rehabilitation of dams such as Alouette Dam and Coquitlam Dam to the earthquake standards of the day.

Much more rigorous and detailed dam safety reviews were recognized to be needed and Comprehensive Inspections and Reviews (CIR) were initiated in 1984. The early application of the CIR process led to the identification of loose liquefiable sands at John Hart Dam. State-of-the-art investigations and analyses were carried out in 1985 and 1986 leading to an early application of jet grouting in 1987 and an almost complete rebuild of the dam under full pool in 1988 (Imrie et al, 1988; Lou et al. 1989; Garner et al, 1989, Lou et al, 1991, Kilpatrick et al. 1992, Marcuson et al, 1993).

The CIR for Duncan Dam was completed in 1986 and this prompted the deficiency investigations on potential liquefaction of the foundation sandy soils and its implications on dam safety. In the initial studies, Seed's approach (Seed & Idriss, 1982) based on field experience during past earthquakes together with empirical correction factors was used. Due to the large implications of the results based on Seed's procedure, a more direct approach involving retrieving and testing of undisturbed samples was undertaken (Byrne et al. 1993). The in-situ ground freezing to obtain undisturbed samples of loose sand beneath the Duncan Dam was the first known use of ground freezing to obtain undisturbed samples at depths greater than 10 m in Canada. The laboratory testing of undisturbed samples and extensive field investigations lead to the conclusion that the confining pressure effects on liquefaction potential being proposed at that time ($K\sigma$ correction curve) could be overly conservative (Pillai and Stewart, 1993).

At about the time of the first CIR's at BC Hydro, there was a growing awareness and interest in the potential for liquefaction in gravelly soils. Accounts of liquefaction in gravelly soils included upstream slope failures in gravelly materials at Shimen Dam and Baihe Dam in China and liquefaction in near level ground conditions at Pence Ranch and Whiskey Springs in the 1983 Borah Peak earthquake.

BC Hydro retained Dr. H.B. Seed in 1984 to provide assistance in developing a procedure to assess liquefaction potential in coarse grained materials at Daisy Lake Dam (Cheakamus Project). This included calibration testing of the Becker Penetration Test (BPT) with the Standard Penetration Test (SPT) at the FMC sand site in Squamish (Harder, 1986; Cattanach, 1987). This initial work with BC Hydro and subsequent calibrations at Duncan Dam formed part of the dataset used in supporting the recommended BPT-SPT correlation curves (Youd et al., 2001).

Further calibration testing was done with two local Becker rigs, an AP-1000 and HAV 180, using both 6.6 inch and 5.5 inch casing. This provided calibration curves for the local rigs, which commonly used the smaller 5.5 inch casing at that time, against the results of Harder's study on US drill rigs. Influence of BPT pipe size and influence of casing depth due to possible frictional effects obtained from these earlier studies were reported by Stewart et al. (1990). These studies revealed that casing friction generally exists in the BPT and re-drive resistance measured at depth following pullback is a significant proportion of the total BPT blow count.

In the early part of these studies, BC Hydro developed a data acquisition system that automatically recorded the bounce chamber pressure to facilitate data collection. This system was a significant advance over visual readings from a fluctuating pressure gauge and was in common use by the local geotechnical community over the years. A program was also developed to assist with subsequent data reduction and interpretation. The system with some minor enhancements remains in use today.

Questions on frictional effects in the BPT such as that evidenced by studies at Duncan Dam and Terzaghi Dam to depths up to 80 m (Stewart et al., 1990), lead to further developments in BPT. An alternative approach to BPT-SPT correlation based on energy measurements was developed by Sy and Campanella (1994). This method explicitly accounted for frictional effects and relied on measurement of the energy transferred to the top of the casing using a pile driving analyzer (PDA). The soil friction and its distribution along the casing can be estimated from the Pile Driving Analyzer (PDA) stress wave measurements by a signal-matching wave equation analysis program. Studies using Harder and Seed's approach and Sy and Campanella's approach were carried out at BC Hydro's Hugh Keenleyside Dam. The results based on the Sy and Campanella correlation and the Harder and Seed correlation are similar, although there is more variation in the Sy and Campanella results that could be interpreted as better reflecting the influence of coarser particles in gravelly soils (Lum and Yan, 1994).

At about this time, another innovative approach based on a mud-injection technique for conducting the BPT was developed to reduce casing friction (Wightman et al., 1993). In this method, bentonite mud is pumped down the Becker casing and the mud comes out through a series of holes behind an oversized, closed end driving shoe. Empirical correlations of the mud-injection Foundex Becker Penetration Test (FBPT) was proposed by Wightman et al. (1993) which are essentially extensions of the Harder BPT-SPT correlation, and used measured peak bounce chamber pressure to correct the recorded BPT blow count.

An alternative, energy-based FBPT-SPT correlation based on transferred energy has also been developed and applied in gravelly soils at the Mica Dam site. The results indicate the potential usefulness of the mud-injection technique in reducing casing friction during the BPT in gravelly soils, and in reducing potential uncertainty in BPT-SPT correlations (Sy and Lum, 1997). Tests at Mica Dam and at a sand test site also provided an opportunity to develop and make use of the first application of the pull-up method using a load cell to evaluate Becker casing friction (Hitchman and Lum, 1996).

The BPT continues to be used for liquefaction assessment of gravelly soils. Difficulties of carrying out these tests on the slopes of dams, particularly on upstream slopes covered with riprap protection led to the concept of hanging the Becker hammer from a crane located on the crest of a dam. This application of a crane-mounted BPT (Figure 1) was first used at Elsie Dam by Addo and Garner (2002). Calibration of the crane-mounted procedure compared to the standard truck-mounted BPT on level ground confirmed that the results from the two procedures are similar (Figure 2).

In-spite of the advances since Harder and Seed proposed their correlations, engineering practice continues to be routed in this earlier work and it would appear that additional research is still needed to develop a sounding tool for gravelly soils that could be efficiently used for all conditions regardless of friction concerns.

Figure 1: Crane-Assisted Becker Penetration Testing

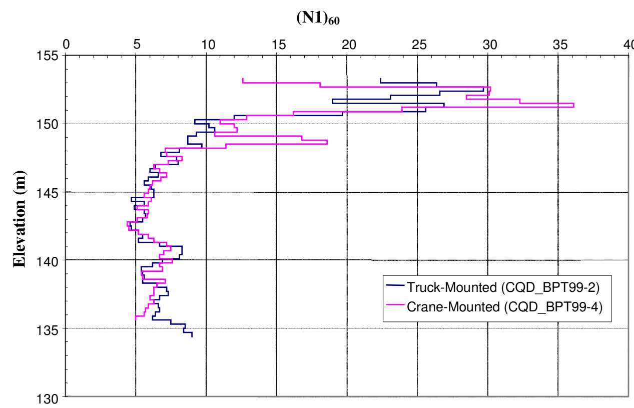

Figure 2: Calibration results of the Crane-Assisted BPT with the standard BPT method

3. ADVANCES IN PIPING AND INTERNAL EROSION

Internal erosion is one of the primary causes of failure of earth-fill dams. The profession still cannot model the mechanics of the process and confidently predict the development and progression of internal erosion. This coupled with our inability to detect physical changes in the early stages continues to be a concern. Nonetheless, significant advances have been made over the years, at BC Hydro and elsewhere.

The cause of a sinkhole that emerged at Coursier Dam in 1992 was not readily apparent through the applications of conventional filter and internal stability methods. Extensive investigations and rigorous analyses eventually led to the hypothesis that inadequate filtering between the clayey-silt core and the complex glacio-fluvial foundation was the root cause of several sinkholes that occurred through the thin upstream sloping core of the dam.

It was not until the occurrence of two sinkholes at the crest of Bennett Dam in 1996 that a concerted effort was made at BC Hydro to improve the understanding of internal instability in till core dams and its implications to dam safety. The extensive investigations and research that took place after the occurrence of the sinkholes provided a wealth of data for carrying out a comprehensive analysis of the performance of the dam and a more detailed understanding of the mechanics of fines migration.

It could be viewed that much of the instrumentation installed in embankment dams should be to provide early detection of changing seepage and internal erosion conditions. The value of this approach has been demonstrated at Coursier Dam where the high frequency of piezometer and weir readings provided an early warning of the high potential for sinkhole development at this dam site. This eventually led to decommissioning of the dam in 2003 (Garner et al. 2004).

One of the most comprehensive instrumentation monitoring systems has been installed at WAC Bennett Dam. This includes state-of-the-art automated seepage collection weirs, piezometers and movement devices as well as more sophisticated multi-port piezometers and less traditional, but highly effective, monitoring tools such as the ongoing use of cross hole geophysics. The application of an Automatic Data Acquisition System (ADAS) provides state-of-the-art real-time monitoring of many key instruments.

4. CASE HISTORIES

The following Keenleyside Dam, Coursier Dam and Bennett Dam examples are discussed in more detail below to demonstrate some of the project-driven geotechnical advances made within BC Hydro's dam safety program.

4.1 Keenleyside Dam

The Hugh Keenleyside Dam is located on the Columbia River about 30 km north of the Canada-United States Border. The dam was completed in 1968 to provide storage for downstream flood control and to increase power generation in the United States under the terms of the Columbia River Treaty. The dam was designed and constructed to the highest standards that prevailed at that time. Prof. Arthur Casagrande acted as an expert consultant during design and construction and explicitly considered the possibility of liquefaction in the design.

The dam has a total length of 810 m and comprises concrete structures and a 52 m high earthfill dam which is 450 m in length. Figure 3 shows a typical section of the earthfill dam. The lower 20± m of the embankment was constructed by bottom dumping from barges and end dumping from trucks to form an embankment to just above the original river level. The upper portion of the embankment was constructed in the dry using conventional construction methods.

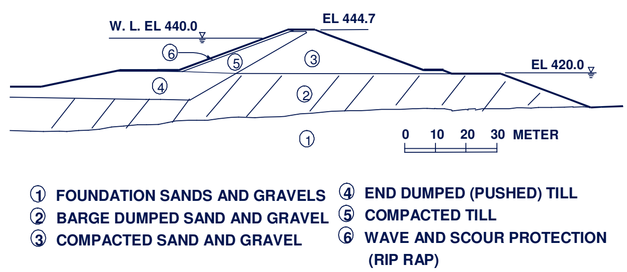

Figure 3: Typical section of Keenleyside Dam

In 1990, BC Hydro's seismic hazard studies indicated that the seismic design parameters were significantly higher than those used for the original design of the project. Consequently, seismic stability studies were initiated to assess the liquefaction potential and seismic stability of the earthfill dam and foundation materials. Screening level studies indicated that extensive liquefaction could be triggered during the Maximum Design Earthquake in the lower portion (20± m) of the earthfill dam. Subsequently, additional field and laboratory investigations and more detailed analyses were carried out, particularly in the coarse gravelly fills that comprise the lower embankment. Field investigations included (1) air rotary drilling with in situ permeability tests; (2) open bit Becker; (3) mud rotary drilling with Standard Penetration tests; (4) Becker Penetration Tests; (5) crosshole and downhole shear wave velocity measurements; (6) Spectral Analysis of Surface Waves (SASW) testing: (7) large diameter in situ ring density tests; (8) Sonic drilling; and (9) Pump tests. Results from these studies have been reported elsewhere (Lum and Yan, 1994; Yan and Lum, 2003).

To further characterize the behaviour of the loosely dumped sand and gravel fills, a series of laboratory tests were also carried out. These included (1) index property tests; (2) consolidated-undrained triaxial tests to determine residual strengths; (3) cyclic triaxial tests; (4) 1-D and triaxial consolidation tests; (5) laboratory shear wave velocity measurements and (6) laboratory permeability tests. Results of the laboratory evaluation of undrained residual shear strength of the Keenleyside gravelly fills have been reported by Yan et al. (1998).

Because of the gravelly nature of the dam fill, the assessment of the seismic stability of the embankment has been based primarily on the results of the BPT using

Harder and Seed's approach. PDA dynamic monitoring was performed at selected BPT holes and Sy and Campanella's method was used for comparison. Figure 4 shows a comparison of the equivalent SPT-N_{60} value derived from the BPT data using Harder and Seed's method and by Sy and Campanella's approach. The equivalent N_{60} values from Sy and Campanella's correlations are generally higher than those obtained from Harder and Seed's correlation for moderate to high blow counts. However, for low blow counts at depths in excess of 15 m where casing friction is significant, Sy and Campanella's equivalent N_{60} values are less than Harder and Seed's values.

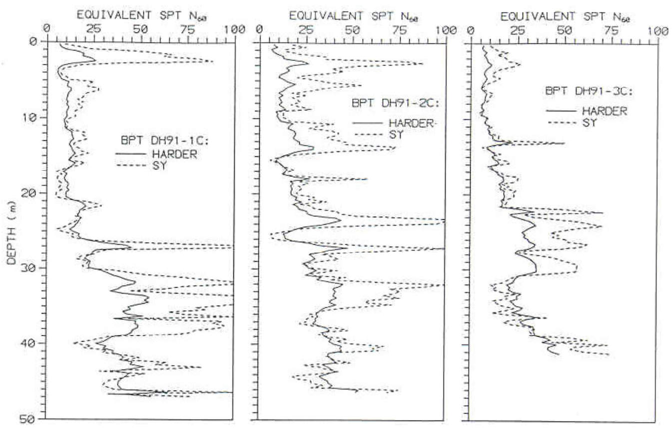

Figure 4: Equivalent SPT-N_{60} from BPT

The results for the shear wave velocity measurements, the large ring density tests and lower bound values from the SPT are consistent with an equivalent SPT $N1_{60}$ of about 8 to 10 interpreted from the BPT (Lum and Yan, 1994; Yan and Lum, 2003). Since great uncertainties still exist with current characterization methods for gravelly soils, multiple methods should be used to gain added confidence in the assessment of liquefaction potential and liquefied residual strength of gravelly soils for important projects as was done for Keenleyside Dam.

In order to complete the assessment, dynamic response analyses and deformation analyses are required. For the purposes of modelling liquefaction and subsequent behaviour, it was necessary to assume that the established procedures for modelling granular soils apply to gravelly soils, although there is some uncertainty concerning the validity of this assumption. To evaluate undrained response, time history analyses were carried out using 1-Dimensional and 2-Dimensional analyses. Effective stress analyses, pore pressure dissipation estimates and post-earthquake deformation analyses were also carried out.

To obtain a better understanding of the risks and uncertainties, a quantitative risk analysis was carried out (Hartford et al., 1997; Lee et al, 1998; Hartford, 2001). The risk analysis is not described here, but constitutes one of the earliest examples to develop a sound and defensible methodology to quantify seismic risk for an embankment dam. The risk management decision considerations for Keenleyside Dam are discussed in Stewart (2000).

4.2 Coursier Dam

Coursier Dam was a 24 m high zoned earthfill dam constructed in a remote area, about 30 km from Revelstoke British Columbia. In 1992, a deficiency investigation was carried out to investigate the occurrence of a sinkhole on the upstream slope of Coursier Dam. The investigations revealed that many other much older pipes and sinkholes had occurred in the dam but they had been largely unnoticed due to difficulties in visual inspections and the historical lack of instrumentation and infrequency of readings. The continued improvements to the monitoring systems allowed BC Hydro to accurately track the effects of the 1992 sinkhole on the rest of the dam and foundation (Stewart et al, 2000).

One of the earliest attempts to use event tree methods for modeling of internal erosion risk was carried out for Coursier Dam. This work demonstrated some basic flaws in the process and there continue to be a number of theoretical and practical difficulties in the use of event trees and fault tress in the analysis of internal erosion risks that remain a subject of debate (Stewart et al, 2005).

Repairs to the sinkholes involved installation of a geomembrane over a portion of the core (Figure 5). During subsequent filling to full pool, the extensive instrumentation and ADAS system detected the signs of another sinkhole in the foundation in another portion of the dam that was not covered by the geomembrane. The presence of the sinkhole was confirmed following a decision to draw down the reservoir.

Figure 5: Coursier Dam – Installation of Geomembrane (1995)

The emergence of the new sinkhole resulted in the decision to decommission the dam (Garner et al, 2004). The decommissioned structure is shown in Figure 6.

Figure 6: Decommissioned Coursier Dam (2003)

4.3 WAC Bennett Dam

Shortly after the Dam Safety Program initiated its first Comprehensive Inspection and Review of WAC Bennett Dam, unexplained pore pressure responses were noted from the hydraulic piezometers in the core of the dam. The observed patterns included "overshots" above the expected levels followed by a slow steady decline of pore pressures. These observations and possible explanations are described in Stewart et al (1990) and Stewart and Imrie (1993). Included in the possibilities was the concept of exsolution of air entrained in the compacted fills.

In 1996 the occurrence of Sinkhole 1 (Figure 7) and a subsequent sinkhole at another location on the dam initiated an intensive and well known deficiency investigation. The investigations required developing and assessing new or unproven methods for safely investigating deep into the core of a very large dam. The results of the investigations are described in Stewart et al (1998).

Figure 7: Sinkhole No. 1 at WAC Bennett Dam (1996)

Methods that were further developed for this investigation included:

- Using a Sonic Drill to continuously sample dam core material at depths in excess of 125 m without inducing hydraulic fracturing.
- Using a freezing tip sampler ("Frosty" sampler) to recover extremely loose soils at depths as deep as 100 m.
- Using a self-boring pressuremeter to measure stresses in extremely loose soil to depths of 100 m to demonstrate the extremely low stress nature of the disturbed zones under the sinkholes.
- Attempting numerous geophysical techniques to determine their effectiveness for assessing conditions in the earthfill dam. (Gaffran and Watts, 2000). For the required application, the most effective geophysical tool was cross-hole seismic. For this project, cross-hole shear wave tomography was applied and evaluated.
- Carrying out large water injection tests into the dam drain, demonstrating the value of designing dams with a high capacity drainage system (Sobkowicz and Holmes, 2000)

In 1997, repairs to the very loose zones below the sinkholes required assessing and adapting compaction grouting methodologies for the first time to remediate sinkholes in dams. The methodologies required significant testing and modifications through field trials so that they could be safely applied to great depths in the dam while it continued to operate (Garner et al, 2000; Shuttle and Jefferies, 2000). Ten years of post-repair dam performance has demonstrated that compaction grouting is effective in stabilizing the very loose disturbed fills (papers in preparation).

In the years following the repairs (1998 to 2005), continued in-depth analyses of the performance of WAC Bennett Dam has resulted in a hypothesis which could explain almost all of the observations. The analyses and research studies have shown that the susceptibility to fines migration in internally unstable materials is related to stress, pore pressure gradients and construction methodology. It has also shown the difficulties that arise from constructing instrumentation in cores of dams (Stewart and Garner, 2000; Sobkowicz and Garner, 2001).

The application of repeat cross-hole seismic was adapted and simplified so that it could be used to monitor changes in the health of the dam (Gaffran and Watts, 2000; Vazinkhoo and Gaffran, 2002). This process has been instrumental in providing confidence that the dam has not changed significantly since the sinkholes were repaired.

Tests were carried out to determine the effects of gas exsolution on permeabilities within the core and transition of the dam (Sobkowicz et al, 2000). This "Air Theory" is based on the observation that significant quantities of air that were entrained into the pore spaces of the core would dissolve into the core seepages under high pressure and exsolve out into the downstream filters, creating temporary low permeability zones, thus explaining the unusual pore pressure patterns in the dam. The tests (Figure 8) indicated that exsolving pore pressures could trigger fines migration and piping in internally unstable materials (Garner and Sobkowicz, 2002).

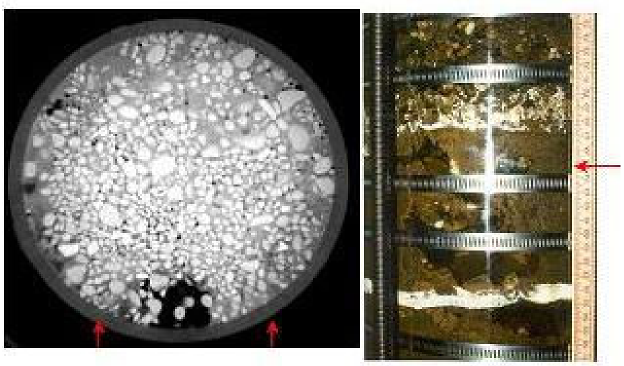

Figure 8: CT image showing effects of piping triggered by gas exsolution

The study of internal instability, including the effects of gradients and stresses on the susceptibility to fines migration and soil collapse has been advanced (Fannin and Moffat, 2002; other papers in preparation).

More recently, a fines migration model has been developed that correlates and predicts the rate of fines migration with changes in pore pressure (Jefferies and Shuttle paper in preparation). Presently, a process for predicting soil collapse due to fines migration based on critical state soil mechanics principles is being developed (Shuttle and Jefferies paper in preparation). This application was mentioned prominently in David Muir Wood's 2005 Bjerrum lecture (Muir Wood, 2005).

5. DISCUSSIONS

The era of major dam construction in BC Hydro ended in the mid-1980's and BC Hydro's Dam Safety Program was formed at around the same time. Over the last 20+ years, BC Hydro has undertaken large and important dam safety projects that have contributed to advances in geotechnical engineering. A brief indication of some of the developments has been discussed and references are provided to allow interested readers to seek more detail in existing publications.

There continues to be a need to better understand liquefaction behaviour of gravelly soils and to develop better characterization tools. Increasing societal expectations and recent trends in escalating earthquake criteria are prompting debate and recognition of a need to re-examine the large uncertainties and assumptions in seismic hazard analyses. Significant progress is still required to understand and manage internal erosion risks. It is possible that improved instrumentation monitoring will play a key role into the future.

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