Aug 11th - Aug 16th

Averted Piping Failure—Earth Dam on Permeable Foundation

Scott Newhouse
Bechtel Power Corporation, Frederick, MD

AVERTED PIPING FAILURE—EARTH DAM ON PERMEABLE FOUNDATION

Scott Newhouse
Bechtel Power Corporation
5275 Westview Drive
Frederick, MD 21703

ABSTRACT

"The dam builder has substantial control over the properties of the structure he builds, but he must take the foundation as it is furnished by nature." (Cedergren, 1989)

This paper presents the case of an earth dam built on a permeable foundation where seepage problems nearly caused failure of the dam. Early during first filling, before the lake was even half full, the dam showed significant seepage. Seepage boils appeared at the dam's toe, indicating the onset of piping failure through the foundation. Although seepage boils indicating a failure mechanism appeared, dam failure was averted. The paper describes the events leading to the dam's first filling incident, the averting of failure, and engineering for renovation.

Construction of dams on permeable soils is relatively common (often unavoidable). The typical dam site has some alluvial soil in vicinity of the water course, soils that are usually permeable. Potential for seepage-related problems generally depends on the engineer recognizing a permeable foundation and designing the dam accordingly. The dam's behavior—good or bad—depends on the measures taken to accommodate seepage, such as a foundation seepage cutoff and filter-drain protection. Higher permeability generally means higher potential for problems at the downstream toe. This paper presents several interesting aspects of a case history supporting/illustrating this contention:

- Original design and construction
- Problems and near-failure conditions encountered at first filling
- Comparison of the dam to others with permeable foundations and evaluation of other dams where design did and did not accommodate permeable foundation conditions
- Engineering approach to renovation
- Performance in service

INTRODUCTION

Lake Mailande Dam was originally built in 1994 as a homogeneous embankment (without filter/drain protection). Figure 1 depicts the typical cross section, taken from the construction plans, and depicts the soil profile beneath the dam. As shown in Fig. 1, design did not include seepage control—neither a cutoff in the foundation nor an internal filter/drain. The construction plans did not address foundation treatment at all, leading to extensive questions during construction regarding soft soils, high groundwater, and seepage control. The dam is about 55 ft high and 1,800 ft crest length, with 337,000 cu yd of embankment fill. The dam has sparse rural development downstream that includes houses in its flood path and a county road at the toe. Accordingly, it is classified high hazard. Lake Mailande is privately owned, used solely for recreation.

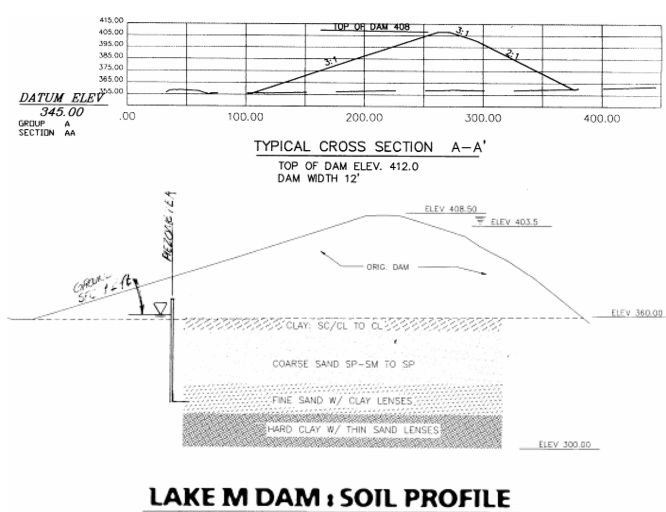


Fig. 1. Lake Mailande Dam—Typical Section and Soil Profile

Initial Exploration

Exploration included only three widely spaced borings, only one of which was close to the dam's footprint. The other two soil borings were in borrow areas. Initial exploration did not include any laboratory testing, neither index nor engineering tests. It appeared that the dam's designer ignored the soil conditions and designed the dam as if the foundation had nothing to do with a successful structure. The homogeneous design was not based on any seepage analysis or prediction of water pressures/hydraulic gradient at the toe. Construction commenced based on essentially no exploration or geotechnical analysis.

Supplemental Exploration

After construction commenced, further exploration was performed to establish the soil conditions depicted in Fig. 1. Exploration shows:

- Significant layers of sand in the foundation
- Significant coefficient of hydraulic conductivity (*k*), of maximum 10^{-3} cm/s
- Artesian water pressure rising to near 2 ft above ground surface

Impact of Permeable Foundation Soils on Dam

Figure 2 illustrates how a permeable foundation results in under-seepage if the dam lacks adequate seepage control measures. As far as the impact on dam safety of seepage into and through the foundation, permeable soil conditions can be interpreted to either enhance dam safety or act against it. Permeable foundation conditions are frequently interpreted as providing drainage, thus lowering water pressure and related hydraulic gradient at the toe. Alternatively, permeable foundation soil can be interpreted to effect the opposite, making water pressure and hydraulic gradient higher at the toe. Stability of the downstream slope is directly dependent on these two parameters—water pressure and hydraulic gradient. Figure 3 shows how permeable soil in the foundation can be interpreted to act as a blanket drain, lowering hydraulic gradient, effecting a stable slope. Figure 4 illustrates a condition where permeable soil creates the opposite effect, where under-seepage drives hydraulic gradient higher than the critical value where soil erosion results, effecting a dangerous condition at the toe.

Potential Piping Through Foundation

Figure 4 is taken from Danny McCook's *A Comprehensive Discussion of Piping and Internal Erosion Failure Mechanisms* (McCook, 2004). This figure illustrates a potential piping failure mechanism for conditions similar to those at the Lake Mailande Dam (Fig. 1). Figure 4 depicts a homogeneous embankment built on a thin surficial clay layer overlying a sand aquifer. McCook notes that such mechanism is a well established one related to failure of flood protection levees, and is more common in levees than in dams. He points out that the mechanism is actually rare in failures of earth dams.

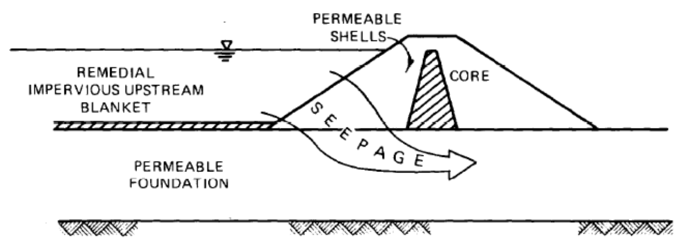


Fig. 2. Under-seepage Through Permeable Foundation (From USACE, 1986)

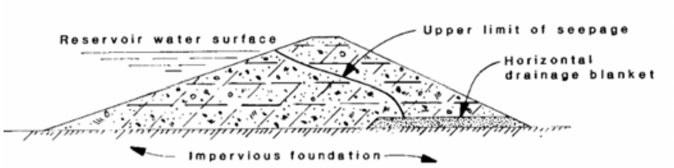
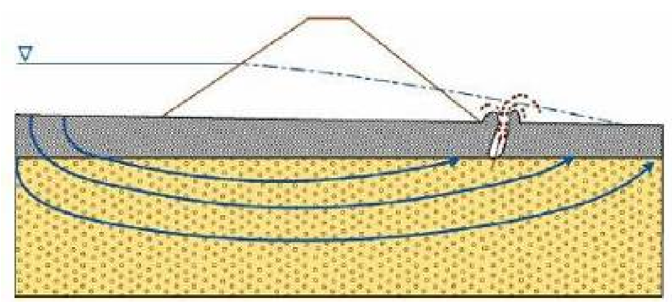


Fig. 3. Effect of Permeable Blanket Drain



(From BuRec, 1987)

Fig. 4. Potential Foundation Piping Mechanism: Heave caused by excessive seepage pressures under surface clay blanket. Piping of sand aquifer occurs from flow of water through defect in clay blanket, creating sand boil at ground surface. (From McCook, 2004)

Could the mechanism illustrated in Fig. 4 form in the Lake Mailande Dam when the lake is filled?

Effect of Horizontal Permeability

Horizontal *k* will almost always exceed vertical *k* in any soil, whether native in situ soil or fill soil in an embankment. References indicate the ratio of k_h:k_v is a minimum of 9 or 10 (Dennis et al., 1971). Seepage analysis must account for this ratio, as illustrated in Fig. 5. Seepage analyses and flow nets based on k_h:k_v ratio of 1 only represent theoretical conditions.

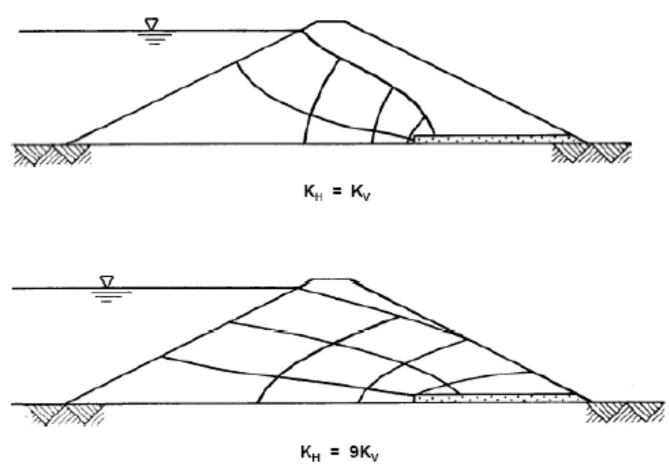


Fig. 5. Effect of k_h:k_v Ratio on Seepage Line
(From US Army Corps of Engineers, 1986)

CONVENTIONAL DESIGN FOR PERMEABLE FOUNDATIONS

In predicting the dam's behavior, one must account for the effect of seepage through the permeable foundation. Under-seepage will affect the position of the seepage line, and thus stability, water pressure, and hydraulic gradient at the toe. The US Bureau of Reclamation design manual states that "*Whenever economically possible, seepage through a pervious foundation should be cut off by a trench extending to bedrock or other impervious stratum.* This is the most positive means of controlling the amount of seepage and ensuring that no difficulty will be encountered by piping through the foundation or by uplift pressures at the downstream toe." (BuRec, 1987) As this excerpt suggests, a dam on a permeable foundation is subject to uplift and potential piping at the toe from under-seepage. Figure 6 (on page 4) illustrates BuRec guidelines for construction on permeable foundations, illustrating the use of a foundation cutoff coincident with an internal drain.

Many dams with seepage-related problems would not have those problems had construction included an adequate cutoff. Cedergren (1989) cites an example of a dam with a foundation so permeable that the reservoir could not fill. On occasions of heavy rain when the reservoir did partially fill, the downstream slope was subjected to such seepage pressure that boils appeared, and it was unstable. Cedergren concluded that the dam's problems were due to a foundation gravel layer that could and should have been cut off in construction, directly aligning with BuRec guidelines presented in Fig. 6.

According to the BuRec design guide, the Lake Mailande Dam should have one of the cross sections shown in Fig. 6. If the dam is to be built without a cutoff, as planned, the design guide indicates its cross section should look like Section (C), in the BuRec figure (Fig. 6). How will the dam perform if it is instead constructed as shown in Fig. 1?

Prediction of Seepage Line within Dam

Figure 7 illustrates a predicted line of seepage within the dam for a full reservoir condition. The predicted line of seepage is based on the piezometer measurements shown taken during initial filling, at the low lake elevation shown. This predicted seepage line was sketched using methods from Cedergren (1989), based on the seepage line exhibited by piezometer measurements and flow net analysis based on an assumed k_h:k_v ratio of 10. The piezometer data show that head and hydraulic gradient were increasing at the toe with increasing lake elevation. This figure illustrates that the dam as designed, with no foundation seepage cutoff and no internal drain to control seepage pressure, would develop intolerable water pressure and hydraulic gradient at the toe long before the lake reached its design elevation. Should this predicted condition be considered accurate? How will the seepage line develop in the dam at higher lake elevation?

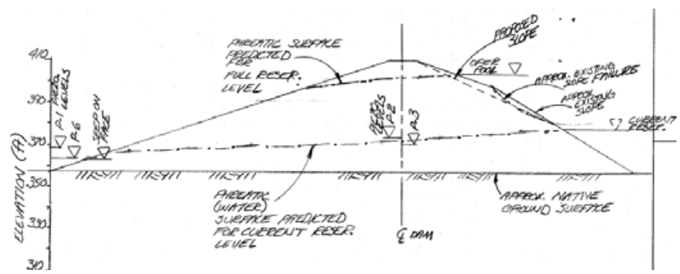


Fig. 7. Predicted Line of Seepage at Full Reservoir

FIRST FILLING—AVERTED PIPING FAILURE

"Lack of viable alternatives always encourages wishful thinking."—J.M. Duncan

At the time conditions in the dam were as illustrated on Fig. 7 seepage problems developed. At this time, reservoir filling had begun, and the lake was less than 50% filled. The toe near maximum section became saturated, a shallow slide developed near the toe, and a seepage boil appeared, as illustrated in Fig. 8 (on page 5). Figure 8 shows the dam at its maximum section. At the time the boil and slide developed, a piezometer at this location indicated head at the toe nearly 12 ft above the ground surface.

The development of the boil indicates that excessive hydraulic gradient developed even with the lake less than 50% full, with a water head near 20 ft of the design 45 ft head. Conditions at this stage clearly showed that continued filling would result in internal erosion of soil from the foundation, and likely a soil pipe, resulting in a breech—the condition illustrated in Fig. 4.

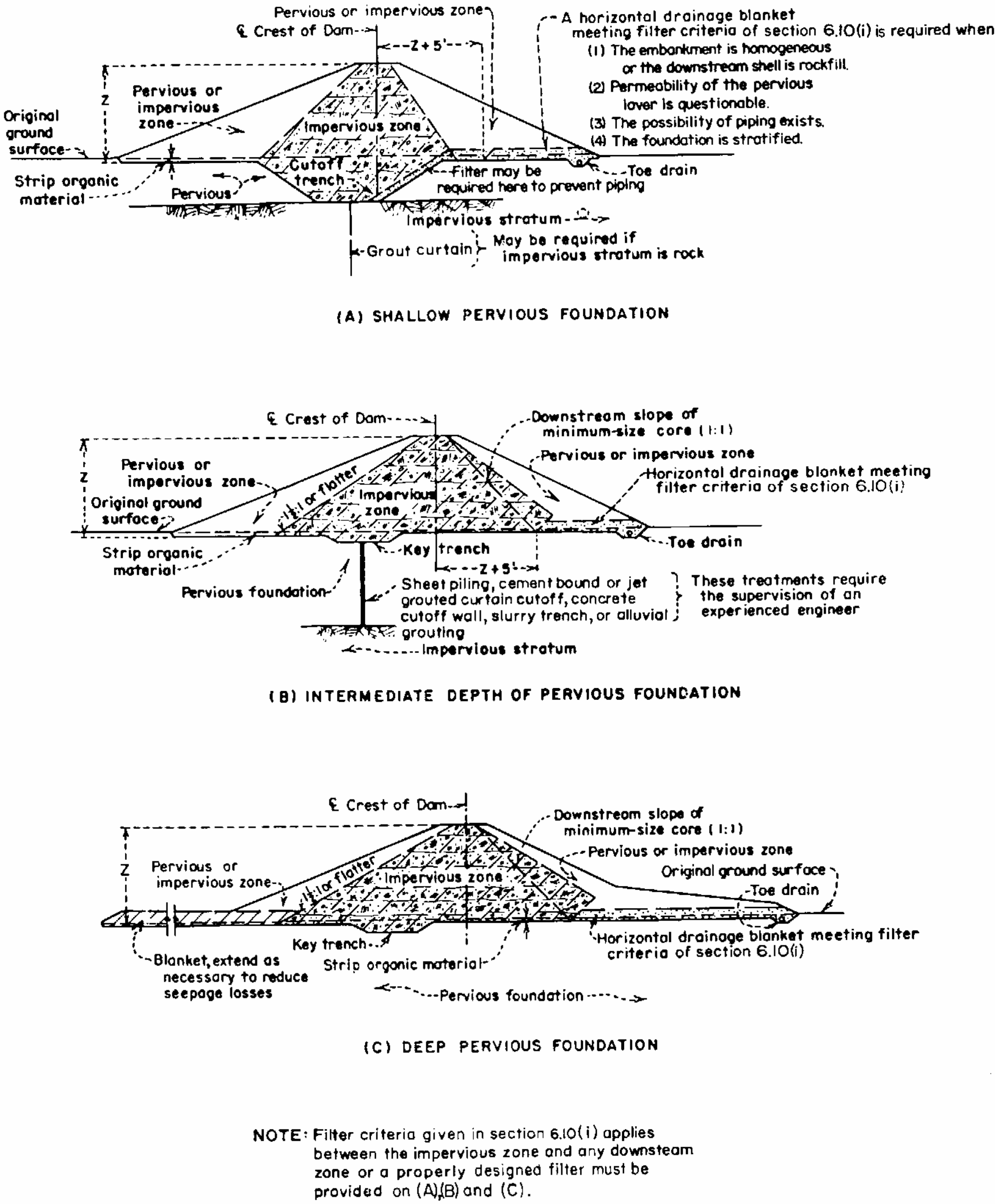


Fig. 6. Seepage Control for Permeable Foundations (From Bureau of Reclamation, 1987)

Fig. 8. Lake Mailande Dam at First Filling, Downstream Slope and Seepage Boil at Toe

The seepage boil was covered with a fabric filter and stone ballast to control erosion. State officials directed that the lake be lowered to a safe level until the dam was renovated. Lowering the lake level and covering the boils averted dam failure by erosion/piping through the foundation. The initial prediction that a homogeneous dam could be built on the permeable foundation at this site was obviously wrong.

At the time the conditions depicted in Fig. 8 formed, the design engineer interpreted the boil as a harmless spring, and interpreted the piezometer level as an effect of consolidation due to pressure on the ground from the embankment. However, facts did not support these interpretations:

- The seepage boil clearly had a cone of deposition showing fine soil being eroded.
- The piezometer level showed steady increase with increasing lake elevation, not with increasing embankment height. Excess pore pressure from consolidation would correlate with the pressure applied by increasing height of embankment fill and would show dissipation over time instead of a steady increase.

REDESIGN AND RENOVATION OF A BRAND NEW DAM

"The ground is not vindictive.…just as it is unsympathetic when winning, it doesn't care at all when it loses."— G.S. Brierly

Figure 9 shows the typical cross section engineers developed to renovate the dam and ensure downstream slope stability and safety against piping. Engineers had difficulty in evaluating the need for a foundation seepage cutoff. As shown in Fig. 9, engineers decided that water pressure and hydraulic gradient could be controlled with drainage works, and that a cutoff was unnecessary. Modifications to the dam included a chimney drain, toe and blanket drains, and relief wells drilled into the artesian zone. The renovated dam was placed in service in 1997 and has performed well. The renovated dam's performance shows that predictions that the dam could be renovated without a cutoff were accurate.

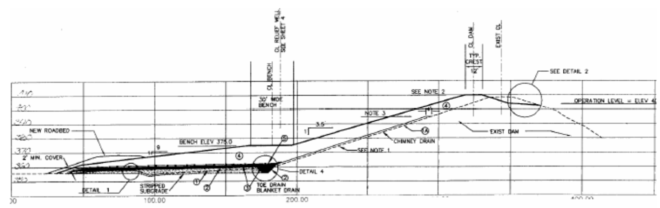


Fig. 9. Renovated Dam Cross Section

PROMINENT LESSONS

This case and others from the literature show that a permeable dam foundation is rarely a benefit and is usually the opposite. Conclusions that a permeable foundation will help the dam by acting as a drain should always be subject to skepticism and a heavy burden of proof.

Comparison to Other Dams

The following sections describe nearby dams of similar size and soil conditions for comparison to the Lake Mailande Dam.

Big Bay Lake Dam. Big Bay Lake Dam (see Fig. 10), near Purvis, Miss., was built in 1991. It experienced a sunny day failure unexpectedly in 2004. The dam is a 57 ft tall earth embankment; the impounded reservoir was about 1,100 ac (ASDSO, 2005). The dam was evidently built with a blanket drain, but without a foundation seepage cutoff. The failure mechanism is theorized to be piping through the foundation.

Not enough information on the Big Bay Lake Dam has been published to allow comparison to Lake Mailande. Consequently, one cannot say whether foundation soils in this dam were more or less permeable than at Lake Mailande.

Fig. 10. Big Bay Lake Dam Breach, Lamar County, Mississippi
(Photos from National Weather Service, Jackson, Miss.)

Bonita Lake Dam. Bonita Lake Dam (see Fig. 11) is within 4 mi of Lake Mailande, with similar size of dam and reservoir. It was designed and built by NRCS for municipal water supply and flood control purposes. This dam is about 60 ft high and 1,500 ft crest length, with 380,000 cu yd of embankment fill. Soil conditions here are similar to Lake Mailande, but there is less thickness of alluvial sand in the foundation. Artesian groundwater pressure was not encountered at Bonita Lake.

Bonita Lake Dam was built with the elements that the BuRec design manual calls for—positive seepage cutoff and internal drain, although the drain here is a vertical chimney and not a horizontal blanket. The Bonita Lake Dam has performed without problems related to seepage.

Other Dams in the Literature

Table 1 summarizes many other case histories found in the literature of dams with permeable foundations. Table 1 is only a brief summary of a portion of the literature; it is not meant to be comprehensive. Examples of permeable foundation conditions that create problems are easily found, where examples of the opposite—permeable foundation soils providing benefit—are not.

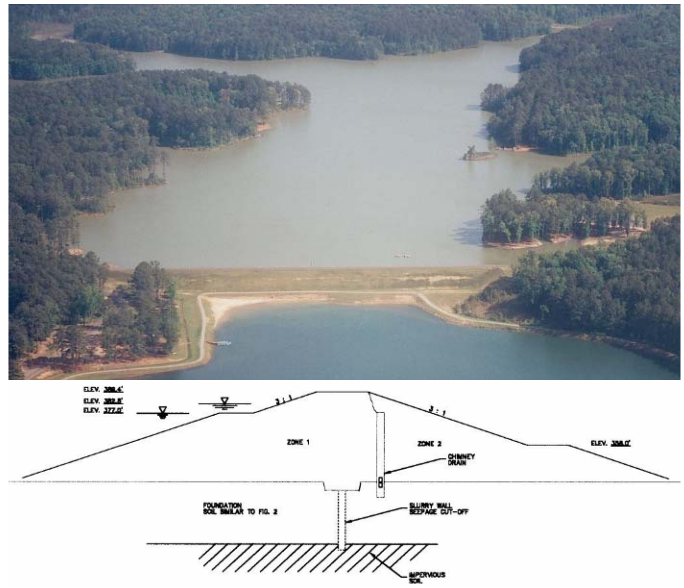


Fig. 11. Bonita Lake Dam Photo and Cross Section

Table 1. Brief Summary of Case Histories

Dam	Description	Reference
Cecil M Harden Dam, Mansfield, IN	117 ft tall, 1,860 ft long. Homogeneous dam on permeable foundation, relief wells installed in original construction. 2 yr after filling required toe drain system due to high head at toe.	ASCE, 1988
Addicks Dam, Houston, TX	49 ft tall, 61,200 ft long. Homogeneous dam on stratified foundation with permeable layers. Sand boils appeared near toe. Soil-bentonite cutoff wall constructed through the dam.	ASCE, 1988 USACE, 1986
Orwell Dam, Fergus Falls, MN	60 ft tall, 1,400 ft long. Homogeneous dam, 90 ft of soil in foundation, 60 ft of stratified glacial soils imparting uplift at toe. Small sand boils and excess head developed at toe, renovated with toe drain, stability berm, relief wells.	ASCE, 1988

Dam	Description	Reference
Sardis Dam, MS	117 ft tall, 15,300 ft long. Foundation: thin layer of silt and clay overlying thick sand. Relief wells part of original construction, clogged after 36 yr of service, resulting in 3 to 7 ft excess head at toe. Renovated by adding relief wells.	ASCE, 1988
Twin Buttes Dam, San Angelo, TX	134 ft tall, 8 mi long. 100 ft overburden soil in foundation including pervious soils. Cutoff wall built only in portion of dam near maximum section. Seepage and saturation, excess head developed at toe. Additional seepage cutoff required.	BuRec, 1998
Power plant storage dike, FL	30 ft tall, 18,000 ft long. Homogeneous embankment of sand on sand foundation. No foundation cutoff. Failed by breaching—suspected piping through foundation.	ASCE, 1988 Cedergren, 1989
West Hill Dam, MA	54 ft tall, 2,400 ft long. Upstream (u/s) seepage blanket and cutoff trench. Foundation of glacial soil with inter-bedded silt and sand layer—cutoff extended to the inter-bedded layer. Boils and excess head developed downstream (d/s), requiring drainage works.	ASCE, 1988
Canby Creek Site R-1, MN	54 ft tall. Foundation soils: surface layer of clay underlain by pervious soil with artesian water pressure. Boils appeared d/s at first filling. Relief wells ineffective. Retrofit toe drain, later required cutoff wall construction.	McCook, 2000
Lake Holiday Dam, IL	45 ft tall, 250 ft long. Foundation soils 50 ft thick with sand and gravel layers. Dam construction included u/s blanket, shallow trench cutoff and d/s horizontal blanket drain. Seepage boils developed at toe d/s of spillway; relief wells installed to rehabilitate dam.	Oskoorouchi, et al, 2000

Dam	Description	Reference
Centennial Narrows Dam, Arizona	32 ft tall, 755 ft long. Homogeneous dam with shallow trench cutoff on permeable foundation (alluvial sand and gravel). Flood control dam failed when rapidly filled during Tropical Storm Nora, Sept, 1997—internal erosion of embankment, possibly piping through foundation.	Benoist, 1998
Washakie (Main) Dam, WY	62 ft tall, 1,250 ft long. Built in the 1930s, homogeneous dam on permeable foundation, shallow cutoff trench 5 ft depth. Seepage problems encountered in glacial soils requiring renovation work at toe for seepage control.	France, 2002
Quail Creek Dike, UT	78 ft tall, 1,980 ft long. Earth dam with chimney drain, cutoff trench excavated into weathered rock. Dike failed at first filling by piping through the foundation—attributed to joints/fractures in the weathered rock that were not adequately cut off and treated.	Von Thun, 1992
H.B. Norton Dam, PA	30 ft tall, 275 ft long. Earth dam on permeable, fractured rock foundation, steel core/cutoff wall through embankment and soil overburden to rock. Excess water pressure measured 16 ft above ground surface at toe.	Newman, 1997
Fontenelle Dam	165 ft tall, zoned earth-fill on permeable sandstone foundation. Seepage problems required lowering reservoir to prevent failure. Foundation grout curtain effective in treating seepage problem.	USACE, 1986
Hills Creek Dam	338 ft tall, zoned embankment—earth-fill core and rock-fill shells. Seepage through foundation/core contact developed after 6 yr of service requiring remedial grouting program.	USACE, 1986

Dam	Description	Reference
Wolf Creek Dam, KY	200 ft tall, combination earth-fill + concrete dam on foundation of limestone with solution cavities. Seepage through foundation produced muddy flow and sinkholes d/s some 25 yr after first filling, requiring extensive grouting.	USACE, 1986
Saluda Dam, Columbia, SC	200 ft tall, 8,300 ft long. Earth-fill dam with permeable sand and broken rock, artesian water pressure in the foundation. Seeps on d/s slope required remedial drainage measures—rock tunnel drains and rock-fill stability berms.	Newhouse, 2004
Dalewood Shores Dam, Lauderdale County, MS	25 ft tall, 4,500 ft long. Homogeneous earth-fill on permeable sand foundation. Extensive seepage d/s threatened failure by piping beneath principal spillway and around outlet works.	Newhouse, 1997
Salt Fork Dam, Guernsey County, Ohio	65 ft tall, 1,800 ft long. Earth-fill with blanket and toe drains on permeable sand foundation. Artesian head and sand boils developed d/s of the dam.	Newhouse, 2005

REFERENCES

ASCE [1988], *Lessons from Dam Incidents, USA-II*, ASCE.

ASDSO Resource Center [2005], ASDSO web site http://new.damsafety.org.

Benoist, J., and Cox [1998], "Failure of Centennial Narrows Dam," *Proc. ASDSO Dam Safety Conf.*, Las Vegas, NV.

Bureau of Reclamation [1987], *Design of Small Dams*, US Government Printing Office.

Bureau of Reclamation [June 1998], "Water Operation and Maintenance Bulletin," No. 184, US Department of the Interior.

Cedergren [1989], *Seepage, Drainage, and Flow Nets*, Third Ed., John Wiley & Sons.

Dennis et al. [May, 1971], "Soil Mechanics Note No. 3: Soil Mechanics Considerations for Embankment Drains," USDA Soil Conservation Service.

France [2002], "Seepage Control in Glacial Foundations—A Lesson in Humility," *Proc. ASDSO Dam Safety Conf.*, Tampa, FL.

McCook, D. [2000], "Three Seepage Case Histories," *Proc. ASDSO Dam Safety Conf.*, Providence, RI.

McCook, D. [2004], "A Comprehensive Discussion of Piping and Internal Erosion Failure Mechanisms," *Proc. ASDSO Dam Safety Conf.*, Phoenix, AZ.

Newhouse, S. [1997], "This Old Dam; Must It Have Outlet Works?," *Proc. Annual Conference of the Association of State Dam Safety Officials*, Pittsburgh, PA.

Newhouse, S., et al. [2004], "A Dangerous Place to Dig: Excavation at the Toe of Saluda Dam," *Proc. Fifth International Conference on Case Histories in Geotechnical Engineering*, New York, NY.

Newhouse, S. [2006], "Can You Build a Dam on a Permeable Foundation?—II. Another Case History," *Proceedings—ASDSO Southeast Regional Conf.*, Myrtle Beach, SC.

Newman et al. [1997], "Stability Of H.B. Norton Dam With Artesian Pressures," *Proc. ASDSO Dam Safety Conf.*, Pittsburgh, PA.

Oskoorouchi et al. [2001], "Maintenance of a Spillway and Dam Foundation Suspected of Piping," *Proc. Annual USCOLD Conf.*, Salt Lake City, UT.

US Army Corps of Engineers [1986], *Seepage Analysis and Control for Dams*, EM 1110- 2-1901.

Von Thun [1992], "The Quail Creek Dike Failure," *Proc. ASCE Conf. Lessons Learned from Failures*, Denver, CO.