Influence of uncertainties in internal erosion assessments of existing embankment dams

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ABSTRACT: The evaluation of a dam's susceptibility to internal erosion is fraught with difficulties related to uncertainties in relation to the in-situ geotechnical properties of materials. These uncertainties include imperfect knowledge of actual soil conditions, imperfect representation of reality by models and variability of soil properties. Experience has shown that our current capability for mathematical analysis and modelling of potential seepage patterns far exceeds our capability to make judgments of comparable accuracy concerning the geology of a dam site or, for example, how the soil properties may be affected during construction of a dam. The uncertainties about the actual performance of embankment dams are discussed in this paper and illustrated by three case histories. These examples show the influence of various types of uncertainties in internal erosion assessments as well as efficient means to reduce them.

1 INTRODUCTION

Internal erosion is the main geotechnical cause of embankment dam safety incidents and failures. It is a mechanical process where soil particles in the structure and/or its foundation are carried away downstream by seepage flow. In other words, internal erosion initiates when hydraulic forces exceed the soil's ability to resist them.

According to ICOLD (2015), there are four initiating mechanisms for internal erosion: concentrated leak, backward erosion, contact erosion and suffusion. Also, the process of internal erosion can be broadly broken into four phases: initiation, continuation, progression and breach,

The assessment of internal erosion potential in existing dams is of utmost importance for a dam owner. Dam surveillance to detect internal erosion mechanisms at the earliest phases of the process can significantly reduce risks of unsatisfactory performance that could lead to failure.

However, the evaluation of a dam's susceptibility to internal erosion is fraught with difficulties related to uncertainties in relation to the in-situ geotechnical properties of materials. Experience has shown that our current capability for mathematical analysis and modelling of potential seepage patterns far exceeds our capability to make judgments of comparable accuracy concerning the geology of a dam site or, for example, how the soil properties may be affected during construction of a dam (Milligan 2003).

The uncertainties about the actual performance of embankment dams are discussed in this paper and illustrated by three case histories. These examples show the influence of various types of uncertainties in internal erosion assessments as well as efficient means to reduce them.

2 TYPES OF UNCERTAINTIES

2.1 *General considerations*

Uncertainties are ubiquitous in safety assessments of existing dams. Some of these uncertainties are related to imperfect knowledge of actual soil conditions and imperfect representation of reality by models. The variability of soil properties, due to natural deposition mechanisms or soil placement practices during construction, is also a major source of uncertainties.

The word uncertainty can have several meanings and is interpreted in various ways according to people and context. In most cases, it encompasses the concepts of ambiguity, randomness and doubt. Figure 1 is adapted from NRC (2000) and shows the main types of uncertainties related to civil engineering structures and more specifically to dam safety assessments.

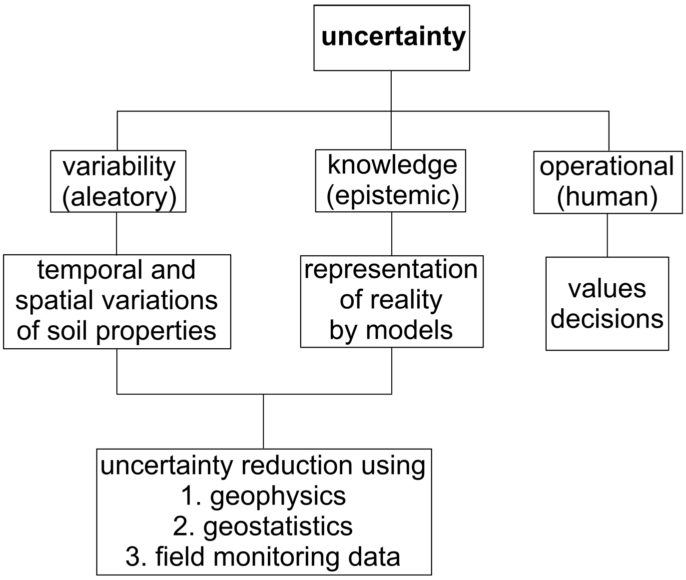

Figure 1. Types of uncertainties.

Figure 1 shows that uncertainties can be associated with the randomness of nature (aleatory) and with an incomplete knowledge of nature (epistemic). Operational uncertainties are related to human values and actions. These types of uncertainties are discussed in the following sections. The presented case histories show how aleatory and epistemic uncertainties were reduced using geophysics, geostatistics and field monitoring data.

2.2 *Aleatory uncertainty*

Aleatory refers to the randomness of nature. However, most engineers think of nature as deterministic where for any effect there are causes which are mechanistically linked. In this context, when describing something as random, it is meant that it is inherently unpredictable except probabilistically. Randomness is thus an assumption, not a property of the world. It is an artifact of modelling (Baecher & Christian 2003).

For example, uncertainties about soil engineering parameters are usually considered aleatory and can be characterized by a mean, a variance and a probability distribution function. Aleatory uncertainty expresses variability at a given time and space or changes in properties with time and space. There is a "true" value to be known.

In geotechnical practice, this type of uncertainty can be reduced with additional data and/or the use of stochastic tools, such as geostatistics, but usually cannot be eliminated.

2.3 *Epistemic uncertainty*

Epistemic refers to lack of knowledge related to processes in a system which results in an imperfect representation of reality. Our knowledge and understanding of phenomena are often embodied in the form of models which allow us to investigate the behavior and attributes of a system to predict outcomes. Models include numerical simulations as well as empirical relations based on laboratory testing. However, more often than not, these representations do not conform entirely to reality. Models can be affected by significant scale effects not always amenable to quantification. Judgement and experience must be used to put modelling results into context and apply commonsense tests.

In geotechnical practice, this type of uncertainty can usually be reduced optimally by using the most representative models that can describe complex phenomena in the simplest form while still capturing those features we are interested in (Smith 2015). Also, a better knowledge of actual in-situ conditions reduces epistemic uncertainties. The latter can be realized using tools such as geophysics.

2.4 *Human uncertainty*

Human uncertainty is an effect of human failings which include yet unquantifiable concepts such as negligence, faulty communications and conflicting demands. This type of uncertainty is prevalent in every engineering project. Sowers (1993) found human factors to be responsible for the vast majority of civil engineering failures. Ignorance and rejection of contemporary knowledge were cited as the prominent causes for these failures.

Human uncertainty will not be presented as such in this paper. However, one has to keep in mind its prevalence and its possible influence on decisions in engineering projects including internal erosion assessments.

2.5 *Uncertainties related to internal erosion*

A conventional approach for dealing with variability (aleatory) and knowledge (epistemic) uncertainties has been the reliance upon factors of safety and precedents. However, factors of safety alone cannot be used for internal erosion assessments since the occurrence of this phenomenon depends on extreme, and not mean, soil properties. Critical seepage conditions are present in the most transmissive and least favorable soil elements and become more variable and more extreme as scale becomes larger.

Uncertainties are unavoidable, they should be described and their effects on internal erosion assessments analyzed to determine optimal means of reducing them. This can be realized using complementary geotechnical tools which consider the problem iteratively and at different scales while taking into account the available field monitoring data.

3 SEEPAGE AT THE JUNCTION OF TWO EMBANKMENT DAMS

3.1 *Site description and observed seepage*

Dam A, located in the province of Québec (Canada) and having a maximum height of 12 m and a total length of 2600 m, was constructed in 1915 as part of a hydroelectric project. This dam consists mainly in random rockfill with an overlying upstream dumped clay core. Dam B, which is a 8 m-high and 320 m-long embankment with a central impervious core, was constructed in 1971 perpendicular to dam A to create an intermediate reservoir (reservoir B) for environmental purposes. The general site layout is presented on Figure 2.

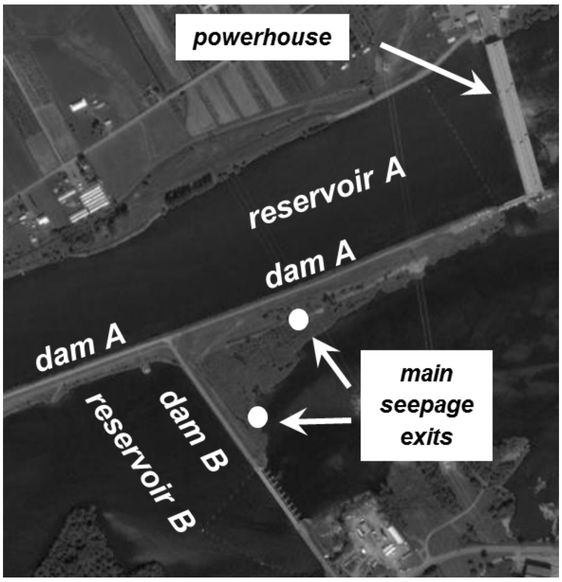

Figure 2. General site layout.

Dam A forms the left abutment of dam B. However, both cores could not be connected together at the junction due to the steep inclination of the dumped clay core in dam A. A connection between both cores would have required emptying reservoir A and excavation of the existing dam which was deemed not feasible economically. A rockfill window was thus left in place at the junction in which a grout curtain was realized from the crest down to bedrock. Figure 3 shows a longitudinal cross section along the axis of dam B as well as the grouted rockfill window.

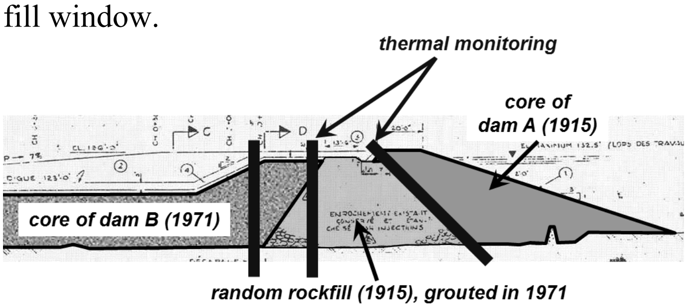

Figure 3. Junction between dams.

Clear seepage was observed since impoundment of reservoir B (see the two main seepage exits on Figure 2). The total measured flow increased steadily from about 20 L/s to more than 230 L/s in a period of 35 years. This flow dropped to initial values during winter when reservoir B was emptied. The effect of the grout curtain was therefore questionable in preventing seepage from reservoir B. Deterioration by contact erosion of the grout curtain in the rockfill window at the junction was suspected to be the main cause of the increasing seepage. More details on this case history are included in Smith et al. (2009).

Rehabilitation works were planned to decrease seepage quantities. However, due to the uncertain nature of in-situ conditions and the unexpected location of seepage exits, far from the probable source, flow patterns could not be identified readily. Epistemic uncertainties had to be decreased to design optimum interventions.

3.2 *Global geophysical survey*

A global geophysical survey of the junction was realized by means of an electromagnetic seepage detection method aimed to characterize the main source and pathways of observed seepage. Because water is a conductor, electrical current follows the path of groundwater between electrodes creating a magnetic field which can be surveyed from the surface using a highly sensitive and specially tuned magnetic receiver. More details on this technology are included in Kofoed et al. (2006).

The geophysical survey showed that the source of seepage is, as expected, the grouted random rockfill at the junction of both dams. Seepage through the core of dam A is however relatively minor and the core of dam B can be considered impervious as well as the rock foundation of both dams. The main seepage paths are shown on Figure 4.

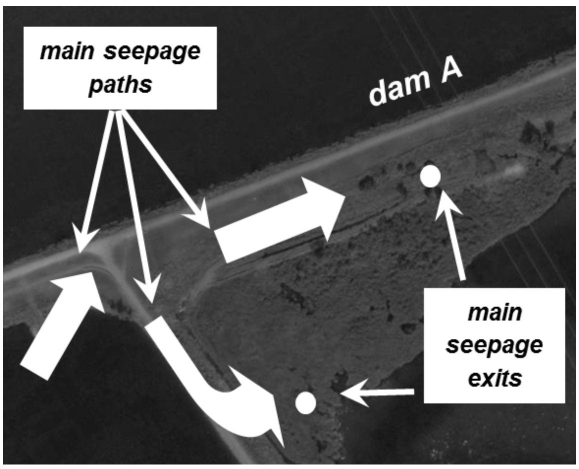

Figure 4. Main seepage paths.

Further analysis of geophysical results in conjunction with field data revealed the presence of natural depressions at the rock surface which concentrate the flow from the junction and direct it to the lower seepage exit on Figure 4. Water in the upper seepage exit follows a linear path in the downstream rockfill of dam A towards the observed exit. Most of the seepage water flows in this pervious rockfill for more than 250 m without exiting near the source as could be expected. This was explained by the presence of a buried wood crib cofferdam in the embankment.

3.3 *Specific thermal monitoring*

A more specific survey of the junction was necessary to further reduce uncertainties by more detailed localization of the main seepage paths and thus the zones more affected by contact erosion. Based on the geophysical survey results, three boreholes were realized at the junction for soil sampling. Two boreholes were used for thermal monitoring (see Figure 3).

Passive thermal monitoring makes use of the fact that increased seepage affects the temperature distribution in an embankment dam. Temperature measurements are realized periodically in the dam and reservoir by means of thermistors. By comparing measured temperature amplitudes and time lags between peaks in the reservoir and in the embankment, it is possible to locate zones with higher seepage velocities.

When seepage velocity is low, the thermal response of a dam is mainly controlled by heat conduction. The thermal behavior becomes affected by advection when Darcy seepage velocity is higher than 10^{-7} m/s (Dornstädter 1997). Advection can be considered as the movement of heat stored in the reservoir and released as water seeps through the embankment. Heat carried by the seepage water along a hydraulic flow line can therefore serve as a natural tracer to help detect zones with contrasting hydraulic conductivities. More details on passive thermometry are included in Smith & Konrad (2008).

The measured temperature profiles at one of the boreholes are shown on Figure 5. Results from thermal modelling to assess the expected response when heat conduction dominates are also shown.

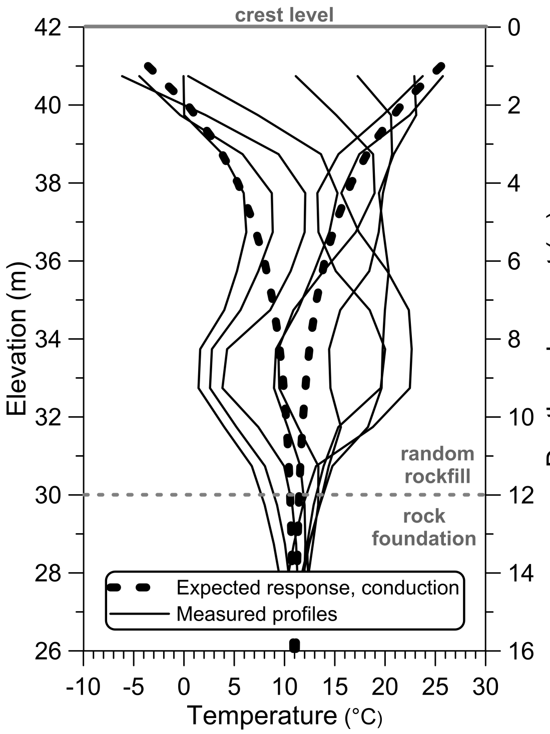

Figure 5. Measured temperature profiles and computed thermal response for heat conduction.

From the crest to elevation 37 m, amplitudes in temperatures decrease exponentially and are similar to the expected heat conduction response. In the rock foundation, below elevation 30 m, heat conduction also dominates. From elevations 37 m to 30 m, measured amplitudes are much greater than the expected temperature response. The maximum amplitude is located between elevations 33 m and 34 m and is equal to 21,3 °C which is more than the anticipated value of 2,8 °C. These substantial deviations from the expected temperature range indicate that heat advection is predominant in this zone. It is thus expected that a more pervious strata centered at elevations 33 m to 34 m exists in the rockfill at the junction. These findings were supported by optical televiewer surveys during the realization of boreholes which suggested the presence of more voids in this zone.

3.4 *Design of rehabilitation works*

Epistemic uncertainties were reduced by using complementary global and specific seepage characterization methods. Results were also compared to field and dam safety monitoring data for plausibility. This increased confidence in results and allowed a comprehensive understanding of seepage patterns which in turn helped design optimum grouting procedures. These rehabilitation works took place and reduced the year-round seepage quantities to their initial values.

4 HETEROGENEITY OF A DAM CORE

4.1 *Detection of a more pervious zone*

The surveillance of a 95 m high sand and gravel dam, located in northern Québec (Canada), by means of thermal monitoring revealed the existence of a zone of significantly higher hydraulic conductivity in its central till core. This could indicate cracking and/or ongoing concentrated leak internal erosion phenomena which could be detrimental to the safety of the dam. However, these monitoring results could also be related to variations in till properties due to construction procedures possibly affecting the hydraulic conductivity of the till core.

A thorough analysis and synthesis of available construction control data was needed to describe the spatial variability of soil properties thus reducing aleatory uncertainties. The use of geostatistics helped characterize heterogeneities in the dam core and determine if they can cause the presence of the more pervious zone detected by thermal monitoring. These causes had to be determined prior to evaluation of possible remedial actions.

4.2 *Geostatistical analysis*

Geostatistics involve the analysis and prediction of spatial phenomena. The main objectives are to characterize and interpret the spatial variability of existing sample data and use that interpretation to predict likely values at locations which have not been sampled. It is generally assumed that there is a relationship between values which depends on the location of samples. Considering that embankment dams are constructed in wide but relatively thin layers (or lifts), the spatial continuity of construction control data is better characterized by the volume of placed soil between construction control sample locations rather than physical distance between them. This leads to an assumption made for the analysis that, for example, two till samples coming from the same truckload during construction are more similar than two samples having a longer placement time (and volume) interval between each. This assumption was confirmed on numerous occasions in the field.

The measured fines content values in the till during construction were treated as aleatory variables in the geostatistical analysis to account for their inherent uncertainties. The spatial continuity of these values was computed and this information used to predict fines content for the entire core volume. More details on this geostatistical analysis are included in Smith & Konrad (2011).

4.3 *Inferred hydraulic conductivities*

The hydraulic conductivity of saturated till depends on the percentage of fines and also on the compaction conditions. When the till is compacted at a degree of saturation lower than that at the Proctor optimum value matric suction causes the development of macro porosity which results in an aggregated fabric and thus an increased hydraulic conductivity. For higher compaction degrees of saturation, the till fabric is considered homogeneous and has a decreased hydraulic conductivity (Leroueil et al. 2002).

The measured densities and water contents during construction were used to determine the till fabric in each sample location. Considering fabric and the predicted fines content in the entire core volume, the hydraulic conductivities were inferred using an empirical model based on laboratory test results. This allowed for a complete representation of the hydraulic conductivity profile of the core. Figure 6 shows the order of magnitude of inferred hydraulic conductivities in the upper part of the core at the maximum dam section.

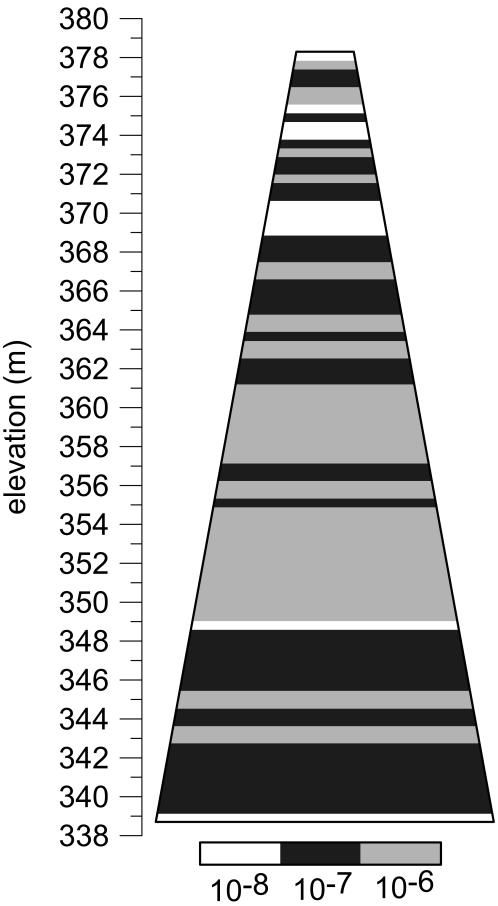

Figure 6. Inferred hydraulic conductivities in the core.

The inferred hydraulic conductivities show a high variability from one placed till lift to another with variations of up to three orders of magnitude. The upper and lower portions of the core represented on Figure 6 are generally less pervious and contain occasional lifts of higher hydraulic conductivity. A thicker zone of higher hydraulic conductivity (k ~

10^{-6} m/s) is present from elevation 349 m to 361 m. The k values even approach 10^{-5} m/s between elevations 350 m and 352 m where the till fabric is aggregated for a number of consecutive lifts. These findings correspond well to the construction control reports where compaction problems and lower fines content in till were noticed in this area during placement. Figure 7 shows a view of a test trench in the core during construction.

Figure 7. Test trench during construction.

At the center of Figure 7 the till has a homogeneous fabric contrary to the overlying and underlying lifts where the fabric is aggregated and the hydraulic conductivity higher. Although in each case the technical specifications were followed regarding fines content and compaction conditions, the inherent allowable variabilities in till properties resulted in hydraulic conductivity values encompassing three orders of magnitude.

4.4 *Representativeness of inferred hydraulic conductivities*

The representativeness of inferred hydraulic conductivities was assessed with temperature and field monitoring data. The maximum annual temperature amplitudes measured in the core correspond to the zone of highest hydraulic conductivities (between elevations 350 m and 352 m) shown on Figure 6.

As a commonsense test, the inferred hydraulic conductivities were used as inputs in a conventional seepage analysis to determine the expected seepage flows. These values were then compared to measured flows and shown to be in close agreement.

The dam core heterogeneities were found to be mainly due to aleatory uncertainties namely the variations of fines content and till fabric that occurred during construction. No internal erosion or cracking phenomena are present in the core. The detected zones of higher hydraulic conductivity in the dam core were related to variations in till properties due to construction procedures. No other remedial actions were needed.

5 INTERNAL STABILITY OF A DAM CORE

5.1 *Main characteristics of dam*

The analyzed dam is a 171 m-high and 380 m-long rockfill structure located in northern Québec (Canada) with a central impervious core made of compacted till (namely non-plastic well-graded silty sand with gravel and having 3% of particles < 0,002 mm). The core and both upstream and downstream filter and transition zones are entirely founded on grouted rock. The placement of till was realized by dumping and spreading the material in 0,45 m-high lifts across the entire width of the core. Laboratory tests, which included the determination of grain size distribution by sieving and hydrometer tests (particles < 0,08 mm), were performed for construction control. As part of a dam safety evaluation realized 10 years after the end of impoundment, the assessment of internal stability of the core material was deemed necessary.

In case of internal instability, internal erosion by suffusion can occur and cause unsatisfactory performance of the dam. Suffusion refers to the migration of the finer particles in a soil through voids formed by the matrix of coarser particles. A soil can thus be considered internally stable (non-suffusive) or internally unstable (suffusive). This could lead to a redistribution of fines in a soil without loss of mass or, in more critical circumstances, to larger scale erosion and a loss of fines. Redistribution or erosion of fines in a dam core can develop quickly after initial reservoir impoundment or progress slowly in the long term.

5.2 *Assessment of internal stability*

Various internal stability assessment methods based on the geometry of grain size distributions are published. Most of them rely on laboratory testing of soil samples. However, the testing conditions (hydraulic gradients, type of soil, compaction of samples etc.) and the criteria for instability used in these experiments are not always defined clearly. Therefore these methods may not be directly applicable to soils and hydraulic conditions encountered in actual dams. To circumvent these difficulties, three methods to assess internal stability of the dam core were used and results compared. These methods are based on the work of Kenney & Lau (1985, 1986), Wan & Fell (2008) and Lafleur et al. (1999). More details on this assessment are included in Smith (2012).

The Kenney & Lau method was developed by testing sandy soils to be used as dam filters. It considers the shape of the grain size curve in its finer portion. It was not specifically developed for well-graded silty soils. Also, some of the testing conditions, namely the use of vibrations and higher seepage velocities, are more severe than the conditions typically encountered in a dam. Moreover, scale effects can influence interpretation of testing results since, for example, the beneficial effects of having wide cores and filters in the field could not be taken into account. For these reasons, and also as suggested by the authors, the expression "potential for instability" is often used instead of instability when using this method.

An application of the method was realized using construction control data for the dam. Considering the importance of the finer portion of the grain size distribution, only samples with hydrometer tests results can be used for this method. Figure 8 show the stable and potentially unstable zones in the core according to the spatial location of each sample.

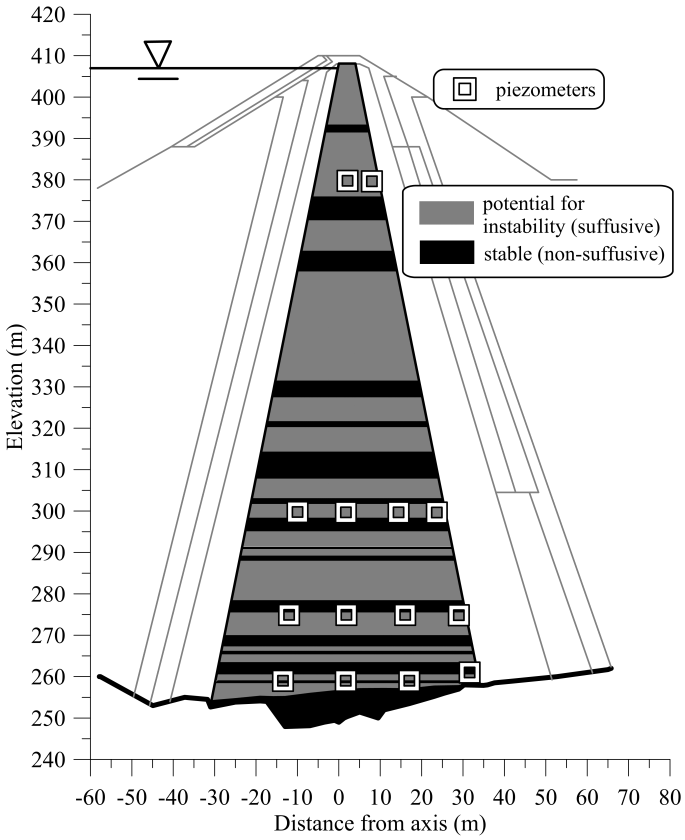

Figure 8. Potentially unstable (suffusive) zones in the core determined using the Kenney & Lau method.

According to Figure 8, the largest portion of the dam core would show potential for instability.

Soil samples were tested in laboratory by Wan & Fell to propose improvements to internal stability criteria existing at the time including those who showed poor predictive ability for well-graded silty soils. In the proposed method, the slopes of the finer and coarser fractions of a soil are compared using particle diameters corresponding to specific percentages passing. Stable (non-suffusive), transition and unstable (suffusive) zones are defined using various diameter ratios. Figure 9 show the results for the analyzed dam.

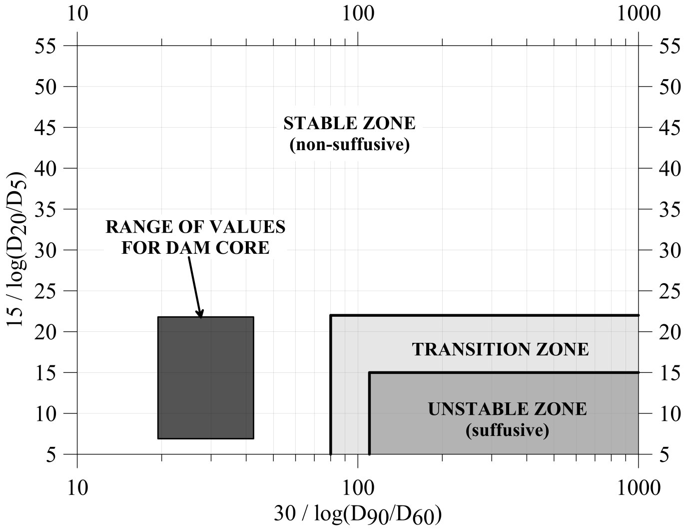

Figure 9. Wan & Fell method, range of values for dam core.

The application of Wan & Fell method to the 174 available grain size distributions with hydrometer tests results gave a range of values represented on Figure 9 and located in the stable (non-suffusive) zone. According to this method, and contrary to the Kenney & Lau method, the entire dam core is deemed internally stable.

Various laboratory tests were realized by Lafleur et al. (1999) on well-graded till samples from northern Québec. Although the purpose of these tests was not specifically to establish an internal stability assessment method, the main conclusions of these tests can be useful to assess the till core presented here.

These laboratory tests have shown internal stability of till (fraction passing 40 mm) when the fines content (particles < 0,08 mm) is more than 12%. The fines content in the analyzed dam varies from 24% to 42%. Therefore, according to this approach, the entire dam core is internally stable (non-suffusive). This conclusion concurs with the findings from the application of the Wan & Fell method.

5.3 *Representativeness of internal stability assessments*

The application of three internal stability assessment methods based on the geometry of grain size distributions (construction control data) led to contradictory results. The core had potential for internal instability for the method developed by testing sandy soils. It was deemed internally stable (non-suffusive) by the two other methods developed by testing well-graded silty soils. These contradictions result in epistemic uncertainties that can be reduced by choosing the most representative model based on soils and testing conditions similar to those encountered in the dam.

However, the representativeness of conclusions drawn from such applications should not be judged only by considering laboratory testing conditions used in establishing the various methods. The assessment must also take into account results from field monitoring data.

5.4 *Consideration of field monitoring data in internal stability assessment*

Fines migration due to seepage forces in an internally stable (non-suffusive) core would be limited. There could be a redistribution of fines in the core, without loss of mass, which would cause local increases/decreases in hydraulic conductivity. The overall effect on the dam behaviour may not be significant enough to be detected by variations in seepage and pore pressure measurements.

Fines migration would be more significant in an internally unstable (suffusive) till core. However, the movement of fines can be stopped at the core-filter interface if the migrated particles are coarser than the constriction size of the downstream filter. This concentration of fine particles would form in the vicinity of the filter interface a cake of material with a lower hydraulic conductivity than the bulk of core material. This behaviour would not cause a significant loss of mass in the core but, if widespread, could cause an increase in pore pressures in the core and a decrease in seepage.

Fines migration in an internally unstable (suffusive) till core may not be stopped if the constriction size of the downstream filter is too large. This phenomenon would cause a loss of mass and permanent damage to the core. There would be a significant increase in seepage. Pore pressures may also be affected depending on the extent of zones with lost fines.

Most of the measured pore pressures in the dam core (see location of piezometers on Figure 8 representing one of the three instrumented cross sections) indicate uniform pressure dissipation across the core. The instruments located near the core-filter interface do not show increased pore pressures. Thus, a concentration of fines near the core-filter interface is not expected. Based on pore pressure measurements, widespread internal instability of the core and fines migration (without loss of mass) leading to concentration of fine particles in the vicinity of the core-filter interface are unlikely. However, piezometer results are only indicative of the core behaviour at specific areas. A global assessment can be realized by considering seepage measurements.

A global trend can be identified in the measured seepage. After a steady increase during first impoundment which ended 10 years ago, the seepage remained more or less constant since. Based on the seepage measurements, widespread internal instability of the core and fines migration with loss of mass are unlikely.

The epistemic uncertainties related to contradictory results were reduced by giving more weight to the most representative internal stability assessment models which were developed using the same type of soils as found in the core. Moreover, the consideration of field monitoring data and the good performance of the dam helped conclude that global internal instability in the core is unlikely.

6 CONCLUSIONS

The presented case histories have shown the ubiquitous nature of uncertainties in internal erosion assessments of existing dams. The epistemic uncertainties, related to imperfect representation of reality, were reduced using geophysics to gain a better knowledge of actual in-situ conditions. The aleatory uncertainties, related to variability, were reduced by the use of geostatistics to quantify spatial variations in soil properties.

The most efficient way to reduce uncertainties in internal erosion assessments is by using complementary geotechnical tools which consider the problem iteratively and at different scales while taking into account the available construction and dam safety monitoring data. This data provides background information and historical context for interpretation. Judgement and experience must be used to put modelling results into context and apply commonsense tests.

Moreover, the knowledge of the geological deposition mechanisms of materials used in dams and the effects of construction practices on their geotechnical properties can explain field observations and measurements that could be otherwise attributed to detrimental effects such as internal erosion.

Finally, one has to keep in mind the prevalence of human uncertainties in engineering projects and its possible influence on decisions. Ignorance and rejection of contemporary knowledge were cited as the prominent causes for failures in civil engineering.

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