Internal Erosion of Zoned Earthfill Dams and Their Foundations: Commentary on the State-of-Practice

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ABSTRACT
The WAC Bennett Dam is one of the largest earthfill dams in North America, and one of the most instrumented and studied dams in the world. Following the 1996 sinkhole incident, specific attention has been given to characterizing zoned materials in large embankment dams comprising materials of glacial provenance with reference to susceptibility to internal erosion. Informed by the findings of this experience, this discussion addresses recent developments in the state-of-practice for assessment of internal erosion in dam engineering. The state-of-the-art is then described, with particular focus on laboratory testing for materials characterization at the University of British Columbia where, in collaboration with BC Hydro, we are seeking to develop a mechanics-based understanding of the phenomenon. From this collective body of work, guidance is offered on the use, interpretation, and limitations of select laboratory tests to evaluate the susceptibility of zoned earthfill materials of glacial provenance to internal erosion.

RÉSUMÉ
Le barrage WAC Bennett est un des plus grands barrages de terre en Amérique du Nord et un des barrages le plus instrumenté et étudié au monde. À la suite de l'effondrement de 1996, une attention particulière a été accordée à la caractérisation des matériaux zonés dans les grands barrages en remblai comprenant des matériaux de provenance glaciaire en termes de sensibilité à l'érosion interne. S'appuyant sur les conclusions de cette expérience, cette discussion aborde les développements récents de l'état de la pratique en matière d'évaluation de l'érosion interne dans la construction de barrages. Nous décrivons ensuite l'état de l'art en mettant l'accent sur les essais en laboratoire pour la caractérisation des matériaux à l'Université de British Columbia où, en collaboration avec BC Hydro, nous cherchons à développer une compréhension du phénomène fondée sur la mécanique. Cet ouvrage collectif fournit des indications sur l'utilisation, l'interprétation et les limites de certains tests de laboratoire visant à évaluer la susceptibilité à l'érosion interne de matériaux de terre zonés d'origine glaciaire.

1 INTRODUCTION

Internal erosion of embankment and foundation soils has been identified as a major contributing factor to dam incidents and failures (Foster et al., 2000; ICOLD, 2017). The WAC Bennett Dam (see Fig. 1) is one of the largest earthfill dams in North America, and one of the most instrumented and studied dams in the world. Following the 1996 sinkhole incident, a series of papers was published on its investigation and repair, in a specialty session at the CGS Montreal 2000 conference titled "The WAC Bennett dam sinkhole" (Stewart and Garner, 2000; Stewart and Watts, 2000; Garner et al., 2000; Gaffran and Watts, 2000; Watts et al., 2000; Sobkowicz and Holmes, 2000). "Working Hypotheses" to explain the sinkhole activity include the likelihood that seepage-induced internal erosion took place in the zoned Transition and Core material (see Fig. 1) of the dam. To better characterize the construction materials of glacial provenance and understand the internal erosion process, laboratory tests

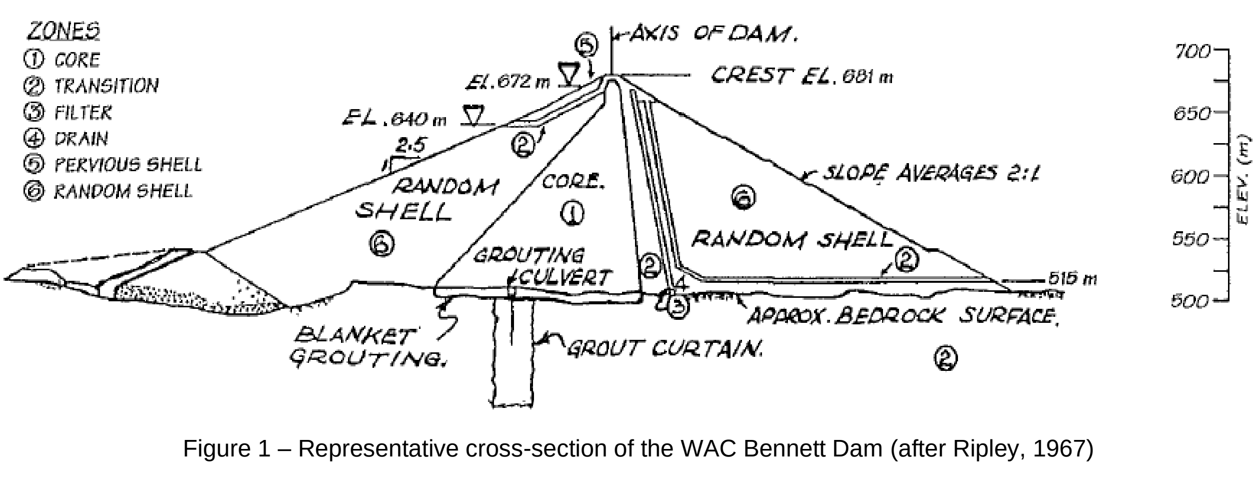


Figure 1 – Representative cross-section of the WAC Bennett Dam (after Ripley, 1967)

and companion research studies were carried out (Garner and Sobkowicz, 2002; Moffat et al., 2011; Moffat and Fannin, 2011; Li et al., 2009; Li et al., 2014). The laboratory findings have informed a general framework to evaluate the susceptibility of a zoned embankment dam to internal erosion (Fannin et al., 2017).

This paper will discuss recent developments in the state-of-practice for assessment of internal erosion in dam engineering, as well as the current state-of-art, with particular focus on laboratory testing for materials characterization. Guidance is offered on the use, interpretation, and limitations of select laboratory tests to evaluate the susceptibility of zoned earthfill materials of glacial provenance to internal erosion.

2 THE BENNETT DAM SINKHOLE INCIDENT

The WAC Bennett Dam is a zoned embankment dam: it consists of a wide impervious central Core zone that is supported on both sides by random shell material (see Fig. 1). The Core is protected by an internal filter and drainage system that comprises a Transition, a Filter, a Chimney Drain, and a horizontal Blanket Drain.

The earthfill dam was constructed primarily of processed granular material that was taken almost exclusively from one source, the glacial deposit of the ‘south moraine’. The deposit is a well-graded sand and gravel. The moraine deposit was bulldozed (see Fig. 2) on to conveyors (see Fig. 3) for transport to the processing plant. The fines-content of the zoned Core was supplemented from a separate glacio-lacustrine silt deposit, with blending undertaken at the materials processing plant. The dam was constructed over a four-year period (1964-67), with a typical construction season limited to 180 days. Challenges encountered during fill placement included those of poor blending and/or segregation when dumping and spreading of materials. Some variation in the gradation of as-placed material is thus to be expected, and is illustrated (see Fig. 4) for the zoned Transition material.

Figure 2 South Moraine – bulldozer loading the hoppers which feed the conveyors

Figure 3 South Moraine – collector conveyors

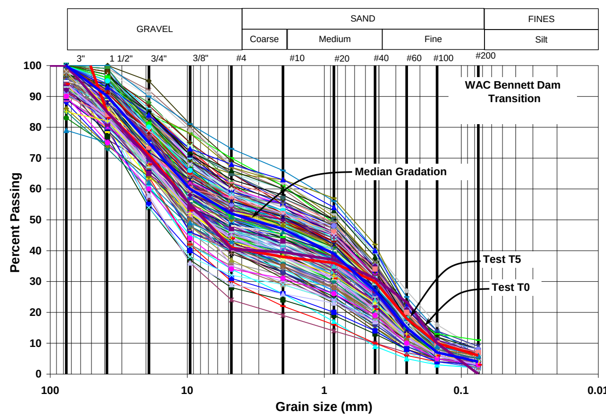


Figure 4 As-built gradations of Transition zone material

Two sinkholes were discovered in the embankment dam in 1996. Sinkhole No.1 was located on the crest of the dam (see Fig. 5), and Sinkhole No.2 on the upstream face of the dam, about 13 meters upstream of the dam axis. Both sinkholes were centered around benchmark tubes installed during construction of the dam (see Fig. 6) and located at the abutments, on either side of the canyon walls. Both sinkholes were remediated by compaction grouting in March 1997 (Garner et al., 2000). Two main mechanisms may explain the formation of the sinkhole No.1: i) settlement due to wetting of lightly-compacted core material around the benchmark tube, and ii) seepage causing internal erosion and migration of fines away from the zone around benchmark tube (Stewart and Garner, 2000). The formation of Sinkhole No.2 may be explained by wetting-settlement alone.

Figure 5 Sinkhole No.1

Figure 6 Survey “benchmark tube”

3 STATE-OF-PRACTICE FOR ASSESSMENT OF INTERNAL EROSION

3.1 State-of-Practice: Mechanisms

Internal erosion occurs when soil particles within an embankment dam and/or its foundation are carried downstream by the action of seepage flow: the potential failure mode cannot yet be analyzed using numerical formulae or models. ICOLD (2017) and USBR/USACE (2018) provide guidance for engineers on internal erosion assessment in dams and levees, based on the current understanding of internal erosion processes and mechanisms. The process of internal erosion is described with reference to four phases (ICOLD 2017, USBR/USACE, 2018):

Initiation -> Continuation -> Progression -> Breach

The event-tree approach has been developed for analyzing internal erosion failure modes, using these four phases. A number of methods, laboratory tests and empirical tools are available to assist in evaluating the potential failure in each phase.

Initiation is the first phase, which occurs if the hydraulic demand arising from local seepage forces exceed the mechanical resistance of the zoned material. Current practice identifies four mechanisms of internal erosion by ICOLD (2017) and USBR/USACE (2018), although the use of terminology embraces some subtle distinctions (Table 1).

Table 1 Four mechanisms of internal erosion

Mechanism (ICOLD, 2017)		Mechanism (USBR/USACE, 2018)
“Concentrated Leak Erosion”		same terms (USACE)
“Contact Erosion”		“Scour” (USBR)
Back-ward erosion	“Backward Erosion Piping”	same term
	“Global Backward Erosion”	“Internal Migration” (“Stoping”)
“Suffusion”		“Internal Instability” (by “Suffusion” or “Suffosion”)

USBR/USACE use the term “internal migration (stoping)” to describe the process by which soil particles move or drop into an unfiltered exit, and a void enlarges and migrates vertically upward. They also distinguish between the phenomena of “suffusion” whereby erosion of a finer fraction yields little or no volume change, and “suffosion” in which mass loss results in volume change. In so doing, USBR/USACE note that suffosion is less likely to be present under the stress conditions and gradients typically found in embankment dams, and it might require considerations of backward erosion, cracking and concentrated leak erosion, or contact erosion.

Following initiation by one or more of four mechanisms, internal erosion may continue, else be arrested, by the filter action of materials in the dam or its foundation. An evaluation of such continuation relies primarily on examining the filter compatibility of the adjacent zones and layers within the earth structure and foundation. The good performance of embankment dams with filters designed in accordance with modern design criteria yields confidence that such filters are capable of reliably arresting erosion. For filter materials which are coarser than required by modern filter design criteria, the Foster and Fell (2001) method may be used to evaluate the continuation process.

Progression describes the process of developing and enlarging an erosion pathway through the embankment core or foundation. The likelihood of internal erosion progressing depends on whether the soil will “hold a roof” over a pipe, else a cracking-filling action arrests the erosion, and any upstream limitation to the seepage flow. ICOLD (2017) and USBR/USACE (2018) give guidance on the assessment of the likelihood of erosion progressing.

3.2 State-of-Practice: Empirical Methods

For a zoned embankment dam (see for example, Fig.1), the initiation of internal erosion is thus envisaged to occur by one or more of the mechanisms illustrated schematically in Fig. 7. Furthermore, it is envisaged the mechanisms may be arrested by zoned transition and filter materials, even if they do not satisfy the modern filter criteria. Accordingly, the susceptibility of zoned dam materials to internal erosion was assessed, with specific reference to the concern for (i) internal instability and (ii) filter compatibility.

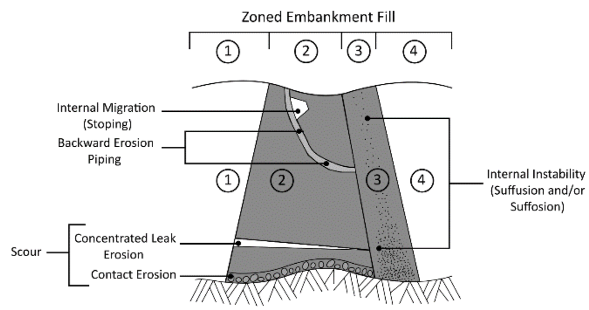


Figure 7 Schematic illustration of internal erosion mechanisms (USBR/USACE terminology)

To assess the potential for internal instability, empirical methods have been developed based on a quantification of the shape of the grain size distribution curve, and/or verified against laboratory test data. Six empirical methods were selected for use in a screening-assessment, on the understanding they were developed for soil types similar to those to which they were being applied: Kezdi (1969), Sherard (1979), Kenney and Lau (1985, 86), Burenkova (1993), Li and Fannin (2008), and Wan and Fell (2008). The percentages of potentially internally unstable gradations in the Transition zone are summarized, for each year of construction record, in Table 2. Some differences are evident in the assessment of each empirical method.

Table 2 Internal stability assessment of zoned Transition material

Year	Kezdi	Sherard	K&L	L&F	Burenkova	W&F
1964	47%	18%	21%	13%	44%	N/A
1965	66%	48%	13%	15%	38%	N/A
1966	46%	33%	5%	3%	51%	N/A
1967	35%	20%	4%	4%	65%	N/A
Total	51%	35%	8%	9%	49%	N/A

Note: NA = Not applicable to gap-graded materials

Filter compatibility is generally assessed using the Foster and Fell (2001), and Foster (2007) method for filters that do not satisfy the current design criteria. Compatibility is described by grouping into four categories:

- Seals with No Erosion (NE)
- Seals with Some Erosion (SE)
- Seals with Excessive Erosion (EE)
- Continuing Erosion (CE)

Filter compatibility at the interface between adjacent zones was assessed with reference to the criterion for Continuing Erosion (Foster and Fell, 2001). The large number of gradation curves available for each zone (see Fig. 8) necessitated the writing of a VBA code to process the data, from which statistical analyses were performed in order to assess filter requirements.

	1 Core	2 Transition	3 Filter	4 Drain
# gradations	9654	2254	1647	1003

Figure 8 Data for filter-compatibility assessment between zoned fill material

It should be noted that the Continuing Erosion criterion cannot be directly applied to filter gradations that are believed internally unstable. These filter gradations require adjusting, by partially or completely removing some fractions of the original filter gradation, so as to account for any internal instability and segregation per Foster (2007) and ICOLD (2017). Accordingly, four scenarios were examined in the assessment of filter compatibility:

1) Design scenario – as-placed gradation
2) Likely wash-out scenario – assumed 50% of the finer fraction is removed by seepage flow
3) Complete wash-out scenario – assumed 100% of the finer fraction is removed by seepage flow
4) Segregated scenario

The assessment compared the value of D_{15max} that was calculated at the Foster-Fell NE/EE/CE thresholds, with the D_{15} of filter material that was assigned to each of the four scenarios. The output of the assessment from the 1964 construction records for the Core-Transition interface is reported in Table 3.

Table 3 Core-Transition filter compatibility assessment (1964 construction year)

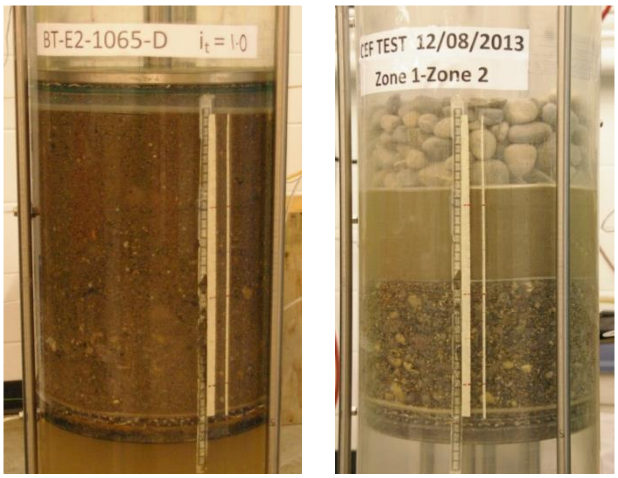
Core D15max (mm)			Transition D15 (mm)			
NE	EE	CE	AP	50%	100%	SG
3.7	5.8	32.5	0.3	0.6	4.5	7.8

Note: AP = As-placed, 50% = 50% wash-out, 100% = 100% wash-out, SG = Segregated

Laboratory tests have been performed to verify the applicability of these empirical methods, including rigid wall multi-stage permeameter tests to assess internal stability, and Continuing Erosion Filter (CEF) tests to assess the severity of erosion (see Fig. 9). The combination of the empirical tools and companion laboratory tests provides an informed insight on susceptibility of the zoned materials to internal erosion.

3.3 Advancing the State-of-Practice

The current assessment of internal erosion of zoned dams is largely based on empirical methods. These methods are necessarily founded on a limited number of tests and materials, and may not be applicable to all soil types. Appropriate empirical methods need to be selected for application to fill materials that are similar to the soils used in original development of the methodology. In addition, filter compatibility criteria have largely been developed for relatively uniform gradations, and the application to broadly-graded materials need to be verified.



a) Multi-Stage Permeameter (MSP) test, and b) Continuing Erosion Filter (CEF) test

Figure 9 Laboratory tests

For important dams or structures, laboratory testing is recommended to verify the application of the empirical methods. However, the laboratory test methods are non-standardized, rendering it challenging to make inter-laboratory comparisons for purposes of interpretation. In addition, the size-limitation of the laboratory test devices, relative to the maximum particle size of dam fills, on occasion imposes a need to “scalp” the test gradation. This has necessarily precluded the testing of the (actual) full range in gradation of broadly-graded fill materials in a dam, and consequently raised questions on the applicability of the test results and assessment criteria. To-date, the effect of oversize particles has not yet been evaluated.

In view of the above limitations on relatively small-scale laboratory testing, BC Hydro is currently working with Powertech Labs Inc. (its subsidiary) to develop an advanced state-of-the-practice laboratory testing facility. This facility will allow BC Hydro to carry out large-scale laboratory testing to characterize the filter and drainage functionality of the broadly-graded dam fill materials that exist in BC Hydro’s dams. The objective is to advance the state-of-practice for assessment of the potential for internal instability in zoned embankment fill materials.

4 COMMENTARY ON THE STATE-OF-ART

For purposes of dam safety risk management, the state-of-practice (a combination of empirical screening tools, and non-standardized laboratory testing), is unsuited to developing a mechanics-based understanding of the underlying processes. Thus in a parallel initiative, the University of British Columbia, in collaboration with BC Hydro and NSERC, is conducting a multi-year research project (2017-2022) with particular focus on double-wall triaxial-permeameter testing of soil for development of a constitutive model.

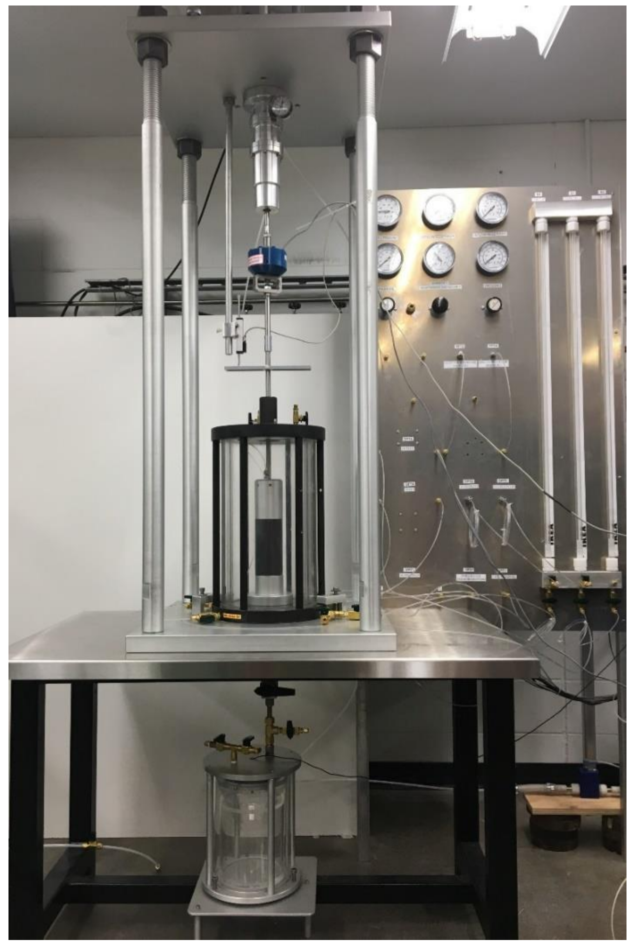


Figure 10 UBC triaxial-permeameter

The triaxial-permeameter (see Fig. 10) is used to consolidate a reconstituted test specimen, and subject it to multi-stage seepage flow, prior to shearing the specimen which, depending on the test conditions, may or may not have experienced internal erosion. The double-wall permits measurement of volume change during multi-stage seepage. The device is also configured to measure any mass loss that occurs in response to seepage flow. Accordingly, the triaxial-permeameter enables the void ratio of the test specimen to be updated throughout the test and, importantly, before it is sheared.

5. SUMMARY REMARKS

The state-of-practice for assessment of internal erosion in embankment dams is described with specific application to the 1996 sinkhole incident at the Bennett Dam. The use of empirical methods, in combination with laboratory testing, offers a meaningful insight to material susceptibility. The limitations of current practice are then addressed, within the context of a BC Hydro initiative to (i) advance the state-of-practice for such non-standard test methods, and (ii) advance the state-of-art in support of developing a constitutive model for internal instability, whereby the finer fraction of broadly-graded soil is eroded by forces imparted on it by seepage flow.

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