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14. ABSTRACT
The scoping level research summarized in this report is intended to develop further research to directly impact uncertainties within the risk estimation process for the internal erosion failure mode. Specifically, this research targets the events of "Progression: constriction or upstream zone fails to limit flows" and "Progression: No self-healing by upstream zone". The research presented includes a literature review related to state of the art and state of the practice methods for directly and indirectly informing the events of flows limiting and no self-healing. This report also provides suggested research topics to further understanding of these events and directly inform the risk assessment process.

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Acronyms and Abbreviations

Reclamation	Bureau of Reclamation
USBR	Bureau of Reclamation
USACE	Army Corps of Engineers
Best Practices document	*Best Practices in Dam and Levee Safety Risk Analysis*
Self-healing	No self-healing by upstream zone
Flows limiting	Constriction or upstream zone fails to limit flows

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Executive Summary

Internal erosion is a leading potential failure mode for embankment dams both in the industry and within Reclamation. About 1 in 4 dams in Reclamation's inventory have experienced an internal erosion incident including the failure of Teton Dam. It is also an identified need for further research to increase understanding and decrease uncertainty within the risk estimation process. Reclamation evaluates the internal erosion potential failure mode using the following event tree.

Water level at or above the threshold level
- Initiation - Erosion initiates
  - Continuation - Unfiltered or inadequately filtered exit exists
    - Progression – Continuously stable roof and/or sidewalls form
      - Progression - Constriction or upstream zone fails to limit flows
        - Progression - No self-healing by upstream zone
          - Unsuccessful detection and intervention
            - Breach (uncontrolled release of impounded water)

The events of "Progression – constriction or upstream zone fails to limit flows" (flows limiting) and "Progression - No self-healing by upstream zone" (no self-healing/self-healing) have been identified as areas of needed research to increase understanding and decreased uncertainty both within Reclamation and the larger community (FEMA, 2005; Lindenbach, 2021). Specifically, the following research questions were addressed by this study in an effort to identify and develop further conducting level research designed to directly impact Reclamation's risk estimation process and the larger community's needs.

1. What research has been conducted related to the "no self-healing" and "flows not limited" progression stages of internal erosion given a crack or void exists?
2. How can we build on previous research, done at Reclamation and also in the industry and academia, to develop laboratory scale testing programs to inform the risk assessment of internal erosion?
3. Can we design future research to better understand how the erosion within cracks/voids progress? Can we develop future research to better understand how the upstream and downstream zones affect the progression or erosion given a crack and whether different zone materials affect the ability to limit flow through the void and/or facilitate self-healing?

A literature review was conducted to address these questions, concluding that there has been limited research conducted to better understand the flows limiting and self-healing events in the internal erosion risk event tree. Beyond the research conducted at Reclamation by Howard et al. (2014) and Howard and Irey (2019), most of the research conducted directly addressing these questions were published by Correia dos Santos (2014) and Correia dos Santos et al. (2017) at Laboratório Nacional de Engenhario Civil (LNEC) in Portugal.

The following areas of research were identified as gaps in the profession's understanding of both self-healing and flows limiting:

1. Impact of the flaw/erosion channel's geometry, size (diameter and length), extent and orientation on the ability of the system to self-heal or limit flows.
2. Impact of hydraulic load including varying hydraulic loads on the ability of the system to self-heal or limit flows. Varying hydraulic loads would simulate seasonal changes in reservoir levels experienced by many embankment dams in Reclamation's
3. Impact of compaction effort, water content, method and directionality of both the core and upstream material on the ability of the upstream to self-heal or limit flows.
4. Varying soils characteristics (e.g. gradient, PI…) within the downstream zones (where relevant), core material and upstream zones to better define susceptibility to self-heal or limit flows and build on the understanding initiated by Correia dos Santos.
5. Numerical modeling of laboratory experiments to develop further understanding and

Additionally, it is recommended that the following ancillary topics are investigated.

1. Crack formation, namely the depth and width of a developed crack or erosion channel
2. Soil erodibility characteristics have been and continue to require extensive research and further understanding.
3. Monitoring continues to be a challenging topic of research, both in the field and in laboratory scale experiments.
4. Numerical modeling is a growing topic of research as a tool for increased insight of processes in the field and of laboratory scale experiments.

This scoping level project resulted in two conducting level proposals being submitted to S&T in response to the FY2022 Call for Proposals.

1 Introduction

Internal erosion, the second most common potential failure mode affecting Reclamation's inventory of embankment dams (Engemoen, 2017), is described as the erosion of soil particles by water moving through a body of soil (USBR & USACE, 2019), or the erosion of soil internal to a structure. Internal erosion through a dam or levee can occur through the embankment, foundation, or a combination of both. Backward erosion piping, internal migration (stoping), scour, and suffusion/suffosion are all distinct mechanisms of internal erosion. The process of each internal erosion mechanism can be separated into a sequence of events, illustrated by the event tree in Figure 1. The sequence of events is based on the four phases of internal erosion: (1) initiation of erosion, (2) continuation of erosion, (3) progression of erosion, (4) initiation of a breach.

- ↳Water level at or above threshold level
  - ↳Initiation – Erosion starts
    - ↳Continuation – Unfiltered or inadequately filtered exit exists
      - ↳Progression – Continuous stable roof and/or sidewalls
        - ↳Progression – Constriction or upstream zone fails to limit flows
          - ↳Progression – No self-healing by upstream zone
            - ↳Unsuccessful detection and intervention
              - ↳ Breach (uncontrolled release of impounded water)

Figure 1. Internal erosion generic event tree.

The generic internal erosion event tree shown in Figure 1 includes the potential that the embankment dam in question is a zoned embankment dam. Zoned embankment dams often contain an internal core (typically an impermeable or water retaining zone), an upstream zone(s) (upstream of the core) and a downstream zone(s) (downstream of the core). Upstream and downstream zones are often characterized by slightly more permeable and coarser material than the core. Additional zones are also possible such as transition zones, filter layers, and drains. The event tree also allows for the analysis homogenous embankments, in which there is no internal zoning and is composed of relatively homogenous earth fill.

The *Best Practices in Dan and Levee Safety Risk Analysis* document (referred to as the Best Practices document) by USBR & USACE (2019) acknowledges that internal erosion is a potential failure mode that cannot be completely analyzed using models and the risk estimation procedures do not result in precise or accurate numerical result. Alternatively, developing the case for the quantitative risk estimates, rather than the quantities, is one of the primary objectives of the risk estimation process. This is done through reviewing available information, relevant analyses, and reviewing pertinent case histories.

Events pertaining to the initiation and continuation phases of internal erosion have and continue to be extensively researched, as these events (i.e. the likelihood of a flaw existing, likelihood of erosion initiating, and likelihood of an unfiltered or inadequately filtered exit exists) govern the Annual Failure Probability estimate. However, this leaves events such as the progression events of "Constriction or upstream zone fails to limit flows" and "No self-healing by upstream zone" with little understanding and input to the risk estimation process. It should be noted that these events occur after initiation and continuation events, therefore, it is assumed that a void, pipe or flaw due to internal erosion already exists when considering these progression events.

"Constriction or upstream zone fails to limit flows" (referred to as "flows limiting" in this report), is the event in which an upstream zone or constriction limits flow rate through the embankment or foundation to a level in which the hydraulic shear stress is less than the critical shear stress for continued erosion, therefore effectively arresting the progression of erosion (USBR & USACE, 2019). This can occur if the erosion path or flaw exists through the entirety of the core or foundation. However, it is unlikely to occur if the erosion path or flaw extends into the upstream zone. Constrictions that limit flow could be from concrete or sheet pile walls, concrete or steel membranes, soil-cement slope protection, geomembranes, bedrock discontinuities, discontinuities within concrete joints, or the material within the upstream zone (USBR & USACE, 2019).

"No self-healing by upstream zone" (in this report referred to as "No self-healing" or "self-healing") is the process in which the material from the upstream zone is/is not washed into the void or flaw. This event is dependent on the existence of a downstream zone which is sufficiently fine to catch the particles from the upstream zone (USBR & USACE, 2019).

The research summarized in this report is intended to be a continuation of the cracked embankment research performed at Reclamation and documented in Howard et al. (2014) and Howard & Irey (2019). Howard et al. (2014) investigated filter layer performance during a cracking event, such as static settlement or seismic loading induced cracking. Howard and Irey (2019) investigated soil characteristics and effects of water content and densities during compaction of typical embankment core zone materials on erosion rates. This report sets the stage for continued research to better inform the risk estimation process of internal erosion by addressing the following questions pertaining to the vents of flows limiting and no self-healing.

1. What research has been conducted related to the "no self-healing" and "flows not limited" progression stages of internal erosion given a crack or void exists?
2. How can we build on previous research, done at Reclamation and also in the industry and academia, to develop laboratory scale testing programs to inform the risk assessment of internal erosion?
3. Can we design future research to better understand how the erosion within cracks/voids progress? Can we develop future research to better understand how the upstream and downstream zones affect the progression or erosion given a crack and whether different zone materials affect the ability to limit flow through the void and/or facilitate self-healing?

A literature review was conducted to address these questions, outlined in Section 3. Further research, outlined in Section 4 of this report, is identified to provide guidance for further research that directly impact and inform the risk estimation process relating to the progression events of flows limiting and no self-healing. Additionally, as a direct outcome of the research outlined in this report, two proposals were submitted to S&T in response to the FY22 Call for Proposals, detailed in Section 4.

2 Methods

The research summarized in this report is for a scoping level project, consisting of a literature review followed by suggestions for further research that would directly impact the risk estimation process of the internal erosion potential failure mode. The focus of this research is the internal erosion phase of progression, especially the events of "Constriction or upstream zone fails to limit flows" and "No self-healing of upstream zone." Related topics to inform the laboratory methods for future research and the risk estimation of the progression phase were also explored. This report will outline the literature review, present areas of further research, and outline several potential research projects to address selected needs.

This research was conducted with input from TSC Groups 8550 (Geotechnical Laboratory and Field Support), 8560 (Hydraulics Investigation and Laboratory Services), 8311 (Geotechnical Engineering 1), and 8315 (Geotechnical Engineering 5). Additionally, discussions to gauge interest in collaboration on future research efforts were conducted with researchers outside of the TSC, including staff from Reclamations Dam Safety Office, the US Army Corps of Engineers, Laboratório Nacional de Engenhario Civil (LNEC) in Portugal, and The University of New South Wales in Australia.

3 Literature Review

A literature review was conducted to better understand the state of the art and state of the practice pertaining to assessing the progression phase of internal erosion, specifically relating to the events of flows limiting and no self-healing. The review concluded that there has been little research conducted to better understand the flows limiting and self-healing from the upstream zone events in the internal erosion risk event tree. The literature review was extended to topics relating to these two events and those that could inform additional research, including:

- Flows limiting
- No self-healing
- Laboratory testing of soil erosion
- Properties effecting soil erosion
- Monitoring erosion
- Numerical modeling
- Crack dimension within embankments

3.1 Flows Limiting

This is the progression event, given a void or flaw exists in the core or embankment, in which an upstream zone or constriction fails to limit the flow rate to appoint erosion is arrested.

The Best Practices document suggests that flow limiting events could be due to the soil in the upstream zone adjacent to the foundation or core, concrete or sheet pile walls, concrete or steel membranes, soil-cement slope protection, geomembranes, or linings on the upstream face (USBR & USACE, 2019). The phenomenon appears to be observed in case studies, including: Balderhead Dam (Vaughan & Soares, 1982 as cited in Correia dos Santos, 2014) and Matahina Dam (Gillon, 2007 as cited in Correia dos Santos, 2014).

Wan and Fell (2004) indicates that this event could occur, but only if the upstream soils are relatively fine grained yet granular material, such as fine rockfill or sandy gravels. Fry (2007) presents hydraulic conductivities of the upstream soil to limit the flow rate. Fry (2007) suggests that hydraulic conductivities less the 10-2 m/s can control flow rate, while hydraulic conductivities of less than 10-5 m/s are required to avoid erosion (as cited in Correia dos Santos, 2014). This suggests that relatively fine materials are required to limit flows to a point in which erosion is halted, which is similar to the suggestions by Wan and Fell (2004). Cyganiewicz et al. (2007) additionally suggests that dams have the potential to restrict flow if the upstream zones are composed of a well-graded soil under a rip-rap layer or if the upstream shell is composed of well graded alluvium. Later Fell et al. (2008) developed probabilities of occurrence for upstream zones limiting flows largely based on engineering judgement.

Best Practices suggests that this event is more likely if there exists an upstream zone with granular fill having low to medium permeability, a central concrete wall or a complete vertical cut off wall, a well-designed concrete-faced rockfill dam or a dam with a soil cement upstream face. However, the guidance given by the Best Practices document does not provide probabilities, simply qualitative guidance, without any basis in historical average base rate (USBR & USACE, 2019).

Correia dos Santos (2014 & 2016) commissioned a laboratory set up to study the flows limiting event. The apparatus, referred to as the FLET (Flows Limitation Erosion Test), was designed to isolate the event of flows limiting and was composed of two soil chambers for the core material and upstream material, as well as the upstream reservoir and downstream settling tanks, as shown in Figure 2. The test was set up to determine the upstream soil's ability to reduce flow and halt erosion, given a void or flaw was continuous through both the core and upstream zones.

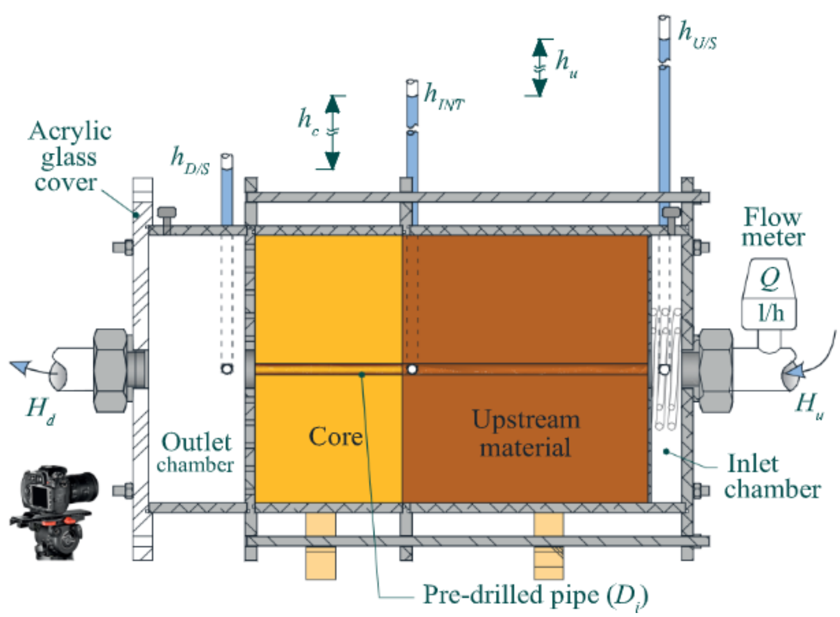

Figure 2. Schematic of the Flow Limitation Test - FLET (from Correia dos Santos, 2014).

Correia dos Santos (2014) and Correia dos Santos et al. (2017) determined the following conditions facilitated flows limiting behavior:

- For upstream materials composed of broadly graded soils:
  - Upstream soils with higher fines contents are more likely to restrict flows.
  - Soils with plastic fines increased likelihood to restrict flows.
  - Soils compacted dry of optimum moisture content increased likelihood to restrict flows.
- For upstream materials composed of gap-graded soils
  - Soils with higher erosion resistance
  - Soils with 5% non-plastic fines content at limited hydraulic gradients

Soils that did not exhibit flow limiting behavior included broadly graded soils with non-plastic fines content greater than 30% by mass and gap-graded soils with no fines. These findings corroborate with those of Wan and Fell (2004). Correia dos Santos (2014), explains these results are limited to the bounds of the tests and suggests further research, as presented later in this report.

Further research is recommended to better understand under which conditions the flows limiting event occurs. Correia dos Santos (2014) recommends investigating the following characteristic on the ability of the upstream material to limit flows:

- investigating an increased variety of broadly graded materials as the upstream zone
- the impacts of water content and density during compaction
- effects of erosion characteristics of the core
- the void's orientation and dimensions
- the effects of changing hydraulic loads during the test.

3.2 Self-healing

Self-healing by the upstream zone is a process in which the soil from the upstream zone is washed into the void/flaw to facilitate self-healing. Although there is evidence of this event occurring in the dam case histories, there is little understanding of the conditions in which this event might occur (FEMA, 2005). Dam cases include: Matahina Dam in New Zealand, Suorva Dam in Sweden, Uliu Dam in Finlad, Viddalsvatn Dam, Wreck Cove dam St. Stephens Powerhouse Dam, Porjus Dam (USBR & USACE, 2019; Correia dos Santos, 2014). Additionally, Sjodoahl (2006) documents 27 dams with large sinkholes, potentially caused by the crack-filling event (cited in Correia dos Santos, 2014).

Little research has been conducted on the event of self-healing by the upstream zone. However, Correia dos Santos (2014) commissioned an apparatus, called the Crack-filling Erosion Test (CFET). The CFET is very similar to the FLET, as described in Correia dos Santos (2014), however, it also contained a downstream filter layer, as shown in Figure 3. The apparatus contained an upstream reservoir chamber, the upstream material, core material, downstream filter layer and the downstream settling tank. In most experiments, only the core material was pre-drilled to mimic a void/flaw. The combination of the void/flaw in the core and the downstream filter layer isolated the event of self-healing by the upstream material.

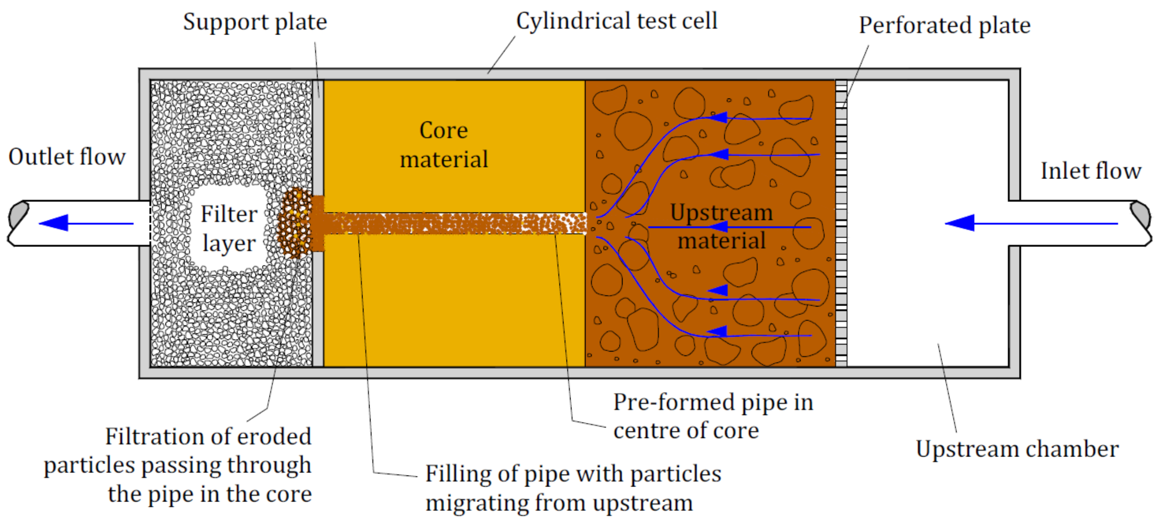

Figure 3. Schematic of the Crack-Filling Erosion Test - FLET (from Correia dos Santos, 2014).

Correia dos Santos (2014) discovered that both uniform sands and some gap-graded soils will facilitate self-healing. Uniform sands are highly effective at rapid self-healing. These tests exhibited rapid filling of the pre-drilled void resulting in a rapid decrease in flow rate and increase in gradient across the core zone. At the same time the upstream zone experienced a decrease in gradient and a loss of material observed at the top of the layer. The loss of the material at the top of the upstream layer mimicked sinkholes occurring in dam cases. Gap-graded materials exhibited similar behavior under only certain conditions, dependent on void diameter, the percent of fines (soils smaller than the #200 sieve) and fine sand content (#40 sieve to #200 sieve) in the upstream material, and the particle size at 15% passing by mass (Df15) of the downstream filter. It was determined that tests initiating with larger void diameters did not exhibit self-healing from the upstream zone. Tests with downstream filter zones with larger Df15 particles required a higher percentage of fine sand content from the upstream zone for the system to allow for self-healing. Additionally, tests with upstream soils with a fines content of 5% or more were unable to facilitate self-healing. Broadly graded soils had the potential to exhibit self-healing after some erosion under certain circumstances. The likelihood that broadly graded soils that were unable to sustain a crack, were able to self-heal were controlled by erosion rate, and filter compatibility of the downstream filter zone. Soils that were able to sustain a crack were unable to self-heal. Soils with high erosion rates resulted in either faster rates of self-healing (dependent on the downstream filter compatibility) or increased rates of continued erosion (Correia dos Santos, 2014).

Additional research is required to better identify under which conditions self-healing could occur. Correia dos Santos (2014) suggests continued research including to better understand the following:

- impacts of void/flaw dimensions
- orientation and roughness of the flaw
- chemical characteristics of the fluid
- impacts of compaction water content and density
- behavior of highly plastic fines in the upstream soil
- further investigate the impacts that downstream filter zone particle size
- varying the hydraulic load during the test

Additionally, it is recommended to investigate the use and capabilities of numerical modeling.

3.3 Laboratory testing of soil erosion susceptibility

There are several testing apparatuses that are designed to measure the erosion characteristics of a soil. These include the SET (slot erosion test), HET (hole erosion test), JET (jet erosion test), rotating cylinder test and hydraulic flume test. This section will focus on each of these tests that are designed to determine the erodibility of soil through the critical hydraulic shear stress (τc), the erosion rate coefficient (Ce) and the erosion rate index (I). The hydraulic shear stress and erosion rate coefficient are related to the rate of erosion, as expressed in equation 1.

$$\dot{\varepsilon} = C_e(\tau_t - \tau_c) \qquad \textit{Equation 1}$$

Such that $\dot{\varepsilon}$ is the rate of erosion and τ_t is the applied hydraulic shear stress along the erosion channel. The erosion rate index is related to the erosion rate coefficient (Ce), as expressed in equation 2.

$$I = -\log(C_e) \qquad \textit{Equation 2}$$

The SET was developed to measure erosion within a crack (Wan & Fell, 2004). The test is set up by compacting a soil sample into a rigid box with dimensions 0.15 m by 0.1 m by 1 m with a formed slot of dimensions 2.2 mm by 10 mm by 1 m. A Perspex cover is placed on the specimen to observe erosion and the width of the slot can be measured throughout the test (Wan et al., 2002). Unfortunately, this test is very difficult to run, and results are similar to those from the HET.

The HET is a commonly used test to measure erodibility of soil to determine the critical hydraulic shear stress (τc) and the erosion rate coefficient (Ce), developed as an easier and more economical testing method than the SET (Wan and Fell, 2002). The test was designed so that specimens could be compacted directly into a standard proctor mold. Once compacted, a 6 cm hole is pre-drilled along the axis (Wan and Fell, 2002). A schematic is shown in Figure 4. Advantages of the HET test include its ease to set-up and run, resulting a test that is also more economical to run. For these reasons, it is a common test to run with a lot of data to compare results. However, disadvantages include the inability to directly capture energy losses at the upstream interface of the specimen, difficulty capturing the final volume and shape of the erosion channel and the pre-drilled channel is prone to collapse especially when the specimen is composed of saturated soils (Wan et al, 2002; Wan and Fell, 2004; Říha and Jandora, 2015).

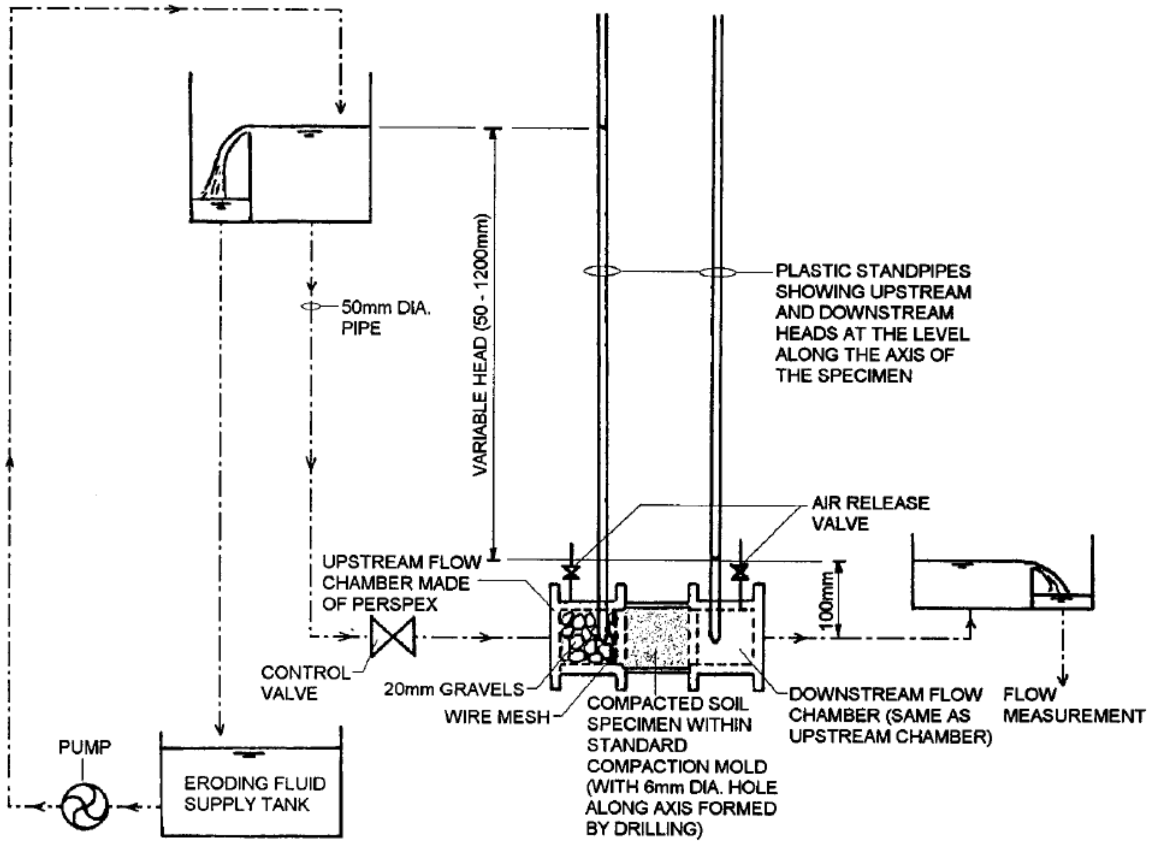

Figure 4. Schematic of the Hole Erosion Test - HET (from Wan & Fell, 2004).

Efforts to better understand and correct for these disadvantages have been studied. It has been determined that energy losses at the upstream interface of the specimen and pre-drilled hole are due to the transformation of pressure into kinetic energy at the entrance of the pre-drilled hole (Říha & Jandora, 2015). Munson et al. (1998) suggests the energy losses cause an overestimation of the critical shear stress resulting an overestimation of the erosion rate index (IHET) by 52-60% (as cited in Říha & Jandora, 2015). Říha & Jandora (2015) confirmed the results from Munson et al. (1998) with the use of CFD numerical modeling. Additional research has also been done to understand the erosion profile within the erosion channel. This includes using 2 Dimensional CFD numerical analysis to study the effects of clay concentration on wall-shear stress and surface erosion by Benaissa et al. (2012).

The JET was designed at the Agricultural Research Service Hydraulic Engineering Research Unit in Stillwater, Oklahoma as described by Hanson and Cook (2004) to determine the erosion characteristics of a soil. The apparatus was designed to be used in-situ, on tube samples in the laboratory, or on remolded specimens using a standard compaction mold (Wahl et al., 2008). In this test the specimen is submerged, and a jet of water is directed at the top of the specimen. A drawing of the apparatus is shown in Figure 5.

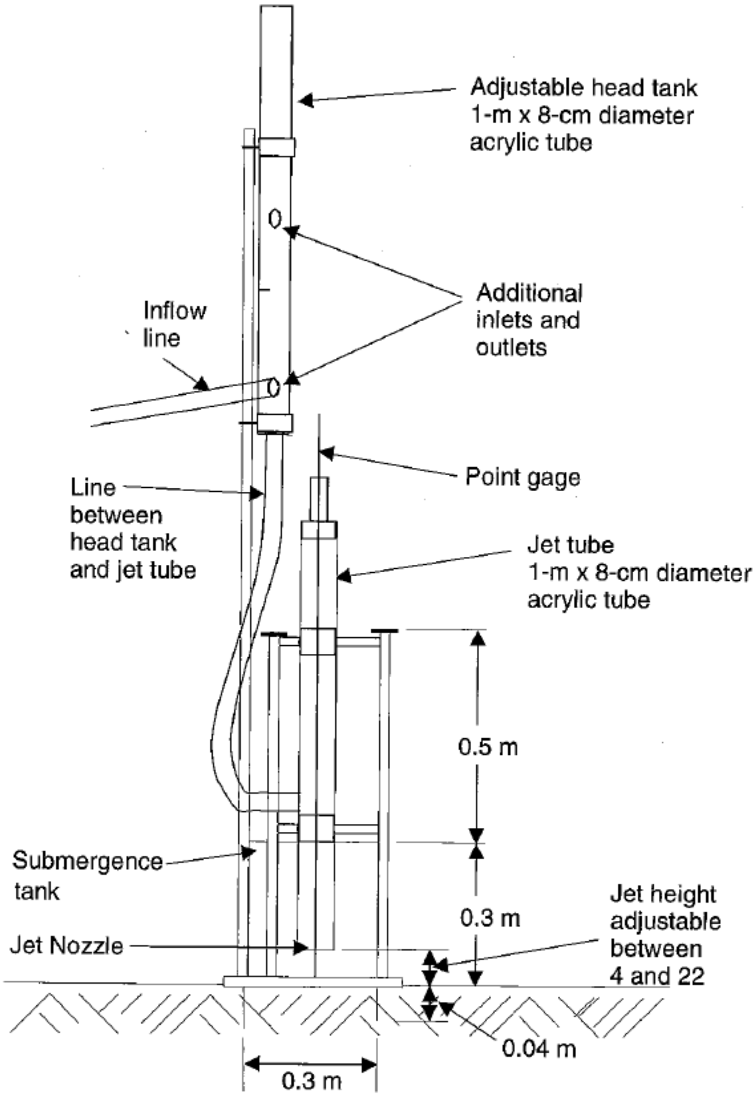

Figure 5. Schematic of the Jet Erosion Test - JET test (from Hanson and Simon, 2001).

The JET is simple to set up, considered to be the best understood and results correlate the best with larger scale erosion processes (USBR & USACE, 2019). It should be noted that although both the JET and HET tests produce repeatable results and characterize a soil in similar erosion rankings, the erosion rate coefficient, erosion rate index, and critical shear stress determined cannot be compared between the two tests (Wahl, 2010). For more information regarding the JET tests, please refer to Hanson et al. (2010), Simon et al. (2010), Wahl et al. (2008), Wahl (2010) and Wahl (2021).

During the rotating cylinder, a cylindrical soil sample is rotated relative to the water that it is submerged in. This test is considered the most accurate measure of critical shear stress and coefficient of soil erosion. However, it is not a common test, as the equipment is complicated and expensive. Additionally, the sample preparation has the potential of drastically altering results (Wan & Fell, 2002).

The hydraulic flume test is a laboratory scale test in which soil erosion is tested in a flume, physically modeling the surface erosion. However, it is difficult to reproduce results and the hydraulic shear stresses are unable to be directly measured and are instead derived from the flow velocity (Wan and Fell, 2002). Additional large scale laboratory tests have been commissioned to study erodibility of soils for specific cases (Howard & Irey, 2019; Wan and Fell, 2002).

3.4 Properties effecting soil erosion

HET, JET, rotating cylinder tests, and hydraulic flume tests are used to determine critical hydraulic shear and erosion rate coefficient for different soils under different conditions. These tests have led to the following understandings. Fell and Wan (2004) demonstrates that as hydraulic shear stress is increased the erosion rate increases. Additionally, it is found that soils with higher critical shear tend to also erode faster once that critical shear is reached, therefor having high erosion rate coefficients (Briaud et al., 2001 as cited in Lim, 2006).

Generally, for clayey soils, the following parameters will increase the rate of erosion:

- If the soils is dispersive the soil will erode faster.
- Lower water contents of the clayey soil will result in faster erosion rates (Christensen and Das, 1973 as cited in Lim, 2006).

The following trends were found in literature

- Increased saturation tends to lead to increased erodibility (Fell and Wan, 2004; Lim, 2006; Hanson & Robinson, 1993 cited in Lim, 2006; Wan and Fell, 2004)
- Water content during compaction is found to be one of the greatest impactors on erodibility, however, the trends do not all corroborate. Generally, erodibility increases drastically when soils are compacted dry of optimum (Fell and Wan, 2004; Lim, 2006; Kandiah and Arulandan, 1974 cited in Lim, 2006; Howard & Irey, 2019). However, in some studies the highest erosion rate index (I), therefor therefore greatest erosion resistance, occurs when soils are compacted at the optimum water content (Fell and Wan, 2004; Lim, 2006; Kandiah and Arulandan, 1974 cited in Lim, 2006; Hanson and Robinson, 1993 cited in Lim, 2006), while others found that increasing water content during compaction led to a continued increase in erosion resistance (Howard & Irey, 2019). Additionally, Arulanandan et al. (1973) demonstrates that erodibility of unsaturated soils is especially dependent on the water content during compaction due to slaking being the dominant eroding process (cited in Lim, 2006).
- Erodibility increases with decreasing dry density (Lim, 2006; Hanson and Robinson, 1993 cited in Lim, 2006; Ghebreiyessus et al., 1994 cited in Lim, 2006; Wan and Fell, 2004).
- Erodibility increases with decreasing clay content and decreasing plasticity (Lim, 2006; Christensen and Das, 1973 cited in Lim, 2006; Shaikh et al., 1988b cited in Lim, 2006; Wan and Fell, 2004; Gibbs, 1962 cited in Lim, 2006; Lyle and Smerdon, 1965 cited in Lim, 2006).
- Erodibility increases with decreasing undrained shear strength (Shaikh et al., 1988 cited in Lim, 2006).
- Physiochemical relationships of the clay and eroding fluid also tend to play a role, Arulanandan et al. (1973) demonstrates that erodibility is highly dependent on the interparticle bonding forces of the soil particles for saturated cohesive soils (cited in Lim, 2006). Erodibility increases with increased sodium adsorption ratio (SAR) of the clay (Wan

and Fell, 2002; Arulanandan et al., 1973 cited in Lim, 2006) and the decreasing salt (NaCl) concentration of the eroding fluid (Wan and Fell, 2002; Lim, 2006). Ma et al. (2020) demonstrates that viscosity of the eroding fluid, pH of eroding fluid, and ionic strength of the soil are critical factors in erodibility. Additionally, Ma et al. (2020) distinguishes between controlling forces of the erosion process between laminar flow (controlled by shear forces) and turbulent flow (controlled by normal lift forces).

3.5 Monitoring erosion

Most laboratory experiments designed to study internal erosion are limited to monitoring flow rate, pore pressure upstream and downstream of the area of interest, and visual observation including digital monitoring (Correia dos Santos, 2014; Howard & Irey, 2019; Howard et al., 2015; Wan and Fell, 2004). Digital imaging and photogrammetry are demonstrated in Howard and Irey (2019), Wilson et al. (2012) and Wan and Fell (2004).

The use of lasers has been used to measure erosion depths in laboratory settings (Vandenboer et al., 2018). Geophysical methods have been used to measure the existence and length of a pipe and the existence crack such as in Parekh (2016). Further, Parekh (2016), Rinehart et al. (2012) and Mooney et al. (2014) demonstrated the use of acoustic sensors to monitor for changing seepage conditions in large scale experiments.

There are several techniques to measure scour in the field, as presented in Prendergast and Gavin (2014). Considering the set up and objectives of the laboratory experiment, a few of these techniques could be useful, including

- Pulse or radar devices that use a series of signal or electromagnetic pulses to determine changes in material properties.
- Sound wave or acoustic devices to measure changes in acoustic waves and/or boundary surfaces through refraction.
- Fiber-Bragg grating sensors that measure strain along an imbedded rod.
- Electrical conductivity devices to measure changes in electrical resistance indicating changes in erosion depth and patterns.

4 Recommendations for Further Research

Through this scoping level research project, it became clear that there are gaps in the profession's understanding regarding the progression of internal erosion and work that can be done to benefit industry and the risk estimation process at the Bureau of Reclamation. Apart from this research, the *Geotechnical Research Roadmap* (Lindenbach et al., 2021) identifies research focused on increasing understanding and reducing uncertainty at each branch of the internal erosion event tree as a main research objective to advance geotechnical engineering practice. This highlights the need for the research areas identified in this section. Below are suggestions of areas to focus on when developing further research to better inform the internal erosion events of flows limited by the upstream zone and self-healing from the upstream zone. In addition, at the end of this section there are notes regarding areas of research related to these topics that would help inform these events but that are not directly related; including estimating crack dimensions and numerical analysis of internal erosion.

This scoping study results in the development of two proposals that were submitted to S&T in response to the FY22 Call for Proposals. Each was related to these events and internal erosion. The first proposal is designed to study self-healing by the upstream zone. The second proposal is designed to better understand and inform crack dimensions.

4.1 Flows Limiting

Correia dos Santos (2014) outlined additional research using the FLET apparatus to better understand what soil parameters of the core material and upstream soil control the ability to filter flows and limit erosion progression. These suggestions include:

- Increasing the variety of broadly graded materials used for the upstream material to better understand their capabilities and limitations to limit flow.
- Study the impacts of water content and density during compaction on the upstream soil's ability to limit flows.
- Investigate if and how the erosion characteristics of the embankment core material have an impact on the ability of an upstream material to limit flow.
- Investigate the characteristics of the erosion channel/flaw and how changing dimensions, shape, and orientation impacts the ability of the upstream material to limit flows.
- Investigate the impacts of changing hydraulic load on the ability of an upstream material to limit flows.

The following list of research areas have been identified by this study in addition to those identified by Correia dos Santos (2014) to inform the risk estimation process.

- Identify the capabilities of typical upstream materials used at Reclamation to limit flows through laboratory testing.
- Investigate the impacts on compaction methods and directionality of the upstream soil on its ability to limit flows.
- Investigate scale of specimen and initial channel/flaw on the ability of an upstream zone to limit flows.
- Investigate the affects cyclic increases in hydraulic head, simulating seasonal changes in reservoir levels, on the event of flows limiting by the upstream.
- Identify the capabilities of concrete or sheet pile walls, concrete or steel membranes, soil-cement slope protection, geomembranes, bedrock discontinuities, discontinuities within concrete joint to limit flows.

4.2 Self-healing

The self-healing probable failure mode event was directly called out in the *Geotechnical Research Roadmap* (Lindenbach et al., 2021), highlighting the importance of addressing the following research topics. Correia dos Santos (2014) outlined further research to better understand the ability of the upstream soil material to self-heal an erosion channel within the core, including:

- The impact of erosion channel's geometry, size, and orientation on the capability of the upstream soil to fill and self-heal the eroding channel.
- The impact on flow characteristics, such as laminar or turbulent, within the erosion channel on self-healing capabilities.
- The impact of physio-chemical characteristics of the system, such as the chemical characteristics of the pore fluid on self-healing capabilities.
- The impact of compaction water content and density of both the core material and upstream material.
- The impact of highly plastic fines within the upstream soil material.
- Expanding the relationship between the gradation characteristics of the downstream filter and the upstream soil to allow for self-healing. Particularly varying the downstream filter material gradation.
- The impact on hydraulic load and varying hydraulic load during a test.
- The capabilities and insight that numerical modeling has on the self-healing event.

The following list of research areas have been identified by this research in addition to those identified by Correia dos Santos (2014) to inform the risk estimation process:

- The capabilities of soils used for the core and upstream zone to facilitate self-healing.
- The impact of erosion channel dimension on the self-healing event.
- The impact on compaction directionality, method and effort of the upstream zone and core on the self-healing event.
- The effect of channel/flaw extent, such as into or through the downstream and/or upstream zones, on the self-healing event to simulate likelihood of self-healing at varying stages of the internal erosion potential failure mode.
- The impact on varying downstream zone materials, including using the same material for both the upstream and downstream zones.

A proposal to better understand the self-healing by upstream zone was submitted to S&T in response to the FY22 Call for Proposals. This proposal outlined research to investigate the following questions:

- How does the upstream material in an embankment dam facilitate the process of self-healing or contribute to continued erosion progression within the core, given a crack exists?
- What conditions, such as upstream, filter and core material properties and crack dimensions influence this behavior?

The research would include the design and development of a laboratory testing device as well as monitoring methods to test various crack dimensions and upstream materials.

4.3 Other Related Research

Related research to inform the flows limiting and self-healing topics and indirectly inform the risk estimation process of these events would include the following topics:

- Crack formation and dimensions, namely the depth and widths of the crack, or erosion channel, has been shown to impact the ability to self-heal and is a critical parameter in the risk assessment process (Correia dos Santos, 2014; USBR & USACE, 2019). However, this parameter is difficult to estimate and measure, resulting in large ranges and uncertainties within the risk estimation. Additionally, this research topic was identified in the *Geotechnical Research Roadmap* as an area of specific need (Lindenbach et al., 2021). A research proposal was submitted to S&T in response to the FY2022 Call for Proposals. The aim of the proposed research is to investigate the capability of numerical modeling techniques to inform crack dimension estimates.
- Soil erodibility characteristics is a topic that is extensively researched and continues to be researched. It would be beneficial to connect the erodibility characteristics of the embankment core material and upstream zones to the system's ability to limit flows and self-heal.
- Monitoring continues to be a challenging area of research of internal erosion mechanisms. Internal erosion naturally occurs internal to the embankment, so it is difficult to directly measure and observe the progression of erosion both in the field and in laboratory settings.
- Numerical modeling of the erosion process as a tool for better insight and estimation. It is important that numerical models are collaborated and corroborated with either field or laboratory data.

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