SINKHOLES: The Hole Story ...Issues are Deeper than you Think!

Introduction

A sinkhole is a depression or void caused by collapse of surface materials due to movement of water removing underlying material. When this removal of material forms an enlarging tunnel, it is referred to as backward erosion piping. Sinkholes are often an indication that it is occurring.

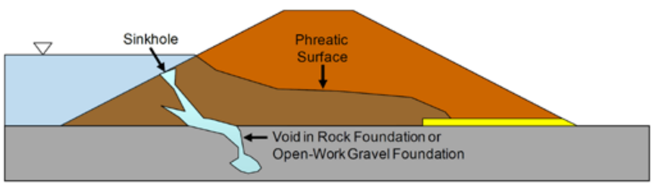

Figure 1: Sinkhole formation (from Reclamation Best Practices Fig 26-3a)

The most common condition causing sinkholes to occur in or near dams is concentrated seepage through voids or cracks causing material to move. This can occur due to:

- Karstic foundation that has voids due to solutioning
- Loose or poorly graded materials that include cobbles or boulders and poor compaction
- Poor treatment of foundation during construction, where there is a prevalence of joints
- Leak in pipe that penetrates the dam, creating increased seepage
- Animal burrows that create shortened seepage paths when they become submerged
- Differential settlement creating cracks or voids
- Construction defects creating cracks or voids

There are several repair options depending on the cause and size of the sinkhole. Sinkholes can be benign and self-healing, but are generally the first sign of a developing problem that could progress to a major dam safety issue if not addressed in a timely manner.

Prevalence in Small Dams

Construction of small dams increased in the U.S. in the early 1900s due to an increased demand for water in agricultural and mining actives. At the time there was a lack of appreciation of the complexities associated with design and construction of small dams. This led to limited engineering with not enough emphasis on subsurface exploration, design of filters and cutoffs, treatment of foundation and quality control during construction (gradation and compaction). Small dams typically have less foundation investigation and preparation due to the smaller head. However, with smaller cross sections gradients can still be high. In addition, more frequent cycles of high and low pool levels can intensify issues such as cracking or animal burrows.

In addition, failure of small dams is also assumed to be less catastrophic and frequent inspection and dam safety protocols may be de-emphasized. Signs of issues may go unnoticed for long periods of time. If issues are noticed, a small repair may be applied without proper engineering. If such repairs do not treat the fundamental issue, reoccurrence is inevitable. Signs of a sinkhole may appear to be only a small surficial depression easily repaired with placement of fill. However, a seepage pipe and potential failure path may exist just below the surface, readily available to promote material transport when the reservoir level rises.

Photo 1: Example of small depression that may go unnoticed (Young Creek Dam)

Signs of Sinkhole Activity

Sinkholes can often be identified by whirlpools forming upstream of the dam. Whirlpools may be significant and easily observable (Photo 2), or they may be slight enough that they simply result in leaves or grasses floating in a circular pattern, which is the more common scenario.

Photo 2: Whirlpool upstream of dam (U.S Forest Service)

Excessive seepage on abutments, embankment, toes, or further downstream from the dam, can signal an issue. Muddy seepage downstream can be an indication that transportation and sediment is occurring and material is being piped out of the dam. Holes and depressions on or near the crest can signal uneven settling and material transport below grade. During low pool, small depressions and holes upstream of the dam, on the embankment, abutments, or even reservoir banks can be indications of sinkhole formation.

Photo 3: Sinkhole on upstream embankment (Paxton Dam)

Potential Breach of Dam

Sinkhole activity can lead to a dam breach if not treated. The overburden or embankment migrates into voids due to seepage from the reservoir. Backward erosion piping occurs causing sediment transport out of the foundation or dam. The material transport is not stopped by a filter or cutoff and a sinkhole forms upstream of the dam as the erosion increases. In some situations, the failure path is high enough that the erosion only results in a loss of water storage above the sinkhole. However, more commonly, the sinkhole and associated pipe is low enough to mobilize sufficient material to undermine the embankment, causing a full breach with possible downstream consequences.

Fixes

Upon identifying a sinkhole, the first and most effective action to be taken is to lower the reservoir pool. Any reduction in gradient will help slow erosion but lowering the pool to below the sinkhole is ideal if possible. Depending on the size and cause of the sinkhole, several repair methods are possible.

Clay Blanket - If the sinkhole is due to a localized issue, such as loose or poorly graded material, excavation of the sinkhole and surrounding area and placement of a clay layer can be a simple repair. The thickness of the clay layer should be based on gradients and material properties and determined by a soils engineer. The clay layer should be covered by native soil or rocks to protect the clay from erosion. Compaction of the excavated area before placement as well as compaction of the clay layer is important. To use this method effectively, there should be no signs of a pipe leading from the sinkhole, as the clay may erode into the pipe upon raising the reservoir.

Reverse Filter - For a larger sinkhole, another repair option may be the placement of a more robust reverse filter. The sinkhole area should be excavated to remove voids and loose material as well as expose the flow path if possible. The number of layers of the filter varies based on depth needed and materials available, but the filter should have a minimum of three layers below the native ground material. Rock should be placed at the bottom of the excavation followed by gravels then sand, before being covered with native overburden and riprap. The gradation specifics depend on the character of the surrounding soils. Proper compaction is required for all layers. See Figure 2 for an example reverse filter.

Geotextile, Geosynthetic Clay Liner, or Geomembrane - Similar to the clay blanket and reverse filter, engineered liners and fabrics can be used after excavation of the sinkhole. Native material should be placed over the liner or fabric. Liners and fabrics can be used in conjunction with reverse graded filters as another layer of protection.

Grouting - Grouting is a repair option especially effective if widespread cracks, voids, and joints are found within the foundation or embankment. Grout is generally applied with low pool and under dry conditions so that the grout can set up. Various mixes are available for grouting and selection of properties is dependent on soil conditions, size of sinkhole, and environmental conditions. Mixtures with fluid-like consistency (low viscosity) take longer to set up but are likely to penetrate more deeply and into smaller voids. Thicker, more viscous mixtures are quicker to set up but may not be as effective at filling the void. A combination of mixes can be used to fill the smaller and deeper areas with fluid grout and then the larger void with more viscous grout. Depending on the size of the sinkhole, soil conditions, and the grout material, the grout can be gravity fed (pipe placed in hole for funneling) or injected under pressure. The hole and pipe are often flushed with water to remove debris and loose material prior to application of grout. When setup is complete, the area should be backfilled with native soil and rocks/riprap placed to protect the grout near the surface.

There are two general families of grout: cement grouts and chemical grouts. Each family has primary grout sub-types. Primary types of cement grout include ordinary Portland cement (OPC) and ultrafine cements. Primary types of chemical grouts include silicates (typically sodium silicates), acrylic gels (acrylamide, acrylic, and acrylates), and polyurethane foams (hydrophilic or hydrophobic). Each grout type varies in appropriate application based on their unique characteristics including viscosity, set-up time, expansion, flexibility, strength, life span, and cost. Due to the wide array of grout products available and the complexity of selecting the appropriate grout mix, a qualified grouting engineer or contractor should be engaged to provide site-specific recommendations.

Photo 4: Application of chemical urethane grout (Big Battlement Dam)

Below is a list of grout types commonly used in geotechnical void-filling applications:

- **Acrylamide Grout** – Highly impermeable and low viscosity. Changes from liquid to a solid in a controllable set-up time. Acrylamides generally have a long life span (100 years+). [5]
- **Polyurethane Chemical Resin Grout** – Hydrophilic foams react with water to form an expansive flexible foam or non-expansive gel that hardens. It can be used for grouting applications where dry conditions are not possible or too costly. Hydrophobic expansive foams require little water to react and easily withstand wet/dry cycles. Polyurethane foam generally has a life span between 75 and 100 years. [5]
- **Epoxy Grouts** – Suitable for underwater applications
- **Ultrafine Cementitious Grout** – Cement grouts generally cost less than chemical grouts and have higher strength. Cement grouts have higher viscosity and faster set-up times, which can be controlled to a degree with water and additives. Life span is typically 100 years+. [5]

Case Studies – Repairs

Fish Lake, CO –This dam has a history of seepage along the downstream toe, believed to be due to the open matrix character of the foundation rock. A sinkhole recently occurred on the upstream side of the dam near the left abutment, presumably due to voids most likely at the interface between the dam embankment and the foundation. The sinkhole was first observed during a routine inspection in July 2011. Further inspection and dye testing by a geotechnical engineer in October 2011 confirmed the location of the entrance and exit point of the seepage flowing from the toe of the embankment. The use of urethane grout was recommended to fill the sinkhole. Grouting took place in August 2012.

The sinkhole was first cleared of rock and debris and then flushed with approximately 5 gallons of water to obtain thorough pre-wetting for the grout application.

Photo 5: Flushing of sinkhole at Fish Lake, CO

The application of the grout into the sinkhole was aided by a steel pipe and tarp to funnel the material. Stratathane ST-504 Vari-Gel Injection resin was used. Lake water was used for flushing and mixing the grout. The grout was applied in stages with three different mixes, becoming more viscous with each application. The mixes were:

- 15 water to 1 grout: 30 gallons of water applied, grout completely absorbed, poured easily.
- 10 water to 1 grout: 30 gallons of water applied, grout completely absorbed, some backing up during pouring.
- 5 water to 1 grout: 5 gallons of water applied, grout was not entirely absorbed, pipe containment was half full.

Photo 6: Final application of grout, contained within pipe (Fish Lake)

The most fluid mixture took longer to set up before the next application could be poured, but obtained the greatest penetration into voids or cracks related to the sinkhole and seepage path. The second and third application took less time to set up but obtained less penetration. All mixtures expanded upon application and the last mixture served to cap the sinkhole. After the grout had set up and cured, the pipe was removed and the area was backfilled with rock to provide protection for the grout. An inspection 6 months after the grout application found some shrinkage of the grout at ground surface, but the sinkhole appeared to be sealed. No issues have been reported around the sinkhole or in other areas of the dam since the repair.

Lake Ann, CO – Seepage 400 feet downstream of the dam has been a longstanding issue at Lake Ann. Evidence indicates water was flowing through the foundation of the dam from upstream. A sinkhole from the 1960s was repaired with a plastic liner. Deteriorated plastic was found and removed in the excavation of a more recent sinkhole in the same area. The recent sinkhole was observed at the dam approximately 15 feet upstream of the intake and 100 feet right of the outlet. The flow was approximately 0.3 cubic feet per second when initially measured in October 2014. The reservoir was immediately drained to below the sinkhole to stop the flow of water through the sinkhole while repairs were developed and implemented.

Photo 7: Sinkhole when first observed at Lake Ann, CO

A reverse filter was designed and constructed to repair the sinkhole. The sinkhole area was excavated to approximately 6 feet deep, 20 feet in diameter at the surface and 9.5 feet in diameter at the bottom. The subgrade was compacted before application of the filter material. The reverse filter was constructed of five layers, each 12 inches thick followed by a layer of native material at the surface. The properties of the five layers were as follows (Layer 1 was placed at the bottom of the excavation):

1. 1.5-inch screened rock
2. No. 67 Aggregate AASHTO M43
3. 50% C33 concrete sand and 50% 3/8 inch screened rock
4. Clayey material
5. Clayey material

(Layers 4 and 5 formed a two-foot thick compacted clay liner/cap).

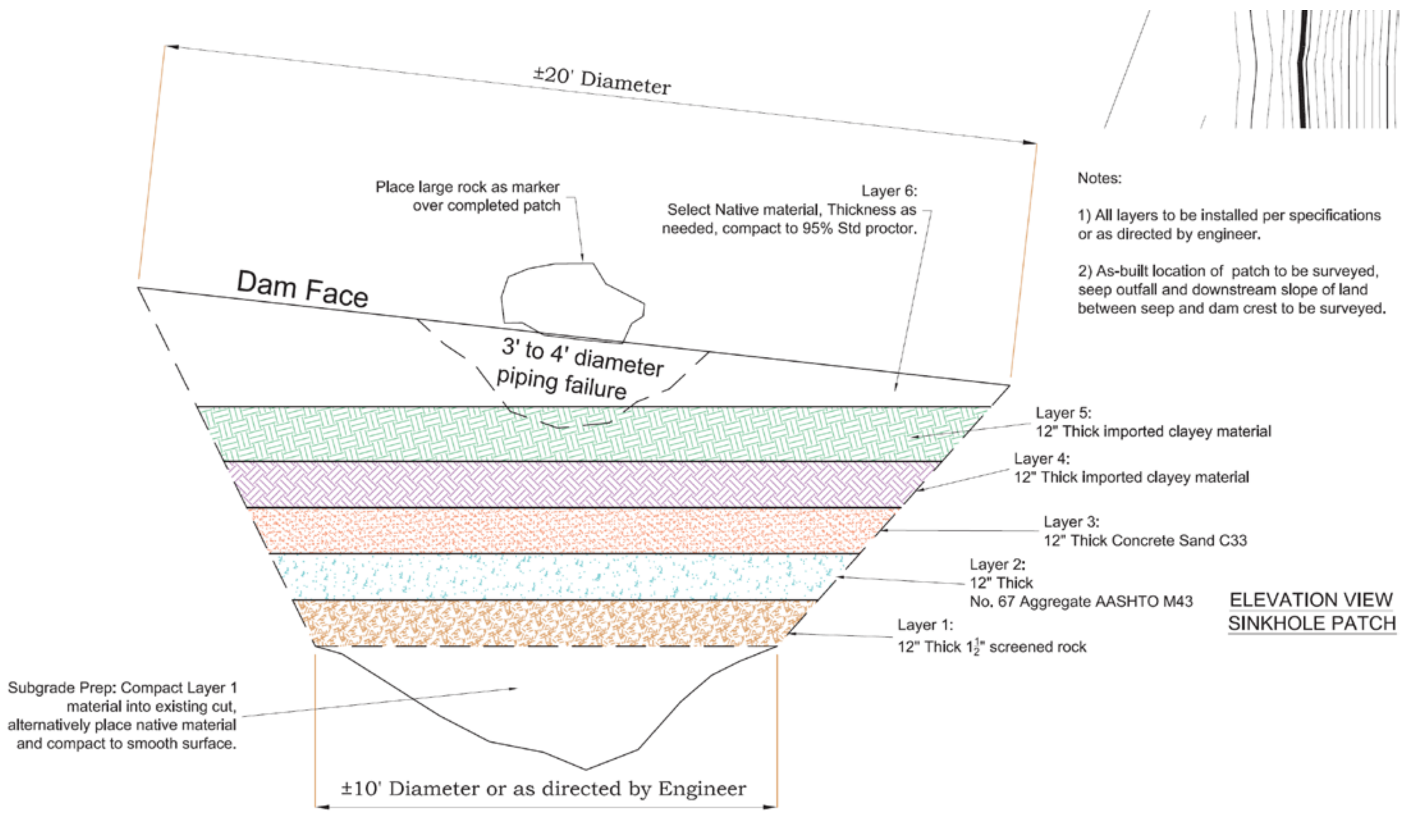

Figure 2: Elevation of sinkhole repair patch

Photo 8: Compaction of clay layer at Lake Ann, CO

Each layer was placed in 3-inch lifts and compacted using a vibrating plate compactor. The clay layers were also compacted with a jumping jack.

The repair was completed on November 28, 2014. No issues have been reported since completion.

Case Studies – Lessons Learned

Anchor Dam, WY – Even with foundation treatment, some geologic conditions are always susceptible to sinkholes, and foundation treatment can do little to achieve preferred conditions. Anchor Dam is a concrete arch dam built on dolomite bedrock with carbonate karst in the abutments and gypsum karst in the foundation. The rock dissolves with groundwater over time, creating networks of cavities. During construction the cavities that were found were filled with concrete but the reservoir never held the volume of water intended. Water continuously leaks through the creek bed and under the dam. More than 50 sinkholes appeared and were plugged in the first twenty years after construction, but the reservoir continues to leak. Soon after construction, one sinkhole was reported to be approximately 300 feet in diameter and 50 feet deep. The dam still stands today but the reservoir is frequently empty and only holds water temporarily after rain and snow melt.

Scholl Dam, CO – Poor underlying soil conditions can create sinkhole issues over broad areas, making localized fixes ineffective. At Scholl dam sinkholes in the upstream abutment have been repaired continuously, but the sinkholes continue to reappear at different locations. Repairs have included geomembrane, clay blankets, and multiple grout mixes and applications. Investigations have suggested that the sinkhole-prone area is founded on landslide material that has formed a matrix with voids that covers an area large enough for the sinkholes to find other seepage paths. The right abutment and groin have leaked since the first filling of the reservoir. So far the sinkholes have been unable to be mitigated with repair measures and there may be no viable permanent fix.

Conclusion

No matter how small a dam, there are unique properties and conditions that can potentially lead to a dangerous situation. Regular and thorough surveillance of a dam can help catch issues early, and with the help of experienced professional engineers most sinkholes can be mitigated or repaired in a timely and cost-effective manner. Without such help, small issues can lead to larger problems that may cost more time and money to repair. Under some circumstances, small issues can signal much larger issues below the surface that may lead to dam failure if dealt with improperly or left unchecked.

Useful References

[1] United States Department of the Interior: Bureau of Reclamation. (1987). *Design of Small Dams*
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[4] D. Magill and R. Berry, *Comparison of Chemical Grout Properties: Which Grout can be used Where and Why?,* Avanti International, 2006, http://pilemedic.com/pdfs/comparison-of-chemical-grout-properties.pdf.
[5] B. Babcock. (2013). *"Sorting out the Grout." World Tunnelling*. June 2013.