Causes of Voids Behind Spillways, Conduits, Canals, Tunnels, and Siphons

Science and Technology Program
Research and Development Office
Final Report No. ST-2024-21045-01
8550-2024-11
Report 1 of 3 on Void Causes, Detection, and Repair

U.S. Department of the Interior January 2025

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 01/31/2025	2. REPORT TYPE Research	3. DATES COVERED *(From - To)* 10/15/2020 to 1/31/2025

4. TITLE AND SUBTITLE Causes of Voids Behind Spillways, Conduits, Canals, Tunnels, and Siphons This is one of three reports covering void causes, detection, and repair	5a. CONTRACT NUMBER XXXR4524KS-RR4888FARD2100401 F397A
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Evan J. Lindenbach, PE, PG	5d. PROJECT NUMBER Final Report ST-2024-21045-01
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bureau of Reclamation Technical Service Center Denver, CO	8. PERFORMING ORGANIZATION REPORT NUMBER 8550-2024-11
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007	10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2024-21045-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The presence of voids behind or below a structure can limit operations at best and at worst be a precursor to failure. Voids could lead to hydraulic jacking, ground instability, and a roofed path for internal erosion processes. Any and all of these conditions could result in a failure, as seen recently at the Fort Laramie tunnel or the Oroville Dam spillway.

This report is intended to provide a high-level overview of the topics as they relate directly to the problem of void formation near spillways, conduits, canals, tunnels, and siphons. A series of questions aimed at guiding the investigator towards structures (inventory-wide) and areas (structure-specific) most likely to have voids is provided to streamline detection efficiency. Subsequent reports build on this work by detailing detection methods and repair techniques with this series of questions used to optimize efficiency.

15. SUBJECT TERMS
Voids, spillway, causes of voids

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Evan J. Lindenbach
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)* 3035151691

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research. The author sincerely thanks the reviewers within Reclamation, and at the USACE and FERC.

Causes of Voids Behind Spillways, Conduits, Canals, Tunnels, and Siphons

Final Report No. ST-2024-21045-01
8550-2024-11
Report 1 of 3 on Void Causes, Detection, and Repair

prepared by

Technical Service Center
Evan J. Lindenbach, P.E., P.G., Civil Engineer

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report No. ST-2024-21045-01
8550-2024-11
Report 1 of 3 on Void Causes, Detection, and Repair

Causes of Voids Behind Spillways, Conduits, Canals, Tunnels, and Siphons

EVAN
LINDENBACH

Digitally signed by EVAN
LINDENBACH
Date: 2025.01.21 07:04:02 -07'00'

Prepared and Technical Approval by: Evan J. Lindenbach, P.E., P.G.
Civil Engineer, Geotechnical Laboratory and Field Support Group, 86-68550

CAROLYNE
BOCOVICH

Digitally signed by CAROLYNE
BOCOVICH
Date: 2025.01.21 07:47:24 -07'00'

Checked by: Carolyne Bocovich, Ph.D., P.E.
Civil Engineer, Geotechnical Laboratory and Field Support Group, 86-68550

Digitally signed by ROBERT
RINEHART
Date: 2025.01.21 08:48:56 -07'00'

Peer Review by: Robert V. Rinehart, Ph.D., P.E.
Group Manager, Geotechnical Laboratory and Field Support Group, 86-68550

Contents

Page

Executive Summary

The presence of voids behind a structure can limit operations at best and at worst be a precursor to failure. Voids could lead to hydraulic jacking, ground instability, and a roofed path for internal erosion processes. Any and all of these conditions could result in a failure, as seen recently at the Fort Laramie tunnel or the Oroville Dam spillway.

This report is Part 1 of a three-part series written to provide tools for identifying the causes of void formation and where those voids are more likely to form, different tools and analysis techniques to locate voids, and methods for repairing voids.

Report ST-2024-21045-01: Void formation has been attributed to many causes, from soil settlement and frost heave, to movement of materials caused by scour processes or internal erosion. In many cases it is likely a combination of factors. Identifying the processes by which a void formed often occurs as a post-failure forensic analysis, which helps to inform future work. This report identifies geotechnical conditions and soil/rock types that may be more susceptible to void formation, elucidates on design or construction practices that have a higher probability of leading to void formation, and comments on observable indicators of void formation. The report concludes with a series of questions to help prioritize inspections from inventory-wide to structure-scale based on likely void locations.

Report ST-2024-21045-02: Detection of voids along conduits has been attempted in the past using thermography and the use of a crawler with a sophisticated wall-tapping system. While progress has been made, underlying difficulties exist that have resulted in only limited adoption of these systems. Developing a set of methods and analysis techniques that can help locate voids in a variety of different mediums (concrete, metal, etc.) in a variety of different conditions (dry, wet, below/above the water table, etc.) is a valuable tool for use in facility inspections. This report details a number of non-destructive tools that can be used for void detection.

Report ST-2024-21045-03: Determining the appropriate action to be taken after a void has been detected involves the careful consideration of many different factors. Selection of the appropriate method is always site specific. Designers must consider factors such as the type of materials used in the original design as well as common design and construction practices at the time of construction. Some other important factors include downstream impacts, extent and location of damage, size and shape of conduit or spillway adjacent to the void, type of material being eroded, size of dam, and cost of repair. This report details each of the different repair, renovation, and replacement techniques for structures associated with void formation, and provides guidance on the appropriate action to be taken. The report provides results from laboratory testing on permeable low density cellular concrete and foam transported sand as methods to repair voids.

Introduction

The presence of voids behind or below a structure can limit operations at best and at worst be a precursor to failure. Voids could lead to hydraulic jacking, ground instability, and a roofed path for internal erosion processes. Any and all of these conditions could result in a failure, as seen recently at the Fort Laramie tunnel or the Oroville Dam spillway.

Void formation has been attributed to many causes, from soil settlement and frost heave, to movement of materials caused by scour processes or internal erosion; these causes may be natural (karst, solutioning, etc.), man-made (poor foundation treatment, improper material placement, filter compatibility issues, etc.) or may be a combination of both. In many cases it is likely a combination of factors that leads to void formation. This report seeks to help identify geotechnical conditions and soil/rock types that may be more susceptible to void formation, elucidate on design or construction practices that have a higher probability of void formation, and comment on observable indicators of void formation.

A significant amount of work has been performed on the various topics presented herein. This report is intended to provide a high-level overview of the topics as they relate directly to the problem of void formation near spillways, conduits, canals, tunnels, and siphons. A series of questions aimed at guiding the investigator towards structures (inventory-wide) and areas (structure-specific) most likely to have voids is provided to streamline detection efficiency. The reader is encouraged to review the references provided in each section for more detail on each topic.

Void Formation

Geotechnical

Geotechnical contributors to void formation include settlement/consolidation of fill and/or the foundation material, frost heave, dispersive clays, slakeable foundation or fill materials, soluble minerals, erodability, and internal erosion and scour.

Settlement/Consolidation

Mechanism

Settlement of fill or the foundation could be caused by a number of factors, including inadequate compaction or moisture conditioning, stress concentrations, and foundation material heterogeneity. Areas impacted by excessive settlement, particularly differential settlement, are more prone to void formation. Deep fills and fill overlying low density deposits (particularly organic materials) can be expected to experience more settlement than shallow fills. This mechanism can also manifest itself as apparent structural movement, such as the movement of a retaining wall relative to fill. Zones of relatively lower stress due to arching action (untreated overhangs, narrow trenches, etc.) may also be regions that can experience differential movement and void formation.

Differential foundation movement can also occur due to faulting, landslides, or other ground movement. Unloading during excavation can cause rebound of foundation materials due to stress relief; rebound of foundation materials can lead to differential movement and void formation.

Soils with medium to high plasticity clay fines are susceptible to drying induced cracking, particularly in regions with fluctuating environmental conditions (Reclamation, 2019). This mechanism can lead to differential movement and void formation. Conversely, clay-rich materials may swell when wetted leading to differential movement and void formation.

Location

Settlement of fills can be expected to occur more often where compaction is difficult, i.e. below the haunches of a circular pipe, against a concrete structure, and along the sides of a conduit or tunnel. Voids are more likely to form in areas where excessive settlement has been observed, particularly differential settlement. Differential and adverse settlement are more likely to occur if organic soils are present in the foundation. Voids may also form in soils with medium to high plasticity fines and a fluctuating groundwater table due to drying induced cracking or wetting induced swelling.

Low stress zones (narrow trenches and untreated overhangs in the foundation) may experience differential settlement and void formation. Where foundation or structure materials strain post-construction due to faulting or other ground motion, the resulting differential movement can cause voids. Areas with high in-situ stresses, particularly shales, can undergo rebound when unloaded during excavation leading to differential movement in the foundation and abutments and void formation.

Projects that have experienced settlement of 3 to 5% during construction and/or 1 to 2% post-construction are more likely to experience internal erosion and potentially void formation (Reclamation, 2019). Settlement greater than the presented values is considered to have an even higher likelihood. Areas of large differential settlement are more likely to have defects and potentially voids; this also includes areas of structural movement.

Freeze-thaw

Mechanism

Ice lens formation and frost heave typically occurs in the active zone of a soil horizon at and above the groundwater table elevation. Water is provided to the ice lenses through capillary action and is of particular concern in silty soils with Unified Soil Classifications (USCS) of ML - silt, MH – elastic silt, and SM – silty sand where the small pores can have significant capillary forces. These ice lenses can cause heave when frozen and subsequent relaxation when melted resulting in void formation. Significant forces can be generated during the frost jacking (heave) resulting in structural distress and defects.

Location

Soils and structures near the groundwater table (or with access to free water) constructed without an adequate capillary barrier (a zone of coarse material that inhibits water flow through capillary action) in shady and/or north facing areas are particularly susceptible. Areas where water can pond underneath a structure in a "bath-tub" situation (permeable fill surrounded by less permeable foundation) can experience ice lensing and uplift with resulting settlement and void formation. Soil freezing can also be caused by cold air temperatures in unwatered conduits or tunnels leading to the creation of ice lenses and defect zones in the surrounding backfill.

Dispersive Clays

Mechanism

Dispersive clays are those with an electrochemical predisposition to deflocculation (going into suspension) when saturated. This is a chemical process, not necessarily an erosive or scour process in and of itself, although the dispersion process can often greatly accelerate the more mechanical processes responsible for transporting material. Dispersive clays are prevalent across the U.S. with many formations of marine origin. Dispersion potential can vary significantly within a deposit or geologic unit so extensive screening level (crumb) testing is generally required to constrain the amount of dispersive clay present (McCook, 2005). Where dispersive clays are identified in the screening level evaluation, additional confirmation testing should be performed. Confirmation testing typically includes pinhole testing, although other agencies may use a double hydrometer.

Location

Areas of fill or native soils that contain dispersive clays and are located below the groundwater table or exposed to surface water are susceptible to void development. Dispersion related issues can happen rapidly and are often apparent during first filling (Reclamation, 2019).

Slakable Materials

Mechanism

Slakable materials are those that experience degradation when subjected to moisture fluctuations, typically from being exposed to atmospheric or liquid water. Slakable materials are typically sedimentary rock or rock-like materials, such as siltstones, claystones, and shales. Where exposed, these materials may be identified visually by their geomorphic expression; initially steep, stable cuts that degrade to flattened, smooth slopes with fissile outcrops. The potential for degradation can be evaluated using simple tests like the jar slake or slake durability tests (Pennsylvania DOT, 2017). Note that the slaking process turns a rock-like material into a soil-like material and does not quantify the erosion susceptibility, settlement potential, or bearing capacity of the soil-like end-product.

Location

Foundations constructed on slakable rock may experience loss of material and void formation where the rock is able to gain access to water. As the degradation process requires moisture, regions in close proximity to flowing water or a fluctuating groundwater table are likely to be particularly problematic.

Soluble Minerals

Mechanism

Soluble minerals may be leached out of bedrock and, depending on the minerology and size of minerals, can create voids directly or lead to significant weakening of material leading to void creation through settlement or collapse mechanisms. Evaporites such as gypsum, anhydrite, and rock salt are susceptible to dissolution and the creation of karstic features (Epstein, 2005). These karstic features can manifest as sinkholes or voids leading to the collapse of overlying, more resistant bedrock or soil. Limestone and dolomite are also susceptible to karst formation but typically are on a larger scale; large-scale karst formation is outside of the scope of this report.

Another mechanism noted at a few dam sites is the dissolution of calcite, usually contained as the cementing mineral in a sandstone. The calcite is dissolved from meteoric water with a slightly acidic pH leading to a disaggregation and weakening of the sandstone. This mechanism can also manifest as erosion or solutioning of cementitious grout resulting in a loss of volume and void formation.

Location

Structures founded on soil or bedrock containing soluble evaporites with access to water may experience void formation. Of particular note is calcite-cemented sandstone bedrock which may create a firm foundation during construction but can be gradually disaggregated over the life of a structure. This is likely to occur in areas where slightly acidic, atmospheric water is in contact with the bedrock, such as along or below a spillway. Cementitious grout may also be eroded in similar areas to those mentioned above.

Surficial Erosion and Internal Erosion

Surficial erosion and internal erosion are different processes but include many of the same considerations. For simplicity in this section, the mechanisms are separate, but the impacted locations are grouped.

Mechanism

Surficial Erosion

Geomaterials can be eroded by hydraulic stresses. This can be a function of soil chemistry (dispersive processes as detailed previously can accelerate this process) and/or a function of hydraulic shear stresses. The relative resistance of a soil can be quantified with detachment coefficient and critical shear stress from the Hole Erosion Test (HET) and Submerged Jet Erosion Test (JET). Erodibility typically refers to surficial (i.e., scour) erosion processes and is distinct from Internal Erosion (see below). It has been noted that the erodability of low plasticity soils increases significantly if the soils are compacted dry of the optimum water content. Additionally, native soils tend to be less erodible if they are over-consolidated and/or cemented.

ICOLD (2015) published Table 1 detailing the erosion resistance of soils (formatting from Reclamation, 2019).

Table 1. Erosion resistance of soils from concentrated leaks adapted from ICOLD (2015), where FC is the fines content and LL is the liquid limit.

1. Extremely Erodible	All dispersive soils; Sherard pinhole classes D1 and D2; or Emerson Crumb Class 1 and 2. And SM with FC < 30%
2. Highly Erodible	SM with FC > 30%, ML, SC, and CL-ML
3. Moderately Erodible	CL, CL-CH, MH, and CH with LL < 65
4. Erosion Resistant	CH with LL > 65

Internal Erosion

Internal erosion is the erosion of embankment or foundation material occurring within or beneath a structure due to seepage resulting from local hydraulic gradients. Internal erosion is known to progress to a breach-type failure and, as a primary failure mechanism for embankment dams, requires immediate mitigation upon location.

Mechanisms of internal erosion include scour, internal instability of soils, internal migration (stoping), and backwards erosion piping. Scour is caused by concentrated flow at an erodible surface, such as the dam/foundation contact. Internal instability refers to the erosion of the finer-grained material through the coarser-grained soil matrix. This process can progress as suffusion (particles removed without a change in overall volume) or suffosion (decrease in volume as particles rearrange under the imparted stresses). Internal migration, also referred to as stoping, is the downward migration of soil particles (e.g., embankment material eroding into the foundation) when the soil is unable to sustain a roof supporting a void or a pipe. Stoping can manifest as sinkholes on the slopes or crest of an embankment. Backwards erosion piping, "piping" occurs as concentrated seepage erodes embankment or foundation material where the overlying material is capable of forming a roof. "Piping" progresses backward (upstream) from the toe of an embankment, toward the highest gradient, forming a "pipe" shaped void.

Soil type is a key consideration when evaluating the potential piping resistance of a soil as shown in Table 2 from Sherard (1953). Note Table 2 is presented in the format provided in Reclamation (2019).

Table 2. Relative piping resistance adapted from Sherard (1953).

Greatest Piping Resistance Category (1)	1.Plastic clay, plasticity index (PI) > 15, well compacted.
	2.Plastic clay, PI > 15, poorly compacted.
Intermediate Piping Resistance Category (2)	3.Well-graded material with clay binder, 6 < PI < 15, well compacted.
	4.Well-graded material with clay binder, 6 < PI < 15, poorly compacted.
	5.Well-graded, cohesionless to low plasticity material (PI < 6), well compacted.
Least Piping Resistance Category (3)	6.Well-graded, cohesionless to low plasticity material (PI < 6), poorly compacted.
	7.Very uniform, fine cohesionless to low plasticity (PI < 6) silty sand, well compacted.
	8.Very uniform, fine, fine cohesionless to low plasticity (PI < 6) silty sand, poorly compacted.

Plasticity of the soil has a strong effect on the ability of internal erosion to initiate and progress. Fell et al. (2008) found the likelihood of backward erosion piping (BEP) and suffusion in soils with a plasticity index (PI) greater than 7 is very low under the typical hydraulic gradients in embankments and foundations. Engemoen (2011) reported a similar finding where the majority of the internal erosion cases at Reclamation facilities were associated with soils with little to no plasticity (PI < 7). Engemoen (2017) noted that about 45% of internal erosion issues are through or into the foundation, with the most susceptible materials being glacial, alluvial, colluvial, eolian, or landslide deposits.

Location

Non-plastic to low PI (< 6) granular materials and clean coarse-grained materials that are well or poorly compacted, and uniform, fine cohesionless silty sand (PI < 6) is the most likely to experience internal erosion issues (adapted from Reclamation, 2019). Voids are more likely to form in these soils where they are in close contact to a penetrating feature or spillway. Note that engineered filters and drains may meet these criteria but are not considered to be likely void forming areas unless poorly designed or if they contain construction defects. The criteria used to design single and multiple stage filters used to control fines migration were developed in 1985 (France et al., 2020); structures build before 1985 are likely more susceptible to internal erosion issues due to the lack of protective filters.

Areas of high velocity water impinging on soils are susceptible to scour erosion and void formation. This can be a leak in a water conveyance feature (pressurized or non-pressurized), exposed soils along a spillway or stilling basin, or near an intake structure. In this case, the voids form in close proximity to the leak and progress towards a free face. Internal erosion requires a head gradient large enough to mobilize particles and an unfiltered exit point for those particles. The exit point may be a broken pipe or other subsurface feature, such as an open discontinuity in a rock foundation, or a free face of the structure. If the soils at the free face are not filter compatible (able to limit the fines migration through compatible void openings) the soil may be able to exit and a void can form. The void formation will start at the exit point and progress up hydraulic gradient as material is lost.

Low stress zones are particularly susceptible to internal erosion due to a lack of confining pressure which can lead to hydraulic fracturing. These may be a zone above a narrow drainage trench where there is arching in the fill soils, zones around seepage cutoff collars where compaction is limited, regions below the haunches of a pipe, or in the soils surrounding a corrugated metal pipe (CMP) where compaction is limited (Reclamation, 2019).

Design and Construction

The design and construction of penetrating (conduits, tunnels, and siphons) and overlying (spillways and canals) features can have characteristics that make it more likely for voids to form. This may be due to the typical practices of design and construction practices during a specific time-period or may be the result of specific feature characteristics or locations near a feature that are known to be problematic. The next section is broken out into cross-cutting features (drains), penetrating features (conduits, tunnels, and siphons), and overlying features (spillways and canals).

It should be noted that older structures may have been constructed with timber cribbing or with other materials that can degrade with time, or with "pudding" to create an impermeable core. Structures with either degradable materials left in place after construction, or with "puddled" cores are particularly susceptible to void formation.

Drains

Mechanism

Drains can be located within the foundation, below the spillway, or beneath key features to manage groundwater and seepage, and limit excess uplift pressures. Drains typically comprise a series of interconnect pipes or filter zones with an outfall(s) and are critical for the proper operation of water conveyance and retention structures. Engemoen (2017) notes that the frequency of issues involving internal erosion into drains is much higher than the frequency of internal erosion into/along conduits.

Trojanowski (2004) details two problems specific to drains in his paper about potential failures of spillways located on a soil foundation. One potential problem is the lack of foundation drainage capacity leading to erosion/scour of the materials surrounding the drains. The other is the lack of filter compatibility between the soils and foundation drainage leading to erosion of material into drains; this is particularly prevalent where clay tile drains or drainage systems with oversized weep holes have been used.

Voids can readily form where the drainage system caves in or breaks. France et al. (2020) note that pipe type can be used to assess whether drain systems are susceptible to collapse or breakage. The authors reference Reclamation (2009) which contains pipe recommendations for toe drains (see Table 3, below).

Table 3. Recommendations on which type of pipe to use for toe drains (adapted from Reclamation, 2009).

Product	Type		Advantage	Disadvantage	Recommended
HDPE	Solid		Strong, welded joints, flexibility of perforation size and type	Highest cost, special ordered or hand-drilled after-market addition of perforations	Highly
	Corrugated	Single	Economical	Poor historic performance, weak	No
		Double	Economical, successful applications, large perforation sizes	Low strength, careful installation required	Moderately
PVC	Solid	Well Screen	Strong	Small perforation aperture	Moderately
		Drainpipe	Economical	Weak, brittle	No
	Corrugated	Double	Economical	Weak, brittle	No

Location

In situations where the drainage system does not have adequate capacity, erosion/scour and void formation may occur near the drain or could move to other preferential flow paths. Where the drainage system has inadequate filtering, oversized weep holes, or has failed due to a defect, voids could be expected to form near the drain system and may stope upgradient or towards the surface. Drain systems comprising single-walled corrugated high-density polyethene (HDPE), solid PVC drainpipe, or double-walled corrugated PVC should be considered suspect.

The drain issues detailed above crosscut the following two feature categories.

Conduits, Tunnels, and Siphons

Mechanisms

Voids can form near penetrating features by a variety of mechanisms. FEMA (2005) noted the following conditions increase the likelihood of backward erosion piping incidents and thus void formation.

1. Features founded on rapidly changing ground conditions (e.g., soil then bedrock) that can lead to differential settlement. Excavation and replacement of unsuitable foundation materials can result in significant fill depths and fill depth variability, leading to the potential for differential settlement.
2. Circular features without cradles or specially designed bedding. Compaction below the haunches of these structures can be difficult.
3. Features with an excessive number of joints or bends.
4. Features penetrating compressible materials where differential settlement or hydraulic fracturing may occur.
5. Features built in closure sections of dams.
6. Features built with material that is susceptible to internal erosion and BEP (as detailed in a previous section).
7. Features built with inadequate compaction due to the type of pipe (e.g., corrugated), shape of pipe (e.g., circular), or location of pipe that limits compaction equipment access.
8. Features without adequate filter designs.
9. Features constructed of degradable materials (e.g., pipes that can corrode). This can include conduits that have deteriorated, are abraded due to flowing water, or are corroded.
10. Features with antiseep collars.

Reclamation (2019) notes a number of other problematic areas including,

1. Features placed in a steep and narrow trench that limits compaction and can lead to arching and a low-density zone susceptible to hydraulic fracturing.
2. A stiff conduit projecting into a brittle embankment.

Location

Voids may form in the localized areas of differential settlement or movement, below circular features or in other areas where compaction is difficult, in close proximity to bends or changes in alignment, in areas of compressible or non-filtered materials, features extending through stiff/brittle materials, at locations of corrosion or abrasion, and in the fill around antiseep collars. Features placed in steep, narrow trenches are more likely to have defects and the formation of voids.

Pressurized conduits are more likely to develop problems than nonpressurized conduits. Penetrating features constructed on piles or piers may experience undermining and void formation at the base of the conduit or tunnel.

Spillways and canals

Mechanisms

According to Trojanowski (2004), a number of design and construction elements can lead to defects which may result in the formation of voids, including: the lack of water stops or inadequate design of water stops, contraction joints that are open, and the lack of cutoffs to limit erosion and seepage. According to France et al. (2018), the use of water stops came into practice in the 1970s so features constructed before that time may be suspect.

Reclamation (2019) notes that compaction against spillway walls can be difficult leading to low density zones more susceptible to defects and void formation.

Locations

Voids may form in the vicinity of construction joints or other open features, particularly if the water stops are either not present or of inadequate design. Spillways or canals designed without cutoffs could be considered to be more likely to be problematic. Areas in close vicinity to the spillway or canal where compaction is difficult are also likely zones for defects to form and differential settlement or movement to occur.

Operations

Soils that undergo significant changes in water level undergo changing stresses that can lead to cracks or low stress zones (Reclamation, 2019). This is exacerbated when the water level is “flashy” or fluctuates rapidly. Zones within a region of fluctuating groundwater and/or surface water are the most likely to have voids form. Areas that undergo watering-up and unwatering in cold, shady areas where ice can form may experience frost heave.

The potential for internal erosion is directly related to the hydraulic gradient and the differential head. Operations that lead to significant head gradients can cause internal erosion and void formation at the locations of those extreme gradients.

Indicators

Trojanowski (2004) lists the following observations which may be indicative of defects and voids formation:

1. Discolored discharge indicating the flow of suspended material
2. Sediment in drains
3. Seepage through cracks and joints potentially indicating a high groundwater table
4. Signs of foundation movement such as cracking
5. Sinkholes or subsidence features indicating a loss of support and/or material
6. Misaligned sections of pipe or ponded water in pipes indicating sagging sections

FEMA (2005) recommends looking for corrosion or other material degradation, plugged drain holes, and areas of excess abrasion. If the feature has recently been unwatered, locations where excess water is coming into the feature from the foundation may be indicative of water-filled voids.

Detection Optimization

The following section is broken into two parts, questions to guide an inventory wide assessment, and questions for the assessment of a specific structure or feature. Where the question results in a "yes" response, further investigation is warranted. Use the descriptions provided earlier to guide the detailed assessments.

Inventory-Wide Assessment

1. Was the structure built with timbers or other lumber that was left in place?
2. Was the filled placed via "puddling"?
3. Was the structure built before the 1970s with no newer modifications; are the water stops inadequate?
4. Was the structure built before 1985 with no new modifications; are the filters not properly designed?
5. Does the structure have a conduit or tunnel made from CMP or other corrodible material?
6. Does the structure have antiseep collars around the conduit?
7. Are the drains made from clay tile, single wall HDPE, solid PVC drainpipe, or corrugated PVC?
8. Does the structure potentially contain dispersive soils used in the fill or as foundation materials?
9. Is the structure founded on bedrock that could degrade over time (soluble or slakable materials) that was not treated according to modern practices?
10. Is the structure founded on glacial, alluvial, colluvial, eolian, organic, or landslide deposits?
11. Are there structures founded on materials that experienced rebound during excavation (high in-situ stresses)?
12. Are there structures where the foundation treatment would not meet the current state of practice that may have open or untreated discontinuities?

13. Are there structures founded on faults, landslides, or other areas of ground potentially moving over time?

Individual Structure Assessment

1. Are there areas where compaction is difficult?
2. Are there areas prone to freeze-thaw action?
3. Are there areas where differential settlement could occur?
4. Are there areas where hydraulic fracturing (narrow trenches or other low stress zones) of the fill could occur?
5. Are there erodible or internal erosion susceptible materials

Case Histories

A series of case histories are summarized here to provide the reader with additional context. Note that this section focuses only on the mechanism by which voids formed or may have formed, and where they formed and references are provided for each so that the reader can pursue additional information. Projects are presented in alphabetical order. Table 4 (at the end of this report) is a summary of the case histories with a matrix of the void formation causes.

Anita Dam

Date Constructed: 1996

Issue Date: March 1997

Source: FEMA (2005)

Large voids formed along the outlet conduit, immediately adjacent to antiseep collars. This was likely due to several factors including: dispersive clays, hydraulic fracture, antiseep collars limiting proper compaction, and freeze-thaw action making relatively weak lenses or voids in the conduit backfill.

Annapolis Mall Dam

Date Constructed: 1992

Issue Date: March 1993

Source: FEMA (2005)

A conduit was installed in a near vertical sided trench which limited the contractor's ability to adequately compact the soils, particularly below the pipe haunches. Flows occurred around the conduit leading to a progressive failure of the conduit with ever increasing amounts of soil lost into the conduit by internal erosion.

Arkabutla Dam

Date Constructed: 1943

Issue Date: 1950 (issues noted earlier but this is first intervention)

Source: FEMA (2005)

The contractor did not install waterstops on the lower portion of the conduit as shown in the design details. The lack of water stops allowed the fine-sand foundation to erode into the conduit resulting in significant settlement with multiple unsuccessful repair interventions.

Bohemia Mill Dam

Date Constructed: Early 1900s

Issue Date: 2004

Source: FEMA (2005)

Deterioration of an older structure necessitated the construction of a new conduit. The new conduit was founded on piles; subsequent undermining of the material below the conduit resulted in void formation and uncontrolled seepage.

Clair Peak Dam

Date Constructed: Unsure

Issue Date: 2003

Source: FEMA (2005)

The CMP conduit pipe deteriorated and failed leading to the loss of embankment material into the conduit.

Dalewood Shores Dam

Date Constructed: 1960

Issue Date: 1993

Source: FEMA (2005)

Failure of the CMP conduit lead to loss of material into the conduit and likely internal erosion and BEP outside of the conduit.

Dickinson Dam

Date Constructed: 1950

Issue Date: 1954

Source: Trojanowski (2008)

The spillway underdrain system plugged due to freeze-thaw, leading to erosion of the soft sandstone and shale foundation into the underdrains. Voids would likely have formed in close proximity to the drains due to the erosion of the foundation materials.

Hernandez Dam

Date Constructed: 1961

Issue Date: 1997

Source: FEMA (2005)

The outlet works conduit is founded on varying foundation conditions including on the cutoff trench. Differential settlement caused the pipe to sag and some welded joints broke and were corroded. It is not clear if voids were formed during this differential settlement.

Hyrum Dam

Date Constructed: 1935

Issue Date: circa 2004

Source: Trojanowski (2008)

Significant erosion around the unfiltered clay tile underdrains located below the spillway occurred over the 70-year lifespan of the structure prior to repairs. Voids formed in close vicinity to the drain system as a result.

Keechelus Dam

Date Constructed: 1916

Issue Date: 1999

Source: Carter and Hansen (1999)

A number of voids were found to be located in areas where wooden piles and other timber had rotted away leaving seepage paths. These voids combined with non-filter compatible materials (rockfill drain and fine-grained foundation and embankments) lead to subsequent investigations into an internal erosion potential failure mode.

Lake Darling Dam

Date Constructed: 1935

Issue Date: 1988

Source: FEMA (2005)

The outlet works consists of two, side-by-side cast-in-place concrete conduits with antiseep collars and no control joints with waterstops. Excessive grout takes were noted during borehole backfilling operations performed as part of a safety assessment. Small voids were found at a number of locations where cracks in the conduit were observed. Relatively high gradients were also observed, particularly near the discharge end.

Lawn Lake Dam

Date Constructed: 1903

Issue Date: 1982

Source: FEMA (2005)

A large leak developed in a pressurized conduit likely due to the deterioration of the lead caulking between the steel outlet conduit and the gate valve. This quickly eroded low PI embankment materials which may have caused BEP or may have hydraulically fractured the earthfill and lead to internal erosion.

Little Chippewa Creek Dam

Date Constructed: 1973

Issue Date: 1973

Source: FEMA (2005)

Settlement of the soft foundation soils lead to conduit pipe distress and separation. This would have resulted in void formation if not for metal shields above the pipe.

Loveton Farms Dam

Date Constructed: 1985

Issue Date: 1994

Source: FEMA (2005)

Large voids formed near the upstream end of the conduit pipe, likely as a result of freezing damage in silty sands and sandy silts. A steep-sided trench and internal erosion in areas of melted ice lenses likely contributed to the void formation.

Oroville Dam

Date Constructed: 1968

Issue Date: February 2017

Source: France et al. (2018)

Unsuitable soils left in place below the constructed spillway coupled with an inadequate drain design below the spillway lead to cracking above and along the underdrain pipes during high flows. The drains were undersized and lacked filter compatibility with the soils allowing voids to form. This was a gradual process over the life of the structure and would have likely resulted in voids forming near the drains.

Pablo Dam

Date Constructed: Three phases – 1911, 1918, and 1934

Issue Date: 1993

Source: FEMA (2005)

Voids were found located at the crown of the conduit where the concrete counterfort walls supporting to the intake tower meet the conduit, likely due to settlement. Efforts to fill the voids with grout appeared to cause the voids to migrate and more extensive fixes were required.

Penn Forest Dam

Date Constructed: 1958

Issue Date: 1994

Source: ASDSO (2021)

Voids were formed by piping of the embankment materials into open fractures in the foundation bedrock.

Prospect Dam

Date Constructed: 1914

Issue Date: 1980

Source: ASDSO (2021)

Voids were formed by piping of foundation material into the toe drain due to lack of a proper filter and possibly an open joint in the toe drain.

Quail Creek Dike

Date Constructed: 1983-1984

Issue Date: 1989

Source: ASDSO (2021)

Seepage channels formed in the rock at the base of the dam due to erosion of soluble materials. Efforts to grout the foundation forced the seepage path the migrate to the foundation contact with the overlying embankment materials, with the continued seepage/erosion leading to the breach of the embankment.

Redacted Name

Date Constructed: 1941

Issue Date: 2020

A field investigation seeking to characterize voids found under the existing service spillway is ongoing. Two possible void causing mechanisms have been postulated. Petrographic analysis of the in-place sandstone bedrock and material found in drains (assumed to be eroded bedrock) shows a significant loss in calcite. This finding indicates that the voids could be caused by rainwater leaching the calcite from the bedrock resulting in disaggregation of the sandstone and a resulting increase in erodability. The bedrock and fill materials have also been found to have a relatively low slake durability, which may be a contributing factor.

Rolling Green Community Lake Dam

Date Constructed: 1965

Issue Date: 1999

Source: FEMA (2005)

The CMP riser failed due to deterioration resulting in the creation of a large void around the original riser location.

Salmon Lake Dam

Date Constructed: 1921

Issue Date: 2000

Source: FEMA (2005)

Voids were found behind poor quality concrete on eroded lift lines in the conduit. The low-quality concrete is attributed to poor consolidation of the concrete and construction practices, with the worst quality concrete located at the sides of the conduit.

Sardis Dam

Date Constructed: 1940

Issue Date: 1974

Source: FEMA (2005)

Differential settlement between the intake tower and transition monolith lead to the rupture of a copper waterstop and the flow of material into the conduit with the eventual surface expression as a sinkhole. The intake tower was founded on piles and the transition monolith was not, leading to the differential settlement.

Sugar Mill Dam

Date Constructed: Uncertain

Issue Date: 2002

Source: FEMA (2005)

Inadequate placement of the concrete cradle below new siphons resulted in the creation of voids under the center of each siphon.

Teton Dam

Date Constructed: 1975

Issue Date: 1976

Source: ASDSO (2021)

Embankment material eroded into open foundation joints causing scour-type internal erosion and void formation.

Willow Creek Dam

Date Constructed: 1911, modified in 1941

Issue Date: 1996

Source: FEMA (2005)

A sinkhole formed over an area of the conduit where material was flowing in through 1-inch weep holes in the tunnel wall. Subsequent excavation revealed a large cavity likely caused by the initial construction practices (significant over-excavation and replacement with puddled backfill) and gradual erosion of the backfill through the weep holes.

References

ASDSO (2021). Association of State Dam Safety Officials Lessons Learned from Dam Safety Incidents and Failures, website accessed 6/24/21, https://damfailures.org/case-study/.

Carter, B.H., and Hansen, P.J. (1999). Void Occurrence and Subsequent Safety of Dams Investigations at Keechelus, ASDSO Proceedings 1999, St. Louis, Missouri.

Engemoen, W.O. (2011). Bureau of Reclamation Experiences with Internal Erosion Incidents, Proceeding of the Internal Erosion in Embankment Dams and Their Foundations, European Working Group of International Commission on Large Dams (ICOLD), Brno, Czech Republic.

Engemoen, W.O. (2017). "Latest Compilation of Internal Erosion Incidents at Bureau of Reclamation Dams," Proceeding of the 37th Annual USSD Conference, United States Society on Dams, Anaheim, California, 433-450.

Epstein, J.B., (2005). National Evaporite Karst – Some Western Examples, U.S. Geological Survey Karst Interest Group Proceedings, Rapid City, South Dakota, September 12-15, 2005.

Fell, R., Foster, M.A., Cyganiewicz, J., Sills, G.L., Vroman, N.D., and Davidson, R.R., (2008). Risk Analysis for Dam Safety: A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping, URS Australia, Sydney, Australia.

FEMA, (2005). Conduits through Embankment Dams Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair.

France, J.W., Alvi, I.A., Dickson, P.A., Falvey, H.T., Rigbey, S.J., and Trojanowski, J., (2018). Independent Forensic Team Report Oroville Spillway Incident, California Department of Water Resources.

France, J.W., Bennetts, C., and Donaghy, H.C. (2020) Filter Compaction and Other Practicalities of Filter/Drain Design and Construction, 2020 ASDSO Conference.

ICOLD, (2015). Internal Erosion of Existing Dams, Levees, and Dikes, and Their Foundations, Bulletin 164 Preprint, International Commission on Large Dams, Paris, France.

McCook, Danny K., (2005). Things Mother Never Told You about Earth Dam Design, 2002 ASDSO Conference.

Pennsylvania DOT, (2017). Chapter 15 – Rock Slake Durability, Publication 293 –2017, Geotechnical Engineering Manual, 2017-11-3.

Reclamation (2009). Physical Properties of Plastic Pipe Used in USBR Toe Drains (Report DSO-09-01). U.S. Department of Interior, Bureau of Reclamation.

Reclamation, (2019). Internal Erosion Risks for Embankments and Foundation, Best Practices Chapter D-6.

Sherard, J.L., (1953). Influence of Soil Properties and Construction Methods on the Performance of Homogeneous Earth Dams, Technical Memorandum No. 645. Bureau of Reclamation, Denver, Colorado.

Trojanowski, J., (2004). Assessing Failure Potential of Spillways on Soil Foundation, 2004 ASDSO Dam Safety Conference.

Trojanowski, J. (2008). Evaluating Spillway Condition, Hydro Review.

Table 4. Summary of case histories with matrix of causes.

Project Name	Date Constructed	Issue Date	Did Voids Form		Conduit/Tunnel/Siphon?	Spillway/ Canal	Geotechnical Contributors							Design and Construction Contributors									
			Yes	Maybe			Settlement	Freeze Thaw	Dispersive Clays	Slake Durability	Solube Materials	Erodable Materials	Internal Erosion	Drain Issues	Rotten Timber	Antiseep collars	Differential Foundations or Foundation Materials	Difficult Compaction	Hydraulic Fracture of Fill	Corroded or Degraded Materials	Inadequate Filters	Water Stop Issues
Anita Dam	1996	1997	X		X			X	X				X			X		X	X			
Annapolis Mall Dam	1992	1993	X		X								X					X				
Arkabutla Dam	1943	1950	X		X		X						X									X
Bohemia Mill Dam	Early 1900s	2004	X		X								X									
Clair Peak Dam	?	2003		X	X															X		
Dalewood Shores Dam	1960	1993		X	X								X							X		
Dickinson Dam	1950	1954		X		X		X					X	X								
Hernandez Dam	1961	1997		X	X		X										X					
Hyrum Dam	1935	2004	X			X							X	X							X	
Keechelus Dam	1916	1999	X										X		X						X	
Lake Darling Dam	1935	1988	X		X							X	X			X		X				X
Lawn Lake Dam	1903	1982	X		X							X	X						X	X		
Lake Chippewa Creek Dam	1973	1973			X		X															
Loveton Farms Dam	1985	1994	X		X			X				X	X					X	X			
Oroville Dam	1968	2017	X			X						X		X						X	X	X
Pablo Dam	1911, 1918, 1934	1993	X		X		X										X					
Penn Forest Dam	1958	1994	X										X									
Prospect Dam	1914	1980	X										X	X							X	
Quail Creek Dike	1983-1984	1989	X								X		X									
Redacted Name	1941	2020	X			X				X	X		X									
Rolling Green Community Lake Dam	1965	1999	X		X															X		
Salmon Lake Dam	1921	2000	X		X															X		
Sardis Dam	1940	1974	X					X					X				X					X
Sugar Mill Dam	?	2002	X		X													X				
Teton Dam	1975	1976	X										X									
Willow Creek Dam	1911, 1941	1996	X		X		X						X							X		
Total Count		**26**	**21**	**4**	**16**	**4**	**5**	**4**	**1**	**1**	**2**	**4**	**18**	**4**	**1**	**2**	**3**	**5**	**3**	**7**	**4**	**4**
Percentage of Total		**100%**	**81%**	**15%**	**62%**	**15%**	**19%**	**15%**	**4%**	**4%**	**8%**	**15%**	**69%**	**15%**	**4%**	**8%**	**12%**	**19%**	**12%**	**27%**	**15%**	**15%**