FACTORS INFLUENCING THE LIKELIHOOD OF PROGRESSION OF INTERNAL EROSION				DATE: JULY 2012
Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Progression – Continuous stable roof and/or sidewalls				If the primary mechanism is "internal migration" without formation of a roof or pipe, then this node can be eliminated from the event tree.
Presence and continuity of hard layer, dense zone or stiff zone	No hard, dense or stiff zones above erodible materials.	The possibility exists that a dense or stiff zone could provide a roof over a developing pipe for a portion of the distance between the reservoir and the exit point, but unlikely that the roof would be supported over the entire distance.	Likely that a dense or stiff zone exists that could provide a roof over a developing pipe between the reservoir and the exit point. Much more likely (approaching certainty) if there is confidence that a hard layer exists from upstream to downstream above erodible materials. Concrete structures such as spillways, conduits, or walls can provide roof support. Hardpan, caliche, basalt, etc. in the foundation soils also are much more likely to serve as a roof.	The primary consideration is whether a hard, dense or stiff zone exists in the embankment or foundation continuously from upstream to downstream above the erodible materials being considered. Dense clayey embankment or foundation materials could support a roof over loose, erodible materials. Guidance for probability estimating is provided in the Best Practices manual (Reclamation 2011).
Impervious zone - soil type, fines content, plasticity and moisture	Granular soils with 5-15% non-plastic fines, either moist or saturated. Much less likely for non-plastic, primarily granular soils with <5% fines, either moist or saturated. Coarse cohesionless shells for backward erosion piping in the foundation immediately beneath the embankment.	Granular soils with 5-10% cohesive fines. Moist soils in this category would be more likely to hold a roof than saturated soils.	Granular soils with 10-15% cohesive fines. Moist soils in this category would be more likely to hold a roof than saturated soils. More likely for granular materials with >15% non-plastic fines. Moist soils in this category would be more likely to hold a roof than saturated soils. Much more likely (approaching certainty) for materials with >15% plastic fines. Also much more likely for primarily fine grained, non-plastic materials with >50% fines.	Factors influencing the ability of a soil to hold a roof include type, fines content, plasticity and moisture. Within each column, density of materials would influence the ability to form a roof, with denser (well-compacted) materials being more likely and looser (poorly compacted) materials being less likely. Detailed guidance for probability estimating is provided in the Best Practices manual (Reclamation 2011).
Other Considerations				The presence of a hard layer and material properties are the primary factors, but soil variability, length of path through the core, potential for stress arching, swelling in expansive soils (most applicable to flood loading), and other factors may need to be considered.

Factors Influencing the Likelihood of Progression of Internal Erosion				**Date: July 2012**
Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Progression – Constriction or upstream zone fails to limit flows				In order for a zone to limit flows, the zone must remain stable while flow through the dam is occurring. Openings in the upstream zone must be sufficiently small to prevent further erosion of downstream zones.
Presence of upstream zones or materials that could restrict flow	Low to medium permeability granular zone (e.g. well-graded, compacted rockfill zone with cohesionless finer materials) upstream of the impervious zone. Central concrete core wall or any vertical complete cutoff such as a cement-bentonite wall, sheet pile wall, secant wall, etc. Much less likely for a well-designed and constructed concrete-faced rockfill dam or a dam with a sound soil-cement upstream face. Typically much less likely for seepage paths into small bedrock apertures, small cracks in conduits, or limited opening sizes and capacity of drains. However, this might not be a significant factor for failure modes in which internal migration and breach by sinkhole development is likely.	Moderate permeability granular zone (e.g. rockfill) upstream of the impervious zone.	Homogeneous dam with no upstream zone that could limit flows. Riprap would provide no flow limitation. Upstream zone judged to be capable of supporting a roof.	Few Reclamation dams have a concrete core wall or an upstream concrete face; therefore, in most cases there is no specific zone that would limit flows. However, in some cases, it may be reasonable to give some credit to the ability of the upstream portion of a homogeneous dam to limit flows, particularly if the upstream portion of the homogeneous dam is judged to be unlikely to support a roof. Also must consider whether a feature that could cause a flaw in the core also could cause a flaw in the upstream zone. The potential for upstream materials falling into and literally filling the crack in highly erodible cores (in the upstream portion) may not provide much benefit. Erodible soils would very likely erode around the edges of the filled erosion path.

Factors Influencing the Likelihood of Progression of Internal Erosion				**Date: July 2012**
Factor	**Influence on Likelihood (see notes)**			**Comments**
	Less Likely	**Neutral**	**More Likely**	
Progression – No self-healing by upstream zone				Are upstream zone materials capable of being transported to a downstream zone or constriction where a filter could form sufficient to prevent further erosion of the core? Crack fillers are discussed in Sherard and Dunnigan (1985).
Material upstream of impervious zone	Coarse, clean, cohesionless upstream materials with wide range of particles sizes. Large volume of upstream materials. Much less likely if dam has an upstream zone specifically designed to provide self-healing.	Materials upstream of impervious zone consist of granular materials with some fines. Materials with limited non-plastic fines would be more likely to be transported than materials with plastic fines. A wider zone would be more likely to provide sufficient quantity of materials to self-heal than a narrow zone. A well-graded granular material is more likely to self-heal compared to a uniform sand.	Materials upstream of impervious zone consist of granular materials with significant amount of plastic or non-plastic fines. Relatively thin upstream zone of riprap and riprap bedding. Much more likely (approaching certainty) for a homogeneous dam, or if there are no materials upstream of the impervious zone capable of filling a crack or erosion pathway.	The zoning configuration of some dams might allow for an upstream zone to fill in a crack or erosion pathway through the impervious zone. Many homogeneous Reclamation dams have a relatively thin upstream slope protection zone of riprap and riprap bedding that could provide very limited self-healing.
Gradation of zone downstream of impervious zone	Filter or transition zone that would be a filter (or a "stop") for the upstream materials washing through the crack or erosion pathway through the impervious zone.	Embankment materials downstream of the impervious zone that might or might not be a filter (stop) for the upstream materials washing through the crack or erosion pathway.	Homogeneous dam with no materials downstream of the impervious zone that would be a filter (stop) for the upstream materials washing through the crack or erosion pathway. Coarse (rockfill) zone downstream of the impervious zone.	If no downstreams zone is present, then no benefit should be given to this node (i.e., p=1.0). Upstream zone benefit is related to filter compatibility between core and the downstream zone or constriction. There is less benefit when sizes in the upstream zone are similar to those already in core In other words, a wide range of sand sizes might be available from the upstream zone that were not available in the core, and could be carried to the downstream zone where self-healing could occur. (Note that "self-healing" of the core materials on the downstream zone was already considered under the "Continuation Node" if excessive and continuing erosion criteria were evaluated.)
Size and nature of the crack or erosion pathway	Crack of limited width or small hydraulic fracture.	Multiple erosion pathways may be possible; it is difficult to envision at what point in the erosion process the crack or	Large erosion pathway such as a rounded pipe.	The size and nature of the erosion pathway would be related to how the potential failure mode is envisioned. There is a

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		erosion pathway would be plugged by the upstream zone. Timing and internal erosion mechanism are important considerations that need to be carefully evaluated. For example, upstream zones may not be effective for backwards erosion piping, but could be effective for scour along a crack.		balance between the upstream zone particle size, the size of the crack and flow required to transport a certain particle size. It is usually more likely to self-heal earlier in the process when sand size particles could be carried to a downstream zone by relatively low flows. Gravel and larger sizes need high flows to be transported, so by the time flows are large enough, significant enlargement of the erosion pathway may have already occurred.

<u>Notes on use of Table:</u>

1. Table is intended to provide guidance on the probability of progression of internal erosion. Unlike the "initiation" tables, there are no historical average base rates to compare relative probabilities. The more likely and less likely factors can be considered qualitatively, and can be considered along with verbal descriptors for a quantitative estimate. The neutral factors listed in the table are factors that have a small influence on the likelihood, or factors that could equally increase or decrease the likelihood of progression. Neutral factors do not automatically imply a 50% probability.

2. For some factors, the "More likely" column also includes factors that would make the probability "much more likely."

<u>References:</u>

Draft Risk Analysis Methodology Appendix E (2000), Estimating Risk of Internal Erosion and Material Transport Failure Modes for Embankment Dams, version 2.4, Bureau of Reclamation, Technical Service Center, Denver, CO. August 18, 2000. (This document was never finalized; it was superseded in 2008 by Dam Safety Risk Analysis Best Practices Training Manual, Chapter 24.)

Fell, R., C.F. Wan, and M. Foster (2004), "Progress Report on Methods for Estimating the Probability of Failure of Embankment Dams by Internal Erosion and Piping," University of New South Wales, Sydney, Australia. UNICIV Report 428. 2004.

Bureau of Reclamation (2011), Dam Safety Risk Analysis Best Practices Training Manual.

Sherard, J.L. and Dunnigan, L.P. (1985). Filters and Leakage Control, in Embankment Dams, in Seepage and Leakage From Dams and Impoundments. ASCE Geotechnical Engineering Division Conference, 1-30.