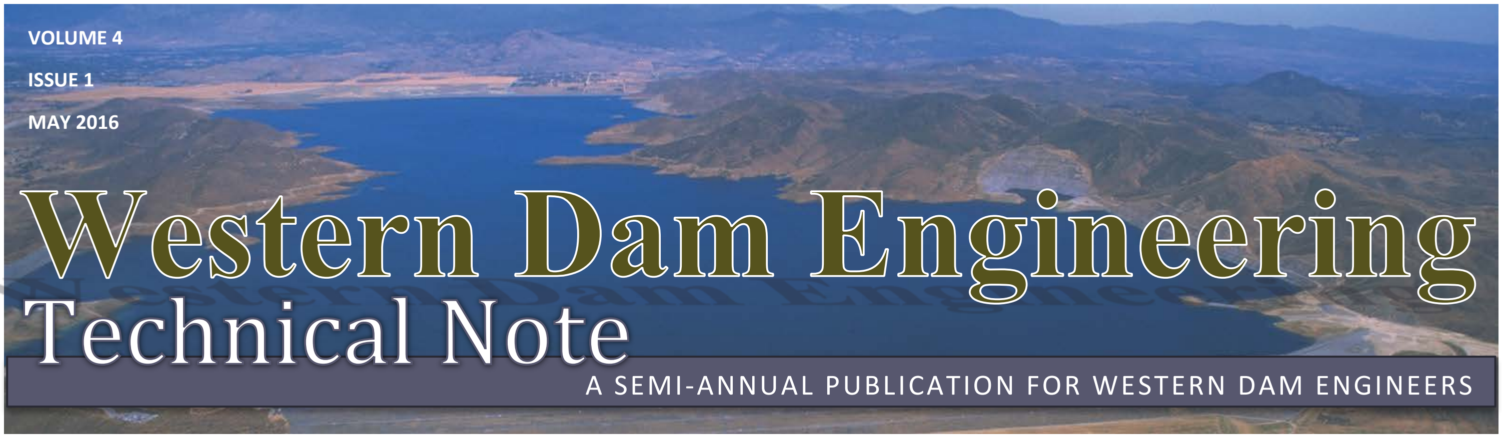

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Western Dam Engineering Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **mobile applications for dam engineers**, considerations for pipe rehabilitation using **cured-in-place pipe (CIPP)**, and a **first on a series of seepage** articles. This semi-annual newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to the design, inspection, safety, and construction of small to medium sized dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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- Montana Department of Natural Resources
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Good to Know

FEMA Training Aids for Dam Safety (TADS): A Self-Instructional Study Course in Dam Safety Practices

Upcoming ASDSO Webinar Dam Safety Training:

- **Strength Selection for Static Slope Stability Analysis** *John France, P.E., and Christina Winckler, P.E.; May 10, 2016 (On Demand)*
- **Cracking and Hydraulic Fracturing in Embankment Dams and Levees** *by Debora J. Miller, Ph.D., P.E.; June 14, 2016*

Upcoming ASDSO Classroom Technical Seminars

- **Inspection and Assessment of Dams**, *Omaha, NE., May 25-27, 2016.*
- **Inspection and Assessment of Dams**, *Jackson, MS, June 7-9, 2016.*

ASDSO Training Website Link

In this Issue

Dam Engineering in the Palm of Your Hand - Mobile Apps for the Modern Day Engineer

Introduction

Modern tablet computers and smart phones provide more computing power in the palm of your hand than in the entire Apollo spacecraft. Both the Android and the Apple (iOS) systems run powerful computers that allow for the operation of sophisticated application programs (apps) using mobile devices. These apps range from high-tech productivity enhancers to addictive games, which most parents (and employers) believe to be productivity killers. This article will look into the current line-up of applications for mobile devices to help the modern engineer perform day-to-day tasks more efficiently, remotely, and even more safely.

This article provides a broad overview of useful applications that may enhance the productivity of dam engineers. From apps useful in field inspection, to sophisticated apps that can tackle complex fluid mechanics, this article is intended to briefly introduce some of the mobile tools available in the new age of engineering. The representative selection offered here is meant to introduce the reader to this avenue of tools, but there is a vast world of available apps beyond those discussed here.

Source: Scott Adams, *http://dilbert.com/strip/2011-08-03*

Mobile App Overview

Operating Systems

The majority of mobile apps are available on two common operating system (OS) platforms: Android and iOS. The Android OS, developed by Google, is currently the most popular OS by sales. Some common devices that support the Android OS include Samsung Galaxy, Motorola Droid, Sony Xperia, Google Nexus, and Kindle Fire Tablets. iOS is exclusively supported by Apple products, including iPhones, iPads, and iPods. It is the second most popular OS by sales. Microsoft offers a mobile operating platform (Windows 10 Mobile), but it remains far less popular than Android and iOS. A good comparison of these three operating systems is found here: Android vs iOS vs Windows [4].

Android apps are available from the Google Play Store [3], while iOS apps are available from the App Store [1], both of which come standard on Android and Apple mobile devices, respectively. Each app store has easy search routines by task, category, discipline, or key word.

Prior to downloading, review the features of the app, customer reviews, and screenshots to see if it is the right tool for the intended task. This article focuses on Android and iOS, but the apps may also be available on the Windows platform. Google Play and the App Store provide a summary of the operating requirements for each app that should be reviewed to verify it works on a particular device.

Offline Functionality

Some available apps, or specific features of apps, require cellular data or Wi-Fi connectivity. Most of the apps presented here operate the majority of their features offline on a mobile device, with no need for cellular connectivity, providing handy tools in remote areas. Most of these apps have additional features, such as data sharing and download of stored information that can be used once the device is reconnected online.

GPS Features

Several of the apps presented here have valuable features that use the device's built-in GPS chip to accurately, and quickly, locate the coordinates of the device. Most cellular phones are equipped with a GPS chip that can operate without Wi-Fi or cellular data. Not all tablets have built-in GPS chips, especially Wi-Fi only models. For those devices with built-in GPS chips, calculating the device's location using only the GPS satellite data is possible, but can take up to a few minutes and have reduced accuracy. Modern mobile devices have the ability to use Assisted GPS (AGPS) to locate the device in just a few seconds by using Wi-Fi and cell tower data, when available, to find GPS satellites more rapidly. There is a good article on this for those who wish to understand more: A-GPS Versus GPS [2].

Recent creative marketing has caused some confusion on the topic by marketing tablets with "aGPS", which essentially means "No GPS", but when connected to Wi-Fi, the network IP address can approximate the device's location.

Cautions

Mobile apps are not typically used for design-related tasks, but can be useful to engineers in various field and day-to-day tasks. As with all engineering tools, it is important to understand the underlying theory behind the technology and its related limitations. Understand the qualifications of the developer and efforts made to validate or calibrate the app. Almost all apps have revised versions, which in some cases were introduced to correct errors found by users. This article is not an endorsement of any application, nor confirmation of its accuracy. The brief descriptions here are intended to introduce the reader to these tools; however, describing the technical theory behind each app or explaining its proper technical use is beyond the practical scope of this article. But the authors have experimented with most of the apps presented and offer some relevant commentary.

Field Inspection Applications

In earlier times, engineers wore thick leather belts because besides holding their pants up, the belt had to carry a flashlight, GPS unit, Brunton Compass, tape measure, camera, hand level, calculator…. Now, that same belt load may be reduced to a phone or tablet.

Maps and Orientation

Map applications are probably the most commonly used.

Google Maps (Google, Inc., Android/iOS, Free):

Map apps require internet connectivity via cellular data or WiFi to operate efficiently. However, they can also be used offline if the maps are downloaded ahead of time and the device has a GPS chip. Google Maps has such broad capabilities that it is difficult to summarize; however, most readers are already familiar with this powerful tool. For dam engineering related tasks, map applications provide directions to the dam site, measuring tools to estimate rough proximity of various features, and satellite imagery. Satellite imagery is especially useful to visualize areas within the downstream flood plain, the condition of the contributing watershed, and proximity of upstream dams and control structures. Its easy operation and power make this one of the most commonly used apps. Google Maps is available for free on both Android and iOS devices. Apple has developed Apple Maps, but it does not offer the same features of the competition. CNET published an article comparing available offline navigation apps: Offline Navigation Apps [5].

Back Country Navigator (CritterMap Software LLC, Android, $11.99):

Backcountry Navigator is another useful mapping application that provides offline topographic maps geared more to…yes…back country areas. It also includes a compass and tracking statistics. It requires upfront work to get familiar with the interface, but provides many useful tools. One feature that makes this app stand out is the large availability of map sources that can easily be downloaded and used once outside of cell coverage. This includes quality international maps. It is worth spending the time reading the help screens to understand how and where these downloaded files are stored, as it is not intuitive. This app also can be used in a fashion that minimizes battery use, a large benefit as navigational and mapping apps are notorious battery hogs.

Theodeolite (Hunter Research and Technology, iOS, $5.99):

Similar to Backcountry Navigator, the Theodeolite app is a map application that provides a compass, two-axis inclinometer, rangefinder, GPS, altimeter, topographic maps, and tracker. The app also allows location-tagging of photographs, which can be useful for field inspections. Some features require data connectivity but most aspects of the application require only the connectivity associated with the device's GPS.

Source: *https://itunes.apple.com/us/app/theodolite/id339393884?mt=8*

Figure 1 – Theodolite Application

Photo Annotator

Context Camera (Cascode Labs Pty Ltd., iOS, $4.99):

The inevitable question that arises back in the office after a field visit is "where was IMG 00336.jpg taken?" Context Camera solves this problem by tagging photos with the direction, coordinates, time, and comments. All information is provided as an overlay on the photo and saved with the image. Location accuracy is based on the connectivity of the device's GPS receiver.

Figure 2 – Context Camera

Measurement

Smart Measure Pro (Smart Tools Co., Android, $1.50); EasyMeasure (Caramba App Development, iOS, Free):

These apps act as range finders that allow the measurement of dimensions ranging from inches to thousands of feet. Measurements are not as accurate as those taken with standard tools, with the accuracy decreasing with distance, but is useful for hard to reach locations to get a quick idea of distances and dimensions during field inspections. Quick calibration measurements should be performed by the user before use as the accuracy also varies with device. The apps use the device's camera and accelerometer to triangulate the distance, height, and width of objects. There are numerous similar applications; these presented were found to be versatile and easy to use, with legible readouts.

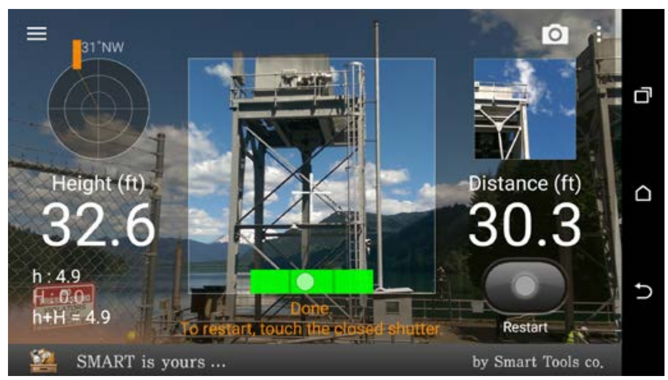


Figure 3 – Measuring Height of Intake Tower with Smart Measure Pro

Clinometer + Bubble Level + Slope Finder (Peter Breitling, Android/iOS, $1.99):

This app is a great tool to have in the field for checking inclinations of side slopes. It doubles as a hand level as well, by using the camera function and on-screen level indicator. It has several options, which may make it look complicated to the novice user, but it only takes a few minutes to learn all the options. This app uses any edge of the device or camera, together with built in accelerometers, to measure a slope. The slope can be displayed in a variety of units (xH:1V, degrees, percentage). There is a voice option that will speak the measurement so it is not necessary to watch the display while measuring the object. It is also capable of measuring relative angles between two different objects. There are detailed instructions for two-way calibration for each side of the device, which results in the most precision possible outside of traditional survey and measurement tools. The developer reports a typical accuracy of about ±0.1 degrees, which is well within the deviation of a constructed slope. Given the typical localized variation in a constructed dam slope compared to the size of the device, it is recommended to carefully select a portion of the slope that best represents the average condition (i.e. not in a localized depression).

Figure 4 – Clinometer

Drawing Reference

AutoCAD 360 (Autodesk Inc., Android/iOS, Basic is Free, Subscription Plan Required for Extended Features):

No longer is it necessary to lug paper drawings around the job site. . The main benefits of this app are the abilities to "carry" a digital set of drawings, overlay aerial photos for ground references, and annotate notes and comments right in the drawing using a finger or stylus. The drawing files uploaded to the device can be used to measure any designed dimension and then compare it to field measurements. Any edits or notes made offline while in the field can be synced or shared once online. Although the app has drawing tools, making anything other than "redline" clouds, notes, or simple line-work is a bit cumbersome on a small device. There is a GPS function within the app that is intended to identify the device's location within the drawing's coordinate space. However, the accuracy and ease-of-use of this feature is dependent on the original coordinate space of the drawing and the device's GPS capabilities.

Engineering Calculators

handyCalc (mmin, Android, Free):

Most people use the calculator app that comes standard on most mobile devices, but there are many more powerful options available. The handyCalc app provides standard calculator options with additional tools such as unit conversions, graphing options, and the ability to solve a system of equations.

DROID48 (Arnaud Brochard, Android, Free); m48 (Markus Gonser, iOS, Free):

Many engineers developed a reliance on the Reverse Polish Notation (RPN) calculators, which were the powerful handheld devices of the late 20th century. There are now several mobile apps that emulate the functionality of probably the most popular RPN calculator, the Hewlett-Packard (HP) 48 model. The most popular are the DROID48, available on the Android OS, and the m48 available on the iOS. Both have skins that duplicate the various screens of the hp48. These apps operate almost identically to the hp48 calculator and, therefore, are easy to use for those proficient in RPN.

Wolfram Alpha (Wolfram Group LLC, Android/iOS, $2.99, Data required):

It is a bit of a disservice to include Wolfram Alpha as a calculator; this app can do it all. It is a knowledge engine that can instantly generate facts and equations on a vast range of topics. Solutions to complex math, physics, and engineering problems are found in Wolfram Alpha's large database. However, it does rely on internet connectivity to retrieve the requested information, and therefore may not work on all devices. The app plugs directly into the Wolfram|Alpha computing cloud, computing answers to questions quickly and efficiently, using specialized math keyboards, displays, charts and graphics. Capabilities include unit conversions, fluid flow calculations, material properties, and section properties, to name a few.

Structural Applications

There are several useful mobile apps for quickly checking structural elements in the field.

LetsConstruct Suite (LetsConstruct, Android, $9.66):

LetsConstruct has developed a suite of ten applications that cover all facets of structural engineering. The apps include structural analysis tools, steel design with shape properties, reinforced concrete design, weld design, Mohr's circle, and many more. This app has an easy-to-use interface that allows for a quick free-body diagram sketch and application of loads, easily solving statically determinate and indeterminate problems. Other aspects of the app suite allow for quick capacity calculations for reinforced concrete and steel sections. With this app, one can quickly evaluate why a concrete retaining wall is cracking or gate hoist frame is showing signs of distress. Some features require data connectivity but most aspects of the application function offline. Prices vary per app or the entire suite can be purchased for $9.66 for Android devices.

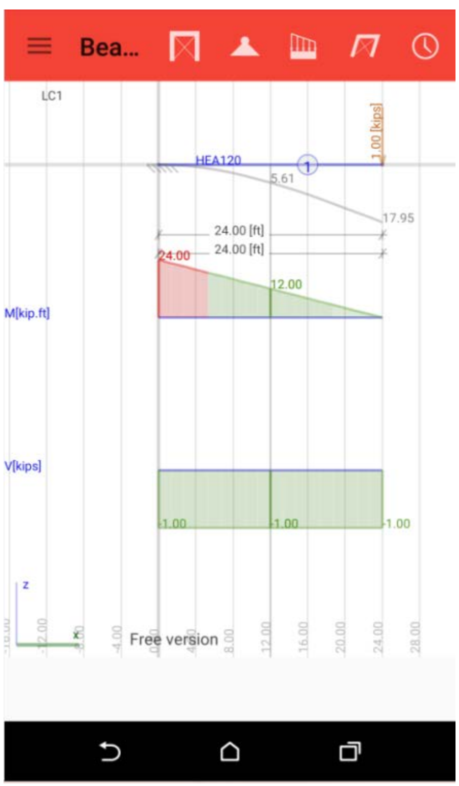
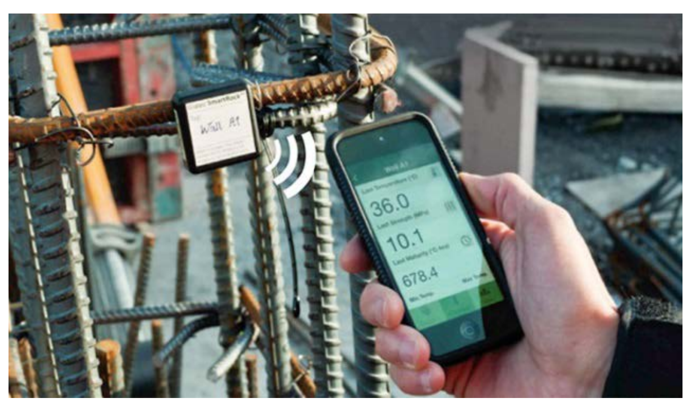


Figure 5 – LetsConstruct Beam Analysis

SmartRock™ (Giatec Scientific Inc., Android/iOS, Free/ Requires Equipment Purchase, Data Required):

The SmartRock app from Giatec Scientific Inc. is part of an innovative system that monitors concrete maturity in the field. The app was introduced last year and is quickly gaining popularity. Prior to concrete placement, a temperature sensor and wireless transmitter is attached to the rebar (Figure 6). After placement, the app uses Bluetooth to monitor and record the temperature history measured by the in-concrete sensor and estimates the concrete strength using the maturity method, as described in ASTM 1074.

The maturity method is a technique for predicting concrete strength based on temperature history. Strength increases as cement hydrates and the amount of cement hydration depends on how long the concrete has cured and at what curing temperature. The transmitter is placed approximately 2 inches from the concrete surface, and at this embedment, the mobile device can communicate with the sensor from a distance of up to about 25 feet. The transmitter comes with a standard 16-inch long temperature cable, such that the temperature sensor can be placed anywhere within 18 inches of the concrete surface. Estimating the concrete strength in real-time is useful in determining allowable times for formwork removal, load application, and post-tensioning. Although the app has a maturity curve database, calibration with site-specific physical testing of the concrete mix and curing conditions is recommended. The authors have not vetted this app in the field yet but are interested in the prospect of the system. The wireless sensors/transmitters are available from Giatec Scientific Inc. and range in $70-$85 per unit depending on the quantity purchased.



Source: *http://www.humboldtmfg.com/smartrock/*

Figure 6 – SmartRock™ System

Geotechnical Applications

GeoID (Engineer Geology & GIS Lab. SNU, iOS, $5.99):

GeoID is a useful tool for measuring and analyzing any geological structure. The app uses a built in magnetometer and accelerometer to assess direction and orientation and gives the Latitude, Longitude, date and time of each measurement taken. A substitute for the typical Brunton compass, this app can accurately and rapidly measure multiple strike and dip orientations of joints, faults and bedding planes, saving lots of time when field mapping. This application includes a geological compass, stereographic projection, instability analysis, and wireless data sharing when connected online. The app is easy to use and does not require cellular data usage to function.

Soil Classify (Mendota Engineer, iOS, $3.99):

Soil Classify is an app that can be used to instantly classify soil per AASHTO and USCS standards without the need to look up the corresponding reference charts. Each system uses soil gradation (sieve data) and plasticity (Atterberg limits) to classify the soil into standardized descriptions.

pLog (Dataforensics, LLC, Android, License Fees Vary):

The pLog app is a tablet application from Dataforensics, LLC developed for geotechnical and environmental site investigation data collection. The app uses integrated GPS for recording hole location and real time data sharing when connected online. The app provides a graphical preview of the log right in the field for easier visualization as the investigation is happening. One of the best advantages of the mobile app is the huge time saver it offers by allowing direct data entry in the field, which can then be exported in CSV or DAT format directly into any software used for drafting boring logs including gINT, LogPlot, HoleBase, ESdat, even Excel, for easy and efficient creation of subsurface logs. It is available on Android tablets with varying license fees based on the quantity purchased.

Hydraulics/Hydrology Applications

Flo Hydraulic Calculator (Dana Shakiba, iOS, $1.99, Data Required/Standalone):

The Flo Hydraulic Calculator from developer Dana Shakiba is a versatile, comprehensive, and easy-to-use hydraulic analysis app that performs flow calculations for several different hydraulic structure types including pipes, channels, weirs, and orifices. The user can choose which parameter to solve for; compute flow for a given geometry or compute required geometry (pipe diameter, channel width, channel depth, or slope) for a target flow. The interface is intuitive, easy to manipulate, and color coding helps guide the user to the required input versus computed parameters. The app has a comprehensive and easy-to-understand information tab that contains quick how-to explanations as well as a thorough database of various required coefficients, such as Manning roughness and weir coefficients. The information tab also provides a quick reference to the relevant equations being used for the selected computation. Calculations are based on the Federal Highway Administration's Hydraulic Engineering Circular No. 22 (HEC-22) and the United States Bureau of Reclamation *Water Measurement Manual*. This is a handy tool to have, especially when in the field for a quick estimate of toe drain, seepage weir, or conveyance channel flows.

Additionally, Android users have a few choices such as Hydraulics Calculator ($4.00) or Channel Hydraulic Calculator and Pipe Hydraulic Calculator (the last two are free).

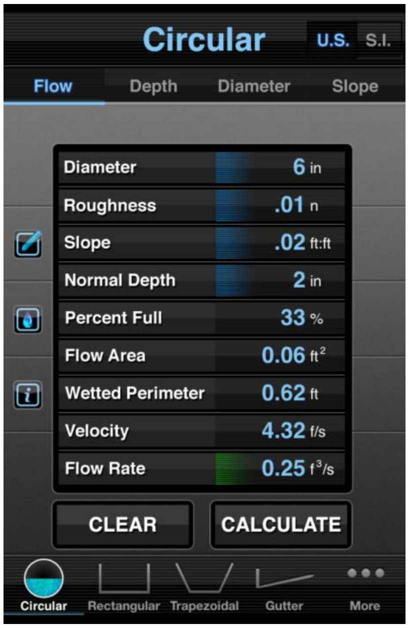


Figure 7 – Flo Hydraulic Calculator

RiverFlows (Subalpine Technologies LLC, Android, Free, Data Required):

RiverFlows provides easy access to streamflow data at river gage sites; these data are useful for tracking river and lake levels. The application pulls data from US Geologic Survey, NOAA, US Army Corps of Engineers, Colorado Department of Water Resources, and the California Data Exchange Center for a comprehensive database of flow data. Check out StreamFlow on iOS for similar features.

Health and Safety Applications

Safety first! These applications are great for quick safety tips and calculations.

First Aid

American Red Cross (American Red Cross, Android/iOS, Free, Standalone):

The First Aid application is one of many useful apps from the American Red Cross. Step-by-step instructions will help in a broad range of first aid situations with full integration with 9-1-1 to call for emergency help if needed. The content is preloaded which is useful for remote jobsites.

General Safety

Occupational Health and Safety (10X Media PTY LTD, Android/iOS, Free, Data Required):

This app from 10X Media PTY LTD keeps up-to-date with workspace safety training and best practices. Available on Android and iOS for free.

IH Calculator Lite (AIHA, iOS, Free):

IH Calculator Lite: The IH Calculator from AIHA allows quick calculations for noise, heat stress, ventilation, and exposure. Other apps such as Decibel 10th on iOS and Sound Meter on Android measure sound levels.

Conclusions

These are just some of the many Android and iOS applications that can be used to become more efficient in the tasks of dam safety, particularly when in the field. These apps are not meant to fully replace more traditional forms of survey measurement or refined engineering calculations, but are useful for quick measurements, access to useful reference information and calculations, and making time away from the office more efficient and productive. As with all computing programs, the old adage "garbage in equals garbage out" holds true for apps. Nothing replaces good engineering judgment, experience and the human touch.

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You Down with CIPP? – Yeah! You Know Me!

Introduction

Cured-in-place pipe (CIPP) is becoming a more common method used to rehabilitate deteriorated outlet piping on dams, and offers many benefits over other pipeline rehabilitation methods. CIPP has been successfully used in renovating deteriorated pipelines, drain pipes, and conduits through levees and has been used for conduit renovation through embankment dams since about the mid-1990s [5]. The CIPP system consists of a flexible fabric tube and a resin system that is hardened by a curing method. The resin is the primary structural component of the system. A fabric tube is used as a means to install and temporarily support the resin until it is cured in place. The CIPP liner resin is typically injected into the fabric ("wet-out") at the manufacturing facility for quality control and shipped to the project site, where it is cured after installation. The fabric tube and resin systems vary depending on the CIPP manufacturer and the design of the CIPP. Some common fabric tube materials are polyester felt and glass fiber composite cloth. Some common resin systems are unsaturated polyester, vinyl ester, and epoxy. CIPP is installed inside an existing pipeline by either an inversion method or a pulled-in-place method. After the CIPP is installed, it is cured in place using one of several available techniques and forms to the shape of the existing pipe, including minor irregularities. This article presents some considerations for selecting and designing an effective CIPP system for pipeline rehabilitation.

CIPP Selection Considerations

Selecting the right rehabilitation method needs to consider the cause of the deficiency prompting the repair. Pipeline repair can range from isolated repairs of a leaky joint or crack, to more global rehabilitation of a deteriorated pipe. A known construction defect that resulted in an open joint could warrant isolated repair using expandable bands or grout; whereas, deterioration due to general aging of the pipe would warrant a more global rehabilitation. CIPP is most often considered as a global rehabilitation method. Although segment lining is possible (lining only a portion with CIPP), it induces greater hydraulic irregularities within the pipe and cost inefficiencies associated with an isolated repair as compared to other alternatives. Global rehabilitation with CIPP can be compared to other common methods such as remove-and-replace using cut-and-cover techniques or slip lining. See the previous Western Dam Engineering article for additional considerations on outlet conduit rehabilitation: Low-Level Conduits - Rehab or Replace?. Table 1 summarizes a few key considerations when initially screening the viability of CIPP as a potential rehabilitation method.

Table 1. Considerations for Evaluating Suitability of CIPP as a Viable Pipe Rehabilitation Method

Conditions	Considerations
Pipe Pressure	CIPP can be a good option for pressurized pipes because of the jointless installation but both internal and external pressures need to be taken into account during the design.
Host Pipe Alignment	CIPP is suitable for pipes with gentle bends; however, certain curing methods work better under certain conditions. Steam curing is best for long runs of steeply sloping pipe to avoid excessive hydrostatic pressure. Water curing is best for pipes with bellies since steam condensation can accumulate in bellies, preventing proper curing due to cooling at those locations. CIPP is not suitable for pipes with significant bends or changes in diameter.
Flow Conditions	Pipes should be fitted with proper venting to prevent cavitation and negative pressures that could damage the lining.
Degree of Pipe Deterioration	Can be used for partially to fully deteriorated pipes; however, not well-suited for deformed/collapsed pipes.
Pipe Size	CIPP can be installed in pipes from 4 to 108 inches in diameter and up to 3,000 feet in length. Liners on the upper end of this range have practical limits due to material handling and transportation limitations as the liner needs to be shipped in one piece.
Access	Access to both ends of the pipe is typically required, regardless of curing method. Site access for equipment mobilization and efficient installation are also considerations as different curing methods require significantly different equipment.
Climate	May influence selection of curing methods and related resin.

Advantages of CIPP

The advantages of selecting the CIPP outlet conduit rehabilitation method include:

- CIPP is a trenchless pipeline rehabilitation process
  - The embankment does not need to be excavated to install the CIPP.
  - The CIPP is installed directly inside the existing pipe.
- No grout is needed of the annulus between the CIPP liner and host pipe.
  - With proper installation, the CIPP lining fits tight against the existing pipeline and should not require grout for a watertight seal.
- Typically no joints are required and installation is rapid
  - The CIPP is installed in one continuous process, extending from one end of the pipe to the other; and does not require joints.
  - Long lengths can be installed quickly, but proper curing is required before recommissioning the pipeline.
  - After curing is complete, the ends of the CIPP liner are cut flush with the ends of the existing pipe and treated to create a seal. End treatments can consist of mechanical seals, grinding the ends of the CIPP smooth, and using epoxy.
  - No thermal or contraction joints are required because CIPP is installed in one continuous piece.
- The CIPP lining decreases the interior diameter of the pipeline, but the smooth interior surface of the CIPP lining usually improves the roughness coefficient, resulting in increased flow capacity in some cases.
- Noncircular pipes can be rehabilitated with CIPP.
- The CIPP lining is capable of accommodating bends, minor changes in cross section, and other slight shape variations in the pipeline.
- The cost of CIPP can be competitive with other rehabilitation methods for longer lengths of pipe (e.g. several hundred feet), but may not be cost-effective for shorter lengths of pipe due to higher installation costs.

Design Considerations

The American Society for Testing and Materials (ASTM) Standards F1216, F1743 and F2019 provide design standards for CIPP. Manufacturers also provide guidelines for designing their individual CIPP products. Most manufacturers specialize in certain CIPP systems, thus ensure the proper CIPP system is selected and understood independent from the manufacturer. Thickness of the CIPP lining depends on the diameter of the existing pipe, the type of CIPP resin system, discharge requirements, condition of the existing pipeline, and loading. Liner thickness typically ranges from about one half inch for smaller pipes to over 2 inches for larger pipes under external loads. CIPP typically has up to a 50-year design life and can be used to rehabilitate pipes ranging in diameter from 4 to 108 inches with insertion lengths of up to 3,000 feet. One limiting factor is weight restrictions for transporting the liner from the manufacturer to the jobsite, as it must be transported in one piece.

CIPP can rehabilitate aging pipes that range from partially to fully deteriorated, as the liner provides improved structural integrity. A fully deteriorated pipe has lost most of its structural capacity and thus the liner needs to provide structural support for the pipe, as well as a water tight seal. The liner thickness can be designed and fabricated to meet the necessary structural criteria for most applications. A partially deteriorated pipe may have sufficient structural capacity to support soil and surcharge loads and the primary function of the liner is to create a water tight seal and slow further deterioration. However, regardless of the degree of deterioration of most host pipe materials, the CIPP should be designed assuming the host pipe provides no support. This more robust design of a self-supporting CIPP improves the longevity of the rehabilitated pipe for a small incremental cost.

Pipes deteriorated to the point of impending collapse may not be a candidate for CIPP, as proper installation is likely infeasible.

Careful attention must be paid to design parameters when determining if CIPP is the best option for an outlet rehabilitation. One of the critical design parameters for CIPP is the liner thickness and resin material required to withstand external and internal pressures. Internal pressures can be induced by static head pressures from the reservoir as well as positive and negative pressures under dynamic flow conditions. Outlet control configurations on gravity piping and pressurized flow within outlets connected to supply, treatment or distribution systems are cases that can induce significant internal pressures. Proper venting of the pipe is also required to prevent collapse of the CIPP lining due to internal vacuum pressures that can develop during operation. See the previous Western Dam Engineering article on pipe venting: Design Considerations for Outlet Works Air Vents

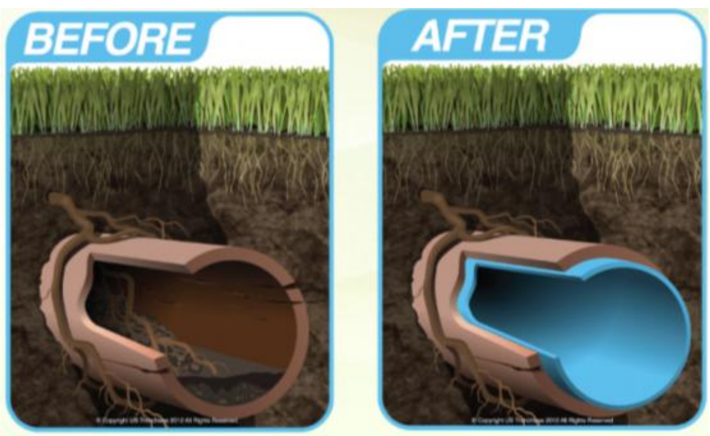


Figure 1 – CIPP Installed inside Existing Pipeline [8]

The minimum required initial modulus of elasticity of the cured liner, per the ASTM Standards, is 250,000 lb/in^2. Typically steam and water cure methods provide an initial modulus of elasticity ranging between 250,000 to 450,000 lb/in^2 and ultraviolet cure methods provide an initial modulus of elasticity ranging between 1,015,000 to 2,600,000 lb/in^2 (see Liner Materials and Curing Methods section for curing procedures). However, the CIPP liner needs to be designed for the long term modulus of elasticity. Typically the long term modulus of elasticity used for a 50-year design life is 50% of the initial modulus of elasticity.

Resins used for CIPP are the most important component to the performance of the CIPP including parameters such as strength, chemical resistance, and creep. Thermoset resins used for CIPP generally fall within one of three categories: polyester, vinyl ester and epoxy resins. Polyester or vinyl ester resins are also formulated for cure by UV. In general epoxy and vinyl ester resins are higher performance products compared to polyester resins. They have higher strength, elongation, elevated thermal and chemical resistance compared to polyesters. Mineral fillers, such as aluminum trihydrate or calcium carbonate, can be added to resins to significantly increase the modulus (i.e. stiffness) of the CIPP without decreasing the strength or the chemical resistance. [7] As may be expected, the higher performance products come at a higher cost, and some projects may not warrant higher performance parameters.

The fabric tube material will also influence the mechanic properties of the combined resin/tube material. Depending on the type of tube fabric, it can either enhance or reduce the mechanical (e.g. strength) properties of the raw resin.

Beside resin type and liner thickness for loading considerations, other key design parameters include entrance and terminal structures, selection of diameter considering both heat-induced shrinkage as well as potential circumferential stretching, and selection of appropriate curing system considering environmental, access, and climate considerations.

Installation

For proper installation of CIPP, both upstream and downstream access to the pipeline is required. The two installation methods are the inversion method (ASTM F1216), in which the liner is installed by progressively turning it inside-out from its initial as-shipped configuration, and the pulled-in-place method (ASTM F1743 and F2019). The installation method is chosen based on site conditions and design of the CIPP resin and curing system. During installation, the CIPP lining is inflated and pushed tight against the host pipe, compressing the fabric and resin against the interior of the host pipe. Once cured, the CIPP resin bonds to the host pipe to prevent sliding of the CIPP lining.

Prior to Installation

- Inspect the pipeline to determine if the pipe is clear of toxic materials in accordance with local, state, and federal safety regulations.
- Clean the pipeline with hydraulically or mechanically operated equipment and clear the pipeline of any debris.
- Perform a second inspection when the pipeline is clean, to determine the location of any conditions that may prevent proper installation, including:
  - Seepage inside the pipe
  - Protruding objects inside the pipe
  - Crushed or collapsed pipe

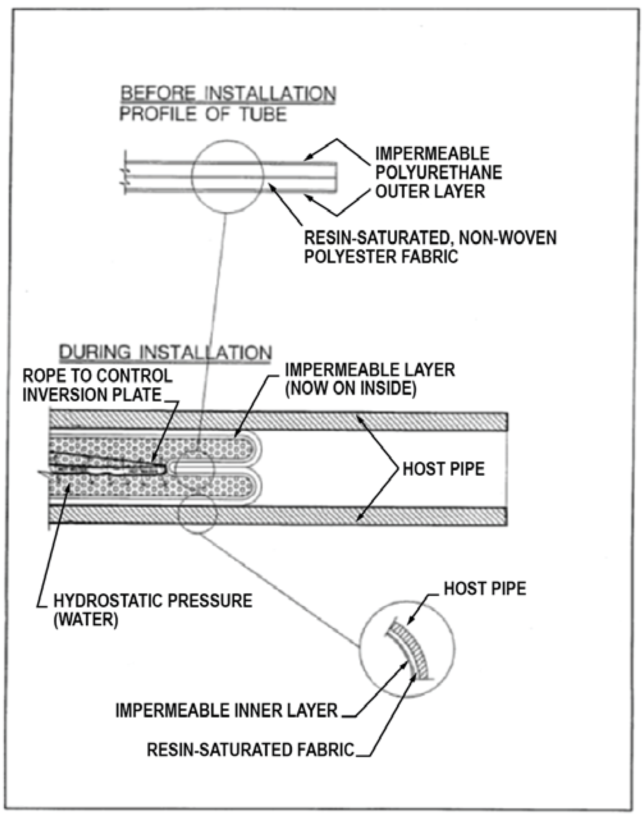


Figure 2 – Inversion Installation Method [5]

Inversion Method

- The CIPP liner is shipped inside-out with the resin already impregnated. Once on site, it is then attached to an inversion standpipe so a leak proof connection is created. The smooth, un-impregnated side if left on the outside for ease of handling.
- Then, either air, steam, or water is pushed into the CIPP liner, inverting it (turning it inside-out) and pushing it into the host pipeline for its entire length. Once inverted, the resin side is directly against the inside of the host pipe, and the smooth side is in the flow area. Compressed air is typically used for inversion in the steam curing application and water is typically used in the hot water curing method.
- The CIPP manufacturer determines the minimum and maximum air or water pressure required to push the CIPP liner tight against the existing pipe without damaging the fabric tube of the CIPP.
- Inversion is the most common installation method, and water is the most common fluid used to invert the liner.

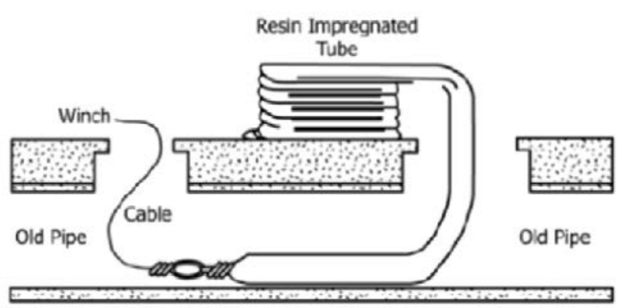
Figure 3. CIPP liner exiting from an existing conduit via the hydrostatic inversion method [5]

Pulled-in-Place Method (also called Winch-in-Place)

- Pulled-n-place liners are typically used for (a) short, large diameter pipes, (b) long CIPP runs where inversion pressures would be overly high, (c) where inversion equipment would have difficult access, or (d) for UV light cured resin applications.
- A pulling tape or cable is first threaded through the host pipe. (This process has its own set of challenges!) The CIPP liner is attached to the cable or tape and to a winch or other mechanically operated device to pull the lining in place.

- Special care needs to be taken when pulling the liner in place so it is not damaged due to friction.
- Liners used for this type of installation require a second inner calibration tube or bladder to inflate the resin-impregnated tube.
- After the CIPP liner is in place, a calibration hose is inverted inside the liner and water or air is forced into the liner, expanding it, and holding it tight against the existing pipe.
- The CIPP manufacturer determines the minimum and maximum air or water pressure required to push the CIPP liner tight against the existing pipe without damaging the fabric tube of the CIPP.

STEP 1 – PULL RESIN-IMPREGNATED TUBE INTO EXISTING PIPE



STEP 2 – CALIBRATION HOSE INVERSION

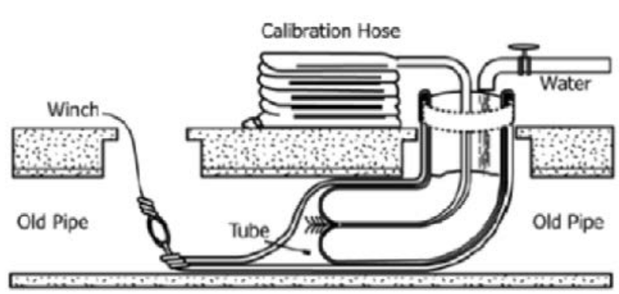


Figure 4 – Pulled-in-Place Installation Method [2]

Post-Installation

The CIPP liner should be inspected by trained personnel following installation. If the CIPP-lined conduit is too small for man-entry inspection, video inspection methods should be used. No dry spots, lifts, delamination, pinholes, wrinkles, twists or infiltration of groundwater should be present and the CIPP liner should be in a fully expanded condition. Some installation and curing systems, such as certain UV systems, have provisions for video inspecting the installation once inflated and prior to curing. This is preferred as installation deficiencies can be corrected prior to curing of the CIPP.

Liner Materials and Curing Methods

Curing of the liner refers to the process of hardening the resin through polymerization induced by either thermal or UV light exposure. Selection of the resin and curing method are interdependent, as the curing methods will dictate the resin to be used. The curing of each liner utilizes a delicate balance of resin catalyst level, curing temperature and time of exposure to maximize the installed physical properties [6].

Proper transportation of the CIPP lining materials is critical, especially for thermally-cured resins in hot climates. Care needs to be taken to avoid damage to the fabric and prevent premature curing of the resin while being transported. Most CIPP resin systems are thermosetting and the resin starts to cure when exposed to heat; therefore, it should be transported in a refrigerated truck. Ultraviolet (UV) light can also be used to cure CIPP and these liners should be transported in light-tight packaging, but have a significantly longer shelf life with no need for refrigeration.

The common curing methods are heated water, steam, ambient, and Ultra Violet light (UV). All curing methods require an internal pressure to press the liner tight against the host pipe before and during curing. Recommended pressures should be maintained throughout the curing process. The curing process used will be based on available resources, access, transportation distance, climate, and the manufacturer's recommendation for the specific resin system. For thermosetting (steam/hot water) curing methods, the CIPP should be cooled in a controlled manner after the curing process is complete.

Circulating Heated Water

Cool water is used initially to invert the pipe to prevent premature curing until the liner is fully installed, and the water inside the liner is subsequently heated. As the liner is inverted, a hose is inserted with the CIPP tube and is subsequently used to circulate hot water from a boiler through the inside of the water-filled liner, heating the water and resin-impregnated liner, causing the resin to cure. Heated water can be circulated throughout the installed CIPP at the required temperature to initiate cure of the resin. The water temperature should be constantly monitored to maintain it above the required cure temperature for the minimum time required. The initial cure will be complete when the exposed CIPP is hard and temperature sensors show the resin has reached the required temperature. After the initial cure, the water temperature should be raised to the required post-cure temperature for the time recommended by the manufacturer.

Steam

The use of steam to cure CIPP liners is most often used for installing liners within pipes from about 6 to 36 inches in diameter. The steam cure method is normally faster than hot water cure, as heat transfer from steam occurs more rapidly. Steam is used in conjunction with pressurized air that inflates the liner against the host pipe and distributes the steam from one end of the liner to other. After the liner has been placed in the host pipe, steam cans, or other similar equipment, are attached at each end of the pipe to distribute steam uniformly throughout the CIPP. Steam with compressed air is then passed through the liner, pressing the liner tight against the host pipe and heating the resin until cure is complete.

The steam generating system should be constantly monitored to maintain the steam temperature above the required cure temperature. The initial cure will be complete when the exposed CIPP is hard and temperature sensors show the resin has reached the required temperature. After the initial cure, the steam temperature should be raised to the required post-cure temperature for the period of time recommended by the manufacturer, then cooled in a controlled manner as described below. Steam is not recommended for pipes that have bellies or vertical bends (such as siphons), as the steam may condense and pool in low areas preventing that portion of liner from reaching the required curing temperature. Condensation also collects at the downstream end of the pipe; therefore, a fitting with a drain hole is usually installed at the downstream end.

Steam curing is two to three times quicker than water curing and is better with restricted-access installations. Steam is also better for steeply-sloping pipes to avoid excessive hydrostatic pressure that can result with water-cured procedures.

Cool-Down

With both the heated water and steam curing methods, the temperature should be cooled below 100°F in a controlled manner before relieving the internal pressure on the CIPP to avoid unwanted shrinkage. The manufacturer will provide the recommended cooling process and temperature drop intervals based on the fabric, resin, and pipe size. The most common cool down process circulates cool water throughout the CIPP. The air or fluid pressure inside the CIPP should be monitored and relieved in a controlled manner so an internal vacuum does not occur and damage the CIPP.

Environmental

Some thermoset resins (e.g. vinyl ester) can contain up to 33 parts per million (ppm) of styrene. Styrene-contaminated resins and water must be disposed of properly and cannot be discharged into stormwater systems because of concerns with its odor and volatile organic compound (VOC) emissions. There are some newer formulations of thermoset vinyl ester resins that reduce VOC emissions. Epoxy resins are naturally VOC-free, but are generally more costly and must be mixed and applied on-site rather than in a controlled factory setting.

UV

There are resin systems that can be cured with UV light. These resins do not react to temperature but rather contain a photo-initiator that reacts to certain UV light wavelengths. UV-curable liners use a nonwoven glass fiber tube, rather than other nonwovens, because the translucent glass fibers permit light transmission through the liner's thickness. A UV light is pulled through the CIPP at the required wavelengths initiating cure of the resin. UV cure is recommended in colder temperatures where heat cure would be more expensive and less efficient. UV may also be a beneficial alternative for remote locations with long transport times, as these products have a much longer shelf-life without refrigeration and do not begin to cure if properly protected from light. Resins cured with UV light can also be used to avoid the environmental impact of some thermoset resins. UV cured resins do not contain styrene but they are more expensive than styrene-based resins. Since UV curing is not heat dependent it has less shrinkage than hot water and steam cure. UV cured CIPP has less than 0.5% shrinkage and hot water and steam cured CIPP can have up to 12% shrinkage. However, UV liners are limited in thickness and diameter because the thicker the liner and the farther its surface is from the light source, the less intense, and less effective the light is at curing the resin. Typical UV liners are limited to about 0.5- to 0.6-inch thick and about 50 inches in diameter.

Ambient

This method of curing is generally not recommended because it takes longer for the resin to cure and the temperature is not as easily controlled resulting in a lower quality product. The CIPP can be cured at ambient temperatures above 65 degrees Fahrenheit, or at the temperature recommended by the resin manufacturer. However, ground temperatures within dams are typically below 60 degrees limiting the effectiveness of this technique.

Termination and End Seals

After the curing process is complete, the ends of the CIPP liner are trimmed flush with the ends of the existing pipe, as needed, and any air vents or other service connections are cut and smoothed and the ends of the CIPP are treated. The ends of the CIPP can be treated using mechanical seals, grinding the ends of the CIPP smooth, or using epoxy. With smaller diameter pipe, where access inside the pipeline is limited, a robotic remote controlled device can be used inside the pipeline to make the necessary cut outs. As required by the contract or purchase agreement, samples of the CIPP can be tested for flexural and tensile strength and chemical resistance. Thermosetting setting resin systems have different shrinkage properties, both radially and longitudinally. The design length of the as-shipped CIPP liner should consider the potential for longitudinal shrinkage.

Table 2. Comparison of Curing Methods

	ADVANTAGES	CONSIDERATIONS
Hot Water	• Historically proven method • Ability to address sags/standing water • One uniform temperature throughout pipe • Accommodates long lengths/large diameters	• Consumption of Water to inflate/cure • Height access for inversion towers • Steep slope limit due to weight of water
Steam	• Less time to complete curing • Higher degree of cure = higher properties • Allows for steep slope installations • Limited water supply and access required	• Safety considerations of steam use • Length and thickness limitations • Potential of coating to blister from heat
UV	• Glass fiber allows for reduced laminate thicknesses • Accommodates both polyester and vinylester resins • Styrene barriers minimize environmental impact • Shelf life up to six months; no refrigeration • Ability to view liner before it is cured • Ability to accommodate and control pipe seepage during installation	• Size limitation of 6-48" • Typically slightly higher cost compared to felt CIPP • Minimal expansion capability for abnormal pipes
Ambient	• Minimal curing equipment • Less expensive	• Requires ambient temperatures above 65°F, which is uncommon in dam outlet works pipes. • Longer cure duration and limited temperature controls may lead to reduced quality

Adapted from inliner™ technologies [6]

Case Studies

Project 1

CIPP was used on one project to rehabilitate an old bituminous coated 48-inch corrugated metal pipe (CMP). The downstream portion of the old CMP was replaced with a new reinforced concrete pipe (RCP) and the upstream portion of the old CMP was slip lined with CIPP. The CIPP was installed through an access point at the gate tower and cured with circulating hot water.

Figure 5 – CIPP installed through gate tower (White pipe is the CIPP and black pipe is used to circulate hot water for curing)

After installation and curing was complete, it was noticed that the CIPP did not fit tightly against the existing CMP and there were gaps between the two pipes. Portions of annular space between the CIPP and the old CMP had to be grouted to fill these gaps. The problems with this installation were thought to be caused by the larger size of the original pipe (48-inch) and the distance from the CIPP manufacturing point to the project site. It was speculated that because of the long travel distance to the site, the CIPP began to cure enroute.

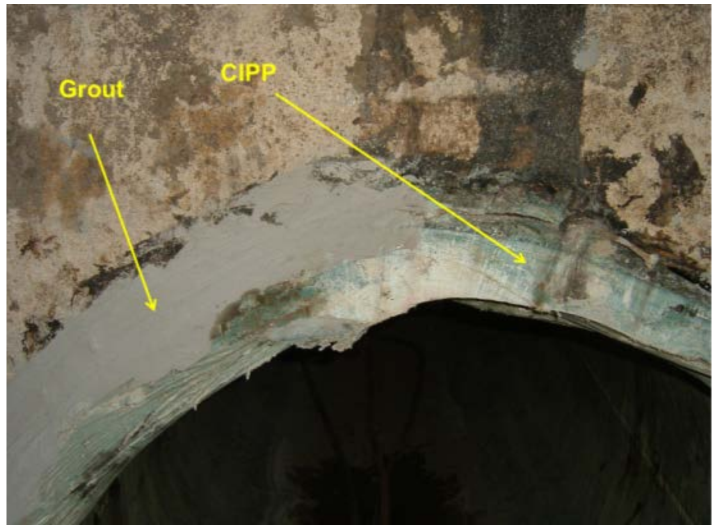


Figure 6 – Loose-fitting CIPP against Old CMP. (Portions of the pipeline had to be grouted.)

Project 2

In this case, CIPP lining was used to rehabilitate a 24-inch CMP successfully. The CIPP fit tightly to the existing CMP and no issues were noted. The difference between the two projects was that Project 2 had a smaller diameter pipe and the project site was close to the manufacturing location.

Figure 7 – CIPP Being Installed to Rehabilitate 24-inch CMP

Figure 8 – CIPP after Installation

Lessons Learned

- The location of the project and travel time from the manufacturing location need to be considered when determining if CIPP is the best option and selecting the appropriate CIPP resin and curing system. CIPP may not be the best option for remote project locations.
- CIPP may be difficult to install in large diameter pipes, particularly those with non-uniformities, and this possibility should be taken into account during the design and installation processes.

Project 3

This project involved the successful CIPP lining of an existing 12-inch CMP outlet conduit. An inspection of the existing CMP pipe showed the pipe needed to be repaired based on the amount of corrosion and seepage into the pipe. The CIPP manufacturer in this case recommended using UV curing identifying the advantages of UV cure; stronger material, thinner walls, and UV/pressure curing allowed the seepage into the existing pipe to be controlled better during installation. The CIPP was installed using the pulled-in-place method and inflated tight against the existing pipe with air pressure. After installation the UV light string was pulled through the CIPP lining for curing. Once curing was complete the ends of the CIPP were cut flush with the existing pipe and Xypex was used to seal the ends of the CIPP. Due to the small diameter of the pipe, a cutter robot was used to go inside pipe and cut out all existing laterals.

Figure 9 – UV-cured CIPP lining installed inside the existing 12-inch CMP

Common Pitfalls of CIPP

While there are many advantages to using CIPP, there are also common pitfalls and disadvantages.

- Successful, high-quality design and installation of CIPP requires a company and personnel with expertise in CIPP and specialty equipment to ensure strength requirements are met.
    - The installation of CIPP is not a common procedure; a company with expertise in CIPP will ensure the CIPP is not damaged during the shipping or installation process, and that resulting installation will meet quality standards.
    - Special equipment is required for a proper cure; curing system equipment must be robust, reliable, and operable by the installing crew.
    - Pressure and temperature need to be monitored constantly throughout the installation and curing processes for most common curing methods.
- While transporting and prior to installation, thermally-cured CIPP needs to be kept in a cool environment so early cure of the CIPP does not occur.
    - Some resins can be sensitive to installation in hot climates.
    - As shown with the case studies, travel distance from the CIPP manufacturer to the project site should be taken into account.
- CIPP installation and curing equipment can include water tanks and boiler trucks for the

hot water and steam cure processes. Such equipment may be difficult to get to remote dam sites.

- CIPP liners with damage from shipping or poor installation techniques including punctures, breaks, or abrasions must be replaced and should not be repaired in the field.
- Infiltration and/or seepage into the existing pipeline need to be controlled prior to installation of the CIPP.
- If the CIPP is not correctly sized, it will not fit properly inside the existing pipeline.
  - Wrinkles can occur if the CIPP is too large.
  - Voids can occur between the CIPP and the existing pipe if the CIPP is too small.

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Is Your Embankment Dam under Pressure – Underseepage Impacts

Introduction

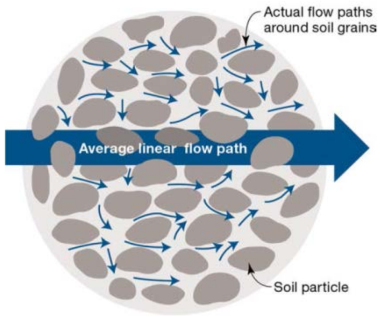
A simple truth: every embankment dam that retains water also seeps water. This is due to the nature of soils and rock that constitute earth dams and porous dam foundations that have a potential to allow flow of water. The question will always be — Does the mechanism, location, and volume of seepage cause concern for the safety of the dam? How does one identify acceptable versus unacceptable seepage? These are lofty questions that dam engineers, top academics, and research agencies have been studying for decades, resulting in a continuous evolution of the understanding of seepage mechanics of earth dams during the past 100 years.

The majority of U.S. dams are more than 50 years old and were designed and built prior to the current understanding of internal erosion control. One of the common challenges of evaluating an existing structure is recognizing what the surface expressions may be telling us about the internal mechanisms at work, (i.e., when a potentially hazardous condition may be developing). This concept is especially applicable to earth dams that are composed of and founded upon natural materials.

Giving dam owners, operators, engineers, and regulators the knowledge and tools to monitor, detect, and evaluate observed seepage is an enduring task. This article introduces the extensive, yet critically important topic of seepage and focuses on the mechanics, monitoring, and investigation of seepage through the soil foundations of earth dams. More importantly, the article provides guidance as to when observed foundation seepage should be a concern. Future articles will focus on other aspects of earth dam seepage including embankment seepage, emergency response to seepage incidents, and long-term remedial measures.

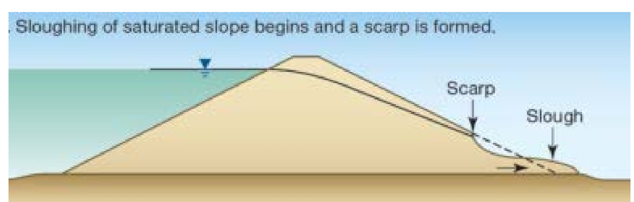
Basic Seepage Knowledge

Seepage is defined as the flow of a fluid (water) through the porous space within a soil mass. Although on a micro scale the seepage follows an irregular path around the solid particles, engineers generally think in terms of the average linear flow path. Much work has been completed on the topic of seepage, and Cedergren's *Seepage, Drainage, and Flow Nets* [1] is an excellent book on the characteristics of flow under and through dams. Most current seepage approaches are based on his assessments.



Seepage that simply results in water loss is not necessarily a dam safety issue. It can, however, be an economic or societal issue, as retaining or storing water is the dam's primary function. If the structure is not good at that, then cost and social impacts of the water loss may warrant improvements. Clean seepage from a dam may result in an inadvertent creek or pond downstream of the dam, unintentionally feeding distant aquifers, or causing settlement of nearby roads or structures—but these may not significantly affect the integrity of the dam structure itself.

When seepage velocity is great enough, erosion of the soil can occur because of the frictional drag exerted on the soil particles. Dam safety engineers are focused on seepage that erodes the soil material of the dam or its foundation. This type of seepage-induced erosion can be considered in two broad categories; surface erosion and internal erosion. **Surface erosion** due to seepage initiates at the point of the seepage exit. The scour caused by the exiting flow of water can progressively destabilize embankments by removing materials which provide external support to the structure.



Internal erosion occurs within the soil mass as soil particles within an embankment dam or its foundation are carried downstream by seepage flow. Internal erosion can progressively deteriorate the integrity of the structure by eventually creating large voids or "pipes" within the dam or foundation, ultimately leading to loss of the reservoir.

Internal erosion has led to more catastrophic dam failures than any other mechanism except overtopping. Internal erosion is itself a broad category, as it encompasses several mechanisms including backward erosion piping, concentrated leak erosion, contact erosion, and suffusion/suffosion. Describing all of the initiating, continuation, and progression mechanics of internal erosion is beyond the practical scope of this article. Three excellent references for further reading on internal erosion mechanisms are [2], [4] and [9]. Look for a summary of internal erosion mechanisms and associated potential failure modes in a future article.

Foundation Seepage and Backward Erosion Piping

The focus of this article is specifically on seepage through a dam's foundation and its impact on dam safety. Seepage through the foundation of an embankment dam is sometimes referred to as "underseepage." Internal erosion through the foundation due to underseepage is especially dangerous because there may be only subtle evidence that it is taking place until the situation has progressed to near failure. This is because the exit point may not be readily visible, as it could be a distance downstream of the dam, be underwater, or be hidden by terrain and/or vegetation and be undetectable to the casual observer.

Underseepage is controlled by the natural conditions of the foundation and any engineered features in the design and preparation of the foundation. Engineered features for foundation preparation may include removal of unsuitable soils (organic, low strength, permeable, etc.), in-situ soil improvements (dynamic compaction, deep soil mixing, etc.), cutoff walls and trenches, surface treatment of bedrock contact, and grouting. Foundation treatment was often limited or absent for small to medium sized dams, especially those constructed before about 1970, as a result of not fully understanding or recognizing the potential adverse impacts of seepage flow through, into, or out of the foundation.

Backward Erosion Piping

Although there are several internal erosion mechanisms that can occur through the foundation, the most common is known as backward erosion piping, or just "piping." Backward erosion piping is erosion of soil by seepage water that initiates at an exit point and progresses backward (upstream) toward the reservoir (generally in a horizontal direction as shown on Figure 1). Particles of soil are carried away by the seepage, until eventually a tunnel, or pipe, is formed from the downstream exit point to the reservoir. A continuous layer susceptible to piping, beneath a layer or structure capable of forming a roof, is needed for backward erosion piping to lead to dam failure. In addition, an unfiltered exit point is required for this type of erosion to initiate.

The typical series of events to describe the mode of failure from initiation to complete breach, known as an event tree, has been developed and is generally described as follows [9]:

1. Reservoir at or above threshold level
2. Initiation – Erosion starts
3. Continuation – Unfiltered or inadequately filtered exit exists
4. Progression – Continuous stable roof and/or sidewalls
5. Progression – Constriction or upstream zone fails to limit flows
6. Progression – No self-healing by upstream zone
7. Unsuccessful detection and intervention
8. Dam breaches

There are two idealized foundation conditions most commonly considered when evaluating the potential for excessive foundation seepage. McCook [5] and Pabst et. al [6] are two excellent references that provide understandable and concise descriptions of these two conditions and methods to estimate factors of safety against the initiation of erosion.

The terms 'heave' and 'uplift and blowout' are sometimes used interchangeably; however, as described below, the mechanisms are physically different. The use of 'heave' should be limited to cohesionless soils (no confining layer) and the use of 'uplift and blowout' to foundations with a confining layer.

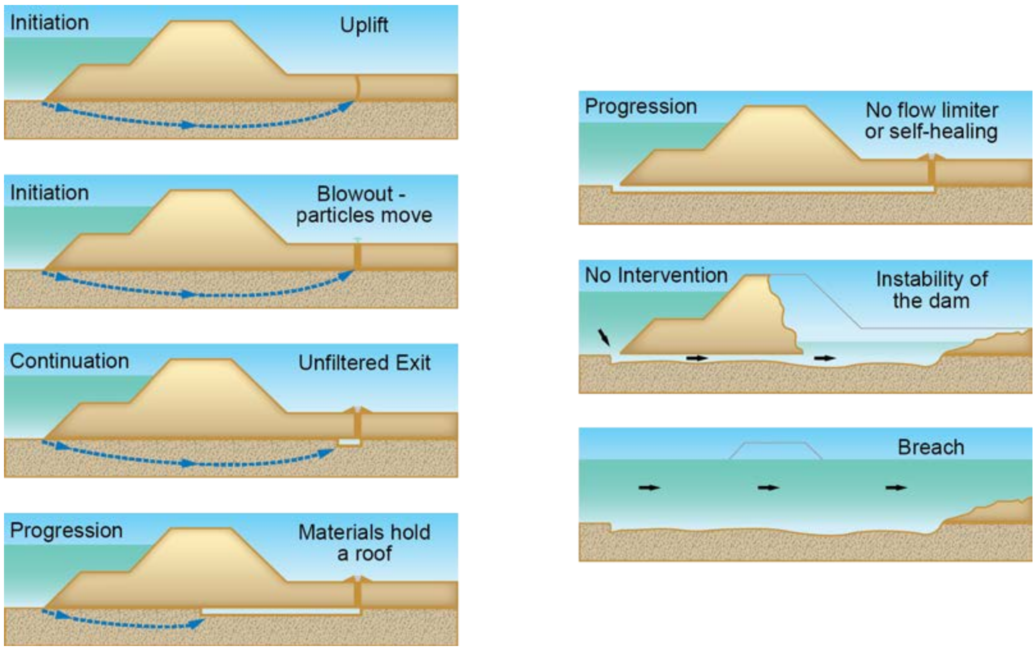


Figure 1. Foundation Backward Erosion Piping Model (*adapted from* [8])

Deep Pervious Foundation => Heave

The first condition is a relatively low permeability structure (dam) constructed on a homogenous, pervious, foundation. Figure 2 depicts a failure initiating for this idealized condition. Breaching of the dam could occur if sufficient sand were eroded from beneath the dam, and a pipe formed under the embankment large enough to empty the reservoir or cause the embankment to collapse into the pipe.

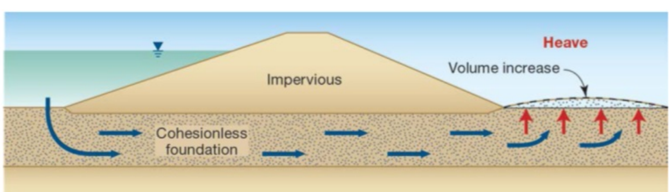


Figure 2. Heave of a Cohesionless Soil (Vertical Seepage Exit)

Confined Pervious Foundation => Uplift and Blowout

The second idealized condition is sometimes termed a blanket-aquifer, which consists of a pervious foundation layer (e.g., sand) overlain by a significantly less permeable (e.g., clay) confining layer. Artesian pressure develops when the piezometric head (pore water pressure) within the pervious layer exceeds the downstream ground surface elevation. When the pressure is great enough to overcome the weight of the confining layer, it is known as *uplift*. This can cause a spongy condition at the toe due to a reduction in the effective stress. When this uplift pressure acting on the bottom of the confining layer results in rupture of the layer, it is known as *blowout*.

If seepage through the pervious layer is sufficient, cohesionless soils within the pervious layer can be carried to the ground surface and deposited in a conical ring, known as a sand boil. This can also occur through defects existing or created through the confining layer. See further discussion below on causing defects to confining layers.

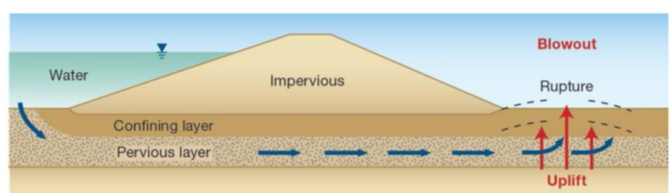


Figure 3. Uplift and Blowout of a Confining Layer (Vertical Seepage Exit)

Many alluvial valleys have a surface layer created by overbank flooding deposits (or remnant organic surface soils) that have hydraulic conductivities lower than the underlying alluvial soils. Foundation treatment for many small to medium sized dams was limited to stripping of vegetation, leaving the low permeable, organic soils to serve as the dam's foundation. This layer of soil creates a low permeable blanket, confining pore pressures in more permeable underlying layers. These dams continue to function, but activities such as digging or drilling at the toe can puncture or reduce the thickness of the confining layer, leading to an elevated risk of blowout.

Figure 4. "Blowout" Caused by Underseepage of a Dam in Montana (MT DNRC)

Critical Gradient and Seepage Exit Direction

Seepage in an upward direction reduces the effective stress within the soil. When the water pressure at a point in the soil is equal to the total vertical stress at that point, the effective stress is zero and the soil has no frictional resistance to deformation. When the effective stress is zero, the gradient is sometimes referred to as the critical gradient, which is defined Υ_b/Υ_w, where Υ_b = the buoyant unit weight of the soil and Υ_w = the unit weight of water. For typical soils $\Upsilon_b/\Upsilon_w \approx 1.0$. This is the point that heave would occur. However, this is not to be confused with the seepage gradient that initiates internal erosion. Internal erosion of certain soils under flow conditions other than vertical can initiate at gradients significantly less than 1.

Making the distinction between vertical and horizontal exit conditions is important, because the direction of the seepage exit influences the gradient that will initiate erosion. A foundation seepage exit may be in a ditch or other excavation penetrating into the erodible non-plastic (cohesionless) pervious soil, resulting in a horizontal or near horizontal seepage exit.

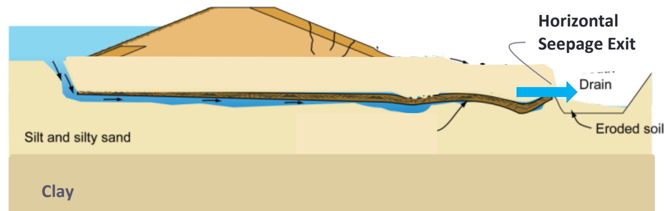


Figure 5. Horizontal Seepage Exit into a Drainage Ditch along the Downstream Toe of an Earth Dam

Vertical seepage exits need to overcome gravity and, in some cases, overcome the weight of a confining layer. Therefore vertical seepage exits typically have a higher gradient required to initiate erosion as compared to a horizontal exit. There are several methods that have been proposed to calculate a factor of safety against heave and uplift/blowout, which apply to vertical seepage ([5], [6]). In the case of horizontal seepage exits, heave and uplift/blowout computations do not apply. There is no generally accepted methodology for calculating a factor of safety against internal erosion for horizontal exits. In practice, horizontal gradients as low as 0.05 in fine, uniformly graded sands have been observed to initiate erosion in some particular soils [6]. Schmertmann [7] and Sellmeijer [8] offer some general guidance on critical gradients based on lab tests; however, the equations include a number of correction factors to apply them to field conditions and they were developed for a limited range of cohesionless soils. Caution should be used in applying these equations. Critical horizontal gradients are a topic of much ongoing research and currently remain a relatively subjective assessment.

Field Detection

Foundation internal erosion failures have occurred during first filling at some dams and at others, only after years or even decades of successful performance. This is one of the main reasons to regularly inspect dams with a trained, curious, and non-complacent eye.

Visual observations are the first line of defense in detecting an initiating internal erosion mechanism in sufficient time to intervene. The initiation of dam safety incidents are often first observed by routine daily site visits by operators, dam owners, or the public noticing an unusual condition, especially since many small dams have little to no instrumentation and only periodic formal engineering inspections. Therefore, the people who are at the site most often need to understand the tell-tale signs of developing adverse conditions. Conditions related to potential foundation seepage failure mechanisms include the following (example photos of some of these conditions are also shown):

- Saturated ground or ponded water from no known surface source
- Water-loving vegetation such as lush grass, brush, willows, or cattails, particularly at a localized area.
- Surface staining
- Deposits of sediment through toe drains or adjacent drainage ditches
- Sand boils
- Crack patterns in downstream dam face
- Bulges at or downstream of the dam toe

Figure 6. Underseepage at Dam Toe Rising to Surface (Wyoming NRCS)

Figure 7. Underseepage at Dam Toe at a Colorado Dam

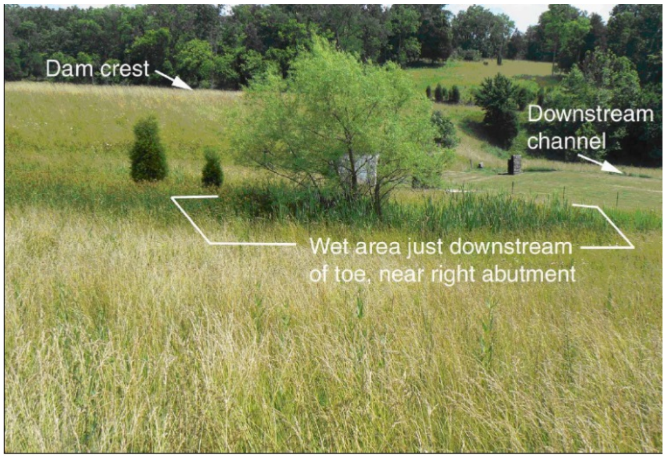


Figure 8. Presence of Phreatophytic Vegetation (willow tree and cattails) in a Seepage Location 200 feet below the Downstream Toe [2]

Figure 9. Surface Staining from Intermittent Underseepage at a Colorado Dam

Figure 10. Sediment Plume within a Drainage Ditch along the Downstream of a Dam Toe [2]

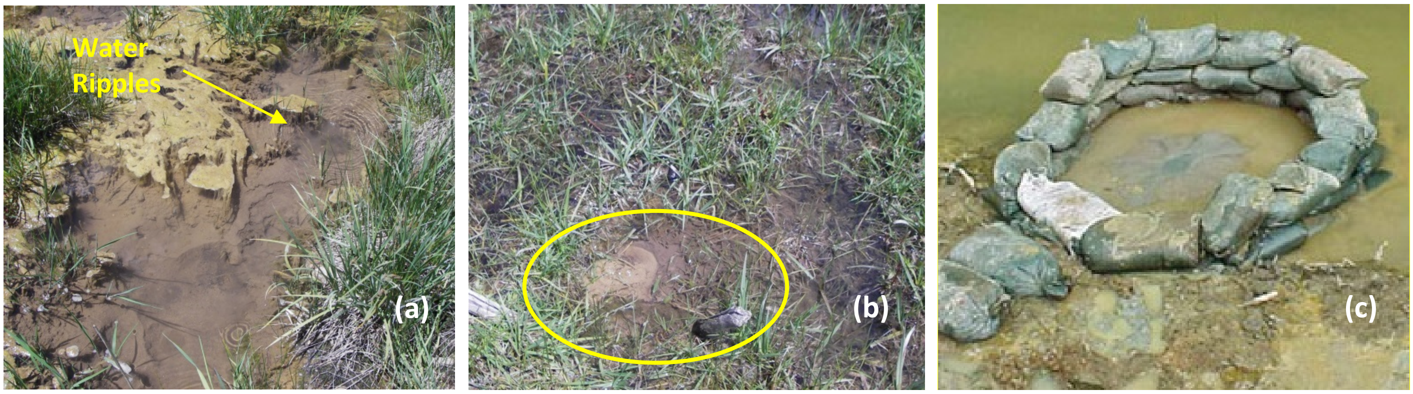


Figure 11. Sand boils on downstream toes are often slightly submerged, and sometimes detectable by water ripples (a). The may start as very small deposits (b). Once observed they are often sandbagged to help limit progression (c).

Sand Boils

'Boils' will often appear at locations of concentrated flow. While particle movement may be evident in these boils, there may be no continuous removal of soil if the material 'rolls' in a steady state condition (i.e., particles simply rise and fall within the boil). The soil stratigraphy also plays an important role in the seriousness of boils. If the sand boil comprises fine-grained soil being removed from a shallow foundation layer that is underlain by a coarser layer, the erosion will likely not progress through the coarser layer. If the sand boil comprises fine-grained sand being removed through a defect in an overlying clay layer (crack, blowout, penetration, etc.) or through a coarse-grained layer, the erosion may progress upgradient. However, boils in any state can be an alarming condition as a slight increase in gradient may result in rapid development of backward erosion piping. [6]

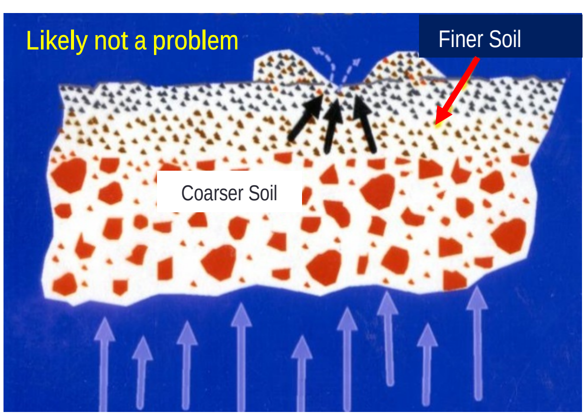


Figure 12. A Sand Boil of Fine Sand being Removed from an Upper Layer Underlain by a Coarse Sand Layer has Limited Potential to Progress [9]

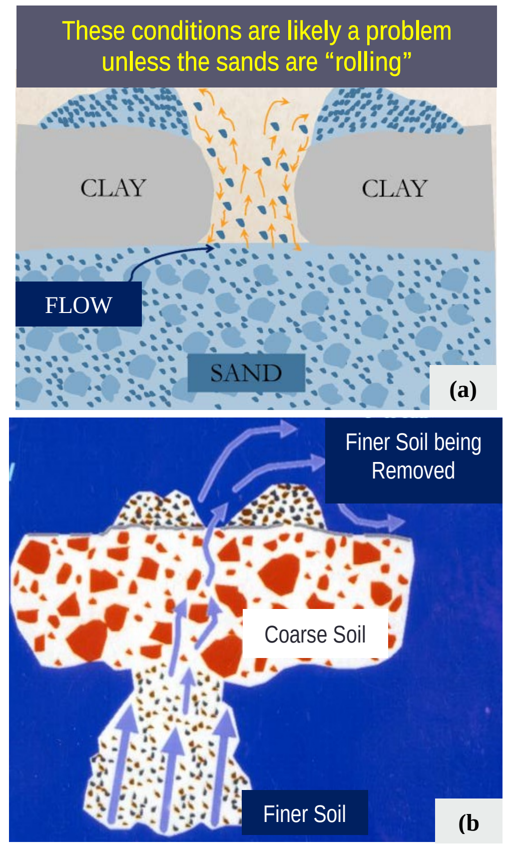


Figure 13. Finer Soil Being Removed through (a) a Defect (crack, blowout, penetration) in a Confining Layer, or (b) a Coarser Overlying Layer can Progress [9]

Other Potential Defects

Other features that can increase the likelihood of backward erosion piping through the foundation due to damage to a confining layer include rodent holes, deep roots, penetrations such as power or telephone posts, and excavating trenches or pits downstream of a dam. See additional cautionary discussion below on drilling and excavating near the dam toe.

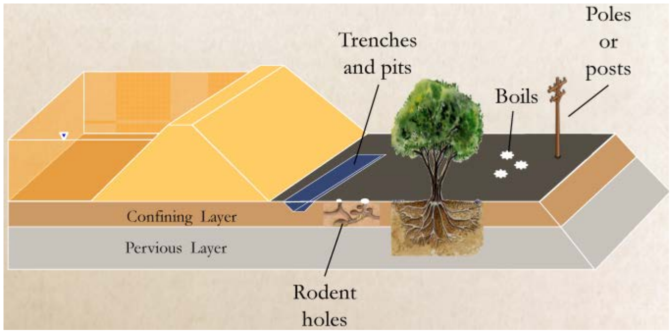


Figure 14. Potential Defects to a Confining Layer

Investigation and Evaluation

In the cases where site observations have provided some indication of an adverse foundation seepage condition—what is the next step? First, take a step back and look at the big picture. Information obtained from the site observations should be combined with as much background information as available, such as past inspection reports, original design records, modifications that have been made, performance data, and geotechnical studies.

Underseepage evaluation would be fairly simple if foundation soils were homogeneous and their properties were isotropic (the same in all directions). That is usually not the case. Dam foundations are typically in valleys with soils that can consist of alluvium (stream-deposited), colluvium (gravity-deposited at the base of slopes), till (deposited by glaciers), residual soils (created in-situ by weathering of bedrock), and past manmade fills. These soils can range from open-work gravels (very high hydraulic conductivity) to high plasticity clays (very low hydraulic conductivity) and can be layered, lensed, segregated, or more likely, can be combinations of all three.

It is important to have a geologic understanding of the dam foundation soils to interpret the soil properties that influence foundation performance. Key properties that influence a soil's seepage and internal erosion potential are the gradation, relative density, and plasticity, all of which also affect the hydraulic conductivity of the soil. Site-specific information on the variable foundation soils is often limited. For dams with little to no information on the foundation, publically available geologic data can provide some insight on the types of native soils that may have been deposited in the foundation. The Natural Resources Conservation Service (NRCS), previously called the Soils Conservation Service, offers an online tool called the web soil survey. This tool acts as a database containing soil maps available for more than 95 percent of the nation's counties: NRCS Web Soil Survey. However, soil surveys only map shallow soils, and more information is usually required to understand the full foundation profile with depth.

After all available data is gathered, the engineer should consider the following questions to help characterize the severity of the foundation seepage condition in terms of dam safety and establish a path forward:

- Are there signs of foundation saturation: Wet ground with ponding water, well-developed water loving vegetation)?
- Are there signs of material erosion: sand boils or sediment plumes at the toe? If not, could ponded water be obscuring such detection or flow be carrying it away?
- Is there geological evidence nearby of conditions that create a confined aquifer situation (fine-grained, cohesive surface soils; likely limited foundation preparation)? Low-permeable layers, if continuous, along with the embankment, could provide a roof-supporting layer as well as a confining layer.
- Does the ground near the downstream toe feel "spongy?"
- Based on the geology of the valley, is it likely that an erodible layer continuous from upstream to downstream could exist in the foundation?
- Are there piezometers that allow for a reliable estimation of foundation pore pressures?

Measurement Instruments

The condition of a deep pervious foundation, not overlain by a confining layer, is more easily characterized. If there is evidence that a pressurized foundation seepage condition exists, along with backward erosion potential, then understanding the foundation seepage pressures is critically important. If no piezometers exist to provide an accurate understanding of the foundation pressures, field investigations to install piezometers may be warranted. A series of piezometers screened to measure pore pressures at different elevations and locations is required to estimate seepage gradients. Seepage gradients, along with the foundation material type, will control the potential to initiate internal erosion. As previously discussed, several methods are available to estimate critical seepage gradients and all cautions previously stated for these methods apply [5], [6], [7], [8].

If piezometers are to be installed, care and proper design are required to strategically select their locations and installation methods. This will help to avoid initiating a dam safety incident due to drilling, yet provide instruments that can capture the desired information. See the section *Don't Rush to Dig In* for more information. An example of piezometers located to measure seepage pressures within the pervious aquifer and overlying confining layer is shown on Figure 15. Piezometers can be installed relatively inexpensively within small dams using truck or trailer mounted drill rigs. Cone Penetration Test (CPT) rigs can also be a cost-effective option for installing fully grouted piezometers while limiting disturbance.

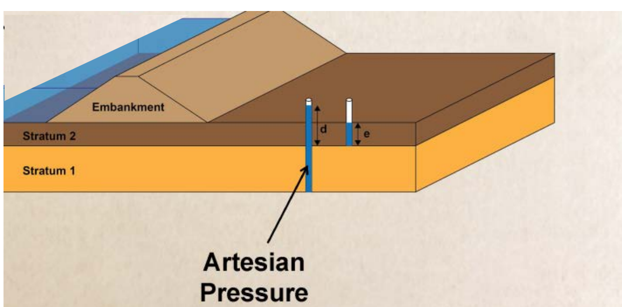


Figure 15. Piezometers Located to Measure Potential Uplift

A rough rule of thumb is to assume a safety factor of 2 when the piezometric surface in the pervious water-bearing strata is at ground surface, based on the unit weight of soil typically being nearly twice the unit weight of water. Higher piezometric levels in the water-bearing strata would result in a reduced factor of safety.

Seepage weirs can also provide a means of monitoring for increase seepage flows or sediment accumulation.

See the previous *Western Dam Engineering Technical Note* article for more information on dam safety instrumentation: [Does Your Dam Measure Up?]

Numeric Seepage Analysis

A qualitative analysis using field observations and instrumentation data can sometimes provide enough information to understand the problem and guide the engineer on what to do, and just as importantly, what not to do. However, if the existing knowledge and instrumentation data are not conclusive, then a two-dimensional model of the dam and foundation can be analyzed using appropriate stratigraphy and material properties.

Seepage analyses can be performed either by computer software (which is typical today) or by manual flow net generation. The results of the seepage model can be used to develop a better understanding of the seepage regime beneath and through the dam and estimate foundation pressures and hydraulic gradients. Calculated gradients can then be evaluated for the potential to initiate erosion. Typical software codes, like Seep/W by Geostudio [3], are relatively easy to learn. However, the model results are only as reliable as the model inputs. If the variation in stratigraphy and material properties is not well defined, then spending time and money to develop a model is a pointless exercise. Before investing in developing a seepage model, first do a reality check by looking at the site configuration and piezometric data (if available) and deciding whether a two-dimensional model would adequately represent the seepage regime. It is common for dams and foundations to have seepage flow (gradient) that is not perpendicular to the dam axis. If this is the case, it can be difficult to develop and calibrate a meaningful two-dimensional model. Three-dimensional models have a higher cost, are more susceptible to inaccuracies, especially with limited data, and require special expertise. All of this needs to be considered when determining the most appropriate, and justified, means of evaluation.

Don't Rush to Dig In

> It is prudent to perform drilling or excavation when the reservoir is at a low pool and to have fill material and equipment nearby in case emergency action is necessary to keep a blowout from progressing

It may seem obvious at this point; however, one more cautionary statement will be made on the implications of exacerbating a foundation seepage condition by careless activities at the downstream toe. Drilling or excavating test trenches or toe drains can often do more harm than good.

Installing a toe drain may seem like a beneficial measure to mitigate the impact of seepage. However, installing a toe drain when pressurized conditions are present may be more detrimental than beneficial as it may not reach the water-bearing layer and instead may simply weaken the confining layer. Other options exist to mitigate the potential for internal erosion through the foundation, such as a blanket drain and/or berm to filter the exit or lengthen the seepage path.

Drilling investigations must also consider potential impacts to dam safety, particularly if the investigations are performed with a full reservoir and with a suspected pressurized foundation. Defects can also develop due to incorrectly constructed or abandoned monitoring wells. See the previous *Western Dam Engineering Technical Note* article: Poking the Bear: Drilling and Sampling Embankment Dams

Conclusion

Although erosion may initiate, there are several steps that need to happen to result in breach. The inability of the foundation layers or the embankment itself to form a roof, the lack of continuity of natural erodible deposits, and the likelihood of intervention by staff (drawing down the reservoir, placing emergency filters, blankets, etc.) may arrest the potential failure mode before it fully progresses. Field observations and engineering judgment need to be applied. As suggested for other aspects of seepage related issues, a geotechnical engineer, experienced in embankment dam design, is an important participant to assist in making dam safety decisions.

Seeping foundations, particularly of existing dams, are mysteries that must be solved to make appropriate decisions on prudent measures. When the evaluations have provided an understanding of the seepage-related issues, decisions can be made regarding the safety of the existing dam and whether remedial measures are needed.

There are many remedial measures available, and each seepage situation requires a specific corrective action to ensure a safe dam. This may range from increased monitoring to major rehabilitation. Determining whether a seepage condition is a steady state condition or one that is progressing is an important determination in deciding the relative urgency of action. Signs of a changing or progressed condition (increasing seepage, sediment pluming, enlarging sand boils, embankment cracking and deformation, etc.) should be promptly reported to dam safety regulators. Remedial measures, emergency responses, and construction issues will be the subject of a future *Western Dam Engineering Technical Note.*

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