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Guidelines for Drilling and Sampling in Embankment Dams

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U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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

Table of Contents

Page

List of Tables

List of Figures

Acronyms

ASTM	American Society of Testing and Materials
DTH	Down The Hole Hammers
EAP	Emergency Action Plan
FER	Field Exploration Request
HASP	Health and Safety Plan
HSA	Hollow-Stem Augers
JHA	Job Hazard Analysis
NEPA	National Environmental Policy Act
PVC	Polyvinyl Chloride
Reclamation	Bureau of Reclamation
SHPO	State Historic Preservation Officer
SPTs	Standard Penetration Tests
TSC	Technical Service Center

Guidelines for Drilling and Sampling in Embankment Dams

I. Introduction

This document provides guidance agency policy on the Bureau of Reclamation's (Reclamation) investigation in embankment dams, including investigation planning, site preparation, borehole advancement, subsurface testing, and borehole completion. When planning and conducting subsurface investigations into or near earthen embankment dam adherence is critical to preservation of Reclamation structures. There is a very real potential for damaging structures during the drilling process if these guidelines are not followed. Damage created by hydraulic fracturing during the drilling process and/or unacceptable methods of completing borings can open seepage paths which could create conditions conducive to piping and ultimately dam failure.

This guidance replaces Reclamation's past policy on drilling and sampling in embankment dams issued in 1989 geologic mapping, logs, and reports from previous investigations and construction.

II. Program Planning

When planning an investigation program, the first consideration is if the need for the data to be collected justifies the cost and potential risk to the structure created by the data collection process. As is standard procedure with Reclamation's Dam Safety Program, a determination of potential consequences if no action is taken should be made to compare with subsequent investigation cost estimates and prioritization of Reclamation programs. These consequences should include both risk and likelihood for worsening conditions, which could drive up future cost of remediation if required. If possible, the determination of consequences should be performed with available data. However, a scaled down investigation program may be required before an adequate assessment can be performed.

If data collection is justified, a multidiscipline exploration team should be formed to determine exploration components required to adequately address the data needs. The exploration team should consist of the principal engineer, the principal geologist, geophysicists, and experts in laboratory analysis, in-situ testing, or other disciplines as needed. The exploration team should thoroughly discuss data needs and investigation plans to ensure compatibility.

A thorough search of all available records should precede any investigation program. Reclamation sources of information that could be useful in evaluating the need to collect additional data include:

- Geologic mapping, logs, and reports from previous investigations and construction
- Safety of Dams data books
- Geotechnical services files
- Earth materials reports (retained by the Materials Engineering Laboratory)
- Technical records of design and construction
- Archived records
- Construction (L-29) reports
- Project records in regional office and at the project site.

The exploration program should consider:

- Purpose of the investigation
- Cost of the exploration
- Required sample type and size (disturbed or undisturbed)
- Acceptable drilling and investigative methods
- Depth, diameter, and inclination of drilling required
- Materials to be drilled and sampled
- Utilities, surface and underground obstacles, and accessibility
- Dam foundation geometry and hazard of fracturing
- Instrumentation and completion requirements

The investigation will likely require clearances, permits, and traffic control plans. The investigation schedule must allow time to obtain clearances and permits. In most cases, National Environmental Policy Act (NEPA) compliance activities will be required. Under the National Historic Preservation Act, some sites may require inspection by an archeologist and a permit from the State Historic Preservation Officer (SHPO). Reclamation's regional or area offices can assist with these activities.

No dam should be drilled or investigated without review of the Emergency Action Plan (EAP). Reclamation dams have EAPs in place; copies may be obtained by the governing regional or area office. The EAP lists the key individuals who should be contacted and informed of proposed activities. There are documented case histories where drilling has caused incidents with dams and knowledge of the EAP and good communications were key contributors to safely solving the problems [3].

As with all Reclamation field activities, a specific job hazard analysis (JHA) should be prepared prior to commencing work.

III. Site Location and Preparation

A. Possible Types and Locations of Investigations

Potential sampling and testing methods and drilling locations vary depending on the data required to be collected to analyze a specific type of dam safety issue. Typical dam safety investigations include sampling and testing methods to determine the potential for liquefaction (dynamic stability), seepage and piping, static stability, collapse of foundation soils, and cracking. Emergency repairs and dam remediation activities typically require some drilling component to collect needed data.

Liquefaction investigations often require drilling through the shell or crest of a dam to perform Standard Penetration Tests (SPTs) in embankment core and/or unconsolidated foundation materials under the structure. Testing can also be performed at the downstream toe; but these soils often are not consolidated like those under the dam, and engineers often prefer to test the material under the structure. However, holes are often drilled in alluvium at the toe of a structure. Materials also can be investigated in accessible test pits to evaluate if the soil is initially loose (relative densities of less than 60 %). In some cases, drilling can be performed from the crest of the dam as long as the cutoff trench or wall is not penetrated. Access roads may be required on the downstream slope or, in rarer occurrences, on the upstream slope if water levels allow.

The preferred method of determining SPT results in loose sands below the water table is by fluid rotary drilling where the mud pressures and hydrostatic forces can be used to stabilize the sands. However, in locations that include concerns with possible hydraulic fracturing, use of hollow-stem augers (HSA) is preferred. For more information refer to the *SPT Drillers Guide* [4].

Drilling in embankments often does not provide conclusive data related to seepage and piping problems within a structure. The chance of finding a disturbed zone in a dam by drilling is small, and there could be great risk. Piezometers can be installed to monitor seepage problems, but they only are effective if the problem area is known. One case for drilling into embankments could be to collect samples to evaluate filter criteria of transition zones within the structure. This can be accomplished with shallow drilling, preferably above the phreatic surface in the dam and sometimes at angles into the structure to target transition zones. Holes could be drilled from the crest or downstream shell of the structure, index tests performed, and soil samples obtained. Care must be taken during drilling to be sure that internal drainage features are not damaged or contaminated. If drilling must be performed in a dam subject to seepage and piping problems, seepage flows need to be monitored continuously during the investigation, and drilling fluids need to be controlled as discussed in the section on drilling.

Dams with seepage problems may require investigation to determine the condition, location, or even whether drains exist in the structure. In these cases, test pit excavations may be attempted. However, the possibility for piping of the foundation into an excavation or drill hole could exist and should be carefully assessed. Some dams already may have evidence of critical gradient development at the toe or into drains or manholes. Drilling at the toe of the dam is risky even if seepage is not evident. If there is concern about the occurrence of piping, a contingency plan must be developed. For example, for test pitting at the toe, if critical gradient piping is a concern, materials to stop progressive erosion in the trench must be ready. For this situation, it is recommended to stockpile fine (C33 concrete sand) and coarse processed aggregates to filter and plug the excavation. If drill holes must be advanced under a critical gradient condition, one should consider the construction of drill berms at the toe.

If holes must be advanced at the toe of a dam that has a critical gradient condition, planning and precautions should be developed. In all cases, issues of this nature should be addressed by the exploration team prior to commencement of work. In these areas, it is necessary to maintain a positive hydrostatic pressure on the drill hole to prevent a "blowout." In instances when higher pressures are not anticipated, the addition of commercial densifiers to the drill mud may successfully address the concern. In most cases, establishing a minimum positive head of 5 feet by maintaining drill fluid in the borehole provides an adequate safety factor. When the static water level is very near the ground surface or artesian conditions prevail, one should consider elevating the drilling rig on temporary drill berms to raise the drill hole collar elevation. The berm should consist of filter zones for extreme cases.

In situations where the presence of higher pressures is suspected, it may be necessary to install surface casing to control artesian pressures if they are anticipated to be significant and/or derived directly from reservoir head. Surface casing or slightly larger diameter than the augers or drill string to be used is grouted in place and allowed to set prior to advancing the borehole to depth. If flow from the borehole occurs, the surface casing provides a means of controlling it by blocking off the space between the augers/drill rods and well casing. Specific details such as height of the drill pad and amount of surface casing, must be developed on a case-by-case basis dependent upon specific conditions present at the site. Even if artesian pressures are not expected at a given site, potential risk requires contingency plans be in place in case these conditions arise.

Sampling of both the embankment and foundation may be required to obtain a specimen for laboratory testing. Often, high quality, undisturbed samples are required for these studies. Generally, the weakest part of the embankment is the plastic Zone 1 core material. If there is no preexisting data on the core, samples may be extracted using HSA dry core methodology. The HSA coring systems can be readily converted to accept acrylic liners for collecting undisturbed samples.

Some earth dams and saddle dikes in the arid Western United States may be built on loose collapsible soils. Wetting and collapse of these soils may cause cracking and failure. The only way to evaluate collapse is to determine the density of deposits under the structure or to perform collapse tests on undisturbed soil specimens. Dry coring methods must be used either by HSA system with large diameter soil cores or through test pits and block sampling.

All earth dams are susceptible to and likely contain cracks in certain areas of the structure (Figure 1 and 2[1]). Investigation of desiccation cracks on the crest of a structure can be performed by hollow stem flight auguring and moisture profiling or by test pitting with density and degree of compaction measurements. A recent survey of cracking in dams reveals that some of these crest cracks can extend to depths well beyond the limits of commonly available excavation equipment, such that test pits may not be effective in determining the extent of cracking. Additionally, large test pits require significant effort to re-compact the backfill soil to optimum conditions.

[1] Figures can be found at the end of this document.

B. Locations to Avoid Damage and/or Hydraulic Fracturing

A major concern with drilling in embankment dams is the possibility of damaging the structure by hydraulic fracturing. Every dam should be inspected prior to drilling. Locations for drilling should be selected to minimize damage to the dam or foundation. A determination whether hydraulic fracturing potential exists should be made by the exploration team. If potential for hydraulic fracturing exists, the type of equipment and the method and technique must have the approval of the exploration team.

Reclamation has many wide Zone 1 core dams. Many dams include a cutoff trench. These cutoff trenches may not be built to standards used today regarding smoothing of steps and overhangs on the abutments and use of dental concrete for sealing overhangs. It is likely cracking of the embankment has occurred over these cutoff trenches; but with a wide Zone 1 core, the chances for cracking completely through the zone are lessened. Thus, it is advisable to not to use any drilling method that uses drilling fluid near these cutoff trenches. Reclamation also has structures where the outlet works conduit penetrates the embankment. These conduits are potential paths for differential settlement, poor compaction, cracking, seepage, and piping. Mud rotary drilling should not be performed near these structures. Many dams contain a concrete or wood cutoff wall. These cutoff walls are locations of high seepage gradients and stress concentrations. Drilling should be avoided near these walls. Many dams have grout curtains that also prevent seepage and should not be damaged by investigations.

IV. Drilling Personnel

When drilling in embankment dams, the personnel involved with the drilling process are as critical as any other component of the program. Potential risk and liability concerns dictate that, whenever possible, drilling in and in close proximity to the core of embankment dams be conducted by experienced Reclamation personnel. Schedule, budget, and other issues should be considered secondary to the safety and integrity of the structure and those potentially impacted by its compromise.

In emergency or other instances when experienced Reclamation personnel are not an option and consequences are expected to be severe if the program is delayed, the following requirements must be met:

- **Employee Experience –** Persons other than Reclamation employees must provide documented evidence that the lead driller, the one pulling the levers, has a minimum of 5 years previous experience drilling in embankment dams within the previous 10-year period. The documentation also should include a copy of their driller's license and references from previous customers.

- **Familiarity with Equipment –** Persons other than Reclamation employees must provide documented evidence that the lead driller is very experienced with the drilling equipment and methods to be employed in the program.

- **Familiarity with Guidelines –** Persons other than Reclamation employees must provide signed documentation that they have read and understand these guidelines.

- **Reclamation Oversight –** In all instances, a Reclamation employee familiar with the potential drilling methods described in the program plan will have site supervision of the entire drilling program. Site supervision will include prior approval of drilling methods, pressures used, or other issues that may increase the risk of structural damage as a result of the drilling program. Additionally, site supervision includes the ability to dictate changes to or termination of the drilling program.

V. Drilling Methods

There are numerous drilling methods available to perform geotechnical investigations. The American Society of Testing and Materials (ASTM D6286) provides a comprehensive guide for drilling methods and groups individual practices for eight drilling methods [5]. Other good texts on drilling include Reclamations *Earth Manual, Part I, Third Edition,* Chapter 2 [6], the *Australian Drilling Manual* [7], and the *National Drill Association Drilling Manual* [8]. Details of these drilling methods are not discussed in-depth in this guide.

Nine major drilling methods are listed with a brief discussion regarding use. Table 1 provides a quick reference to each method discussed. All of the drilling methods that use air or fluid media have potential to hydraulically fracture. Air drilling methods use high pressures and are well known for causing fracturing with air traveling long distances. Therefore, drilling with air as the drilling medium should never be considered when there is potential to encounter the core of an embankment dam.

The drilling methods listed below are in order of preference for use in drilling and sampling in embankment dams. Only the first three are considered preferred methods.

1. **Hollow-Stem Auger** – Auguring is a preferred method of drilling in the core and most other areas of an embankment dam without restriction. Blowout prevention measures, such as sealable surface casing, should be used prior to advancing augers in lower areas in or near the structure if there is potential to encounter artesian conditions. If no fluid is added to the auger column, it does not pressurize the embankment; and no potential for hydraulic fracturing exists. However, for SPT testing of alluvium, it may be required to add some fluid to stabilize loose sands and gravels. In instances when groundwater is encountered or fluids are added to the process, the auger string should be raised and lowered slowly to avoid pressurization, both negatively and positively, respectively, of any open hole. Using a hollow-stem auger permits sampling in the embankment and allows sampling/testing of the foundation through the auger's hollow-stem which acts as casing. Continuous sampling is described in ASTM D 6151 [5]. Small diameter cores of 3-4 inches in diameter can be taken in 5-foot-lengths using the split inner sampling barrel. High quality, undisturbed samples can be taken with larger diameter HSA (6-inch ID and larger) in acrylic liners that provide samples suitable for laboratory testing. The procedure for undisturbed sampling is addressed in detail in Reclamation’s *Earth Manual, Part II, Third Edition, USBR 7105*. Reclamation routinely determines “average tube densities” of these liner samples.

2. **Sonic Drilling –** Sonic (vibratory) drilling is a preferred method of drilling in the core and other areas of embankment dams. This method uses a double casing system and vibrating drill head to set up standing waves or resonance to the drill steel to advance the boring. The method is described in ASTM D6914 [9]. This method of drilling is favored due to its lack of drill fluid and rapid speed of drilling. The drilling process first advances a core barrel. The core barrel is removed, and the sample is extruded while the outer casing is then advanced to the end of the sampling run. There are no cuttings generated, and there is some compaction of soil around the annulus of the drill. Crowd-in and crowd-out bits are used depending on the formation. Some water is required for dry cohesive formations to lubricate the drill stem. The cores, typically 4-5 inch in diameter, are useful for lithology determination and samples may be adequate for standard engineering properties laboratory analysis, but does not meet criteria for many laboratory tests requiring undisturbed samples. Drill production can be 100-150 feet per-day [10]. Many of the drill rigs are easily converted to other drill methods, such as fluid rotary. The sonic drill is especially useful for remediation of seepage problems as the drill stem can be set with packers for grouting.

3. **Cable Tool or Churn Drilling** (ASTM D 5783 [11]) **–** Cable tool or churn drilling, with minor restriction, is a preferred method of drilling in embankment dams. This is an older method of drilling that is infrequently used. Drill action is by up and down movement of the drill string and jars (bit). Water is added to the hole to mix the cuttings into slurry. A sampler can be dropped into the bottom of the hole to take disturbed samples (cuttings). This method of drilling is rated high in desirability because it does not use a full column of drilling fluid and, therefore, has low potential for fracturing. Drilling speed is fairly comparable to HSA drilling. One variation of this "chop and drive" technique requires circulation of water and cuttings continuously to the surface and should not be used in the core of an embankment dam.

4. **Dual Rotation Drilling** (ASTM D 5781 [12]) **–** Dual rotation drilling is not a preferred method for drilling in embankment dams, and its use in embankment core material must be approved by the exploration team prior to use. In all cases, use of clear water or air as a drilling medium is not allowed in embankment core material. Fluid pump pressure must remain low and pressures carefully monitored when this method is used in or near the embankment core. When starting circulation, pumping should be increased gradually to reduce the occurrence and increase the ability to observe evidence of hydraulic fracturing. A pressure relief valve set to the maximum allowable pressure is recommended. The dual rotary drilling method advances both the casing and the drill string/bit separately. The upper and lower rotary drives feed independently by use of separate hydraulic cylinders. Distances between the bit tip and casing shoe are adjustable. With the bit advancing ahead of the shoe, drilling becomes more aggressive. These bit to shoe relationships allow the pressurized drilling medium to come in contact with the unprotected hole wall, and potential for hydraulic fracturing increases. When drilling in embankment core material, the bit should not be advanced significantly ahead of the shoe. Instances when the bit advances ahead of the shoe should be recorded on the daily drill report and, subsequently, geologic log for future reference. The advancing of the casing shoe ahead of the bit is preferred.

5. **Fluid Rotary Drilling** (ASTM D 5783 [13]) – Fluid rotary drilling is not a preferred method for drilling in embankment dams, and its use in embankment core material must be approved by the exploration team prior to use. In all cases, use of clear water as a drilling medium should not be allowed in embankment core material. Fluid pressure must be very low and carefully monitored when this method is used in or near the embankment core. When starting circulation, pumping should be increased gradually to reduce the occurrence and increase the ability to

observe evidence of hydraulic fracturing. A pressure relief valve set to the maximum allowable pressure is recommended. This drilling method uses a rotary cutting bit with circulation of water or drilling mud (bentonite or polymer). Cuttings are returned to the surface and dropped in settling tanks. Ideal bentonite drill mud mixtures do not exceed 72 lb/ft and have 60- to 70-second marsh funnel viscosities. Casing is often advanced with the boring. Sampling and SPT testing can be performed in the boring at required intervals. Fluid rotary is the preferred method for SPT testing for liquefaction, where it is recommended to keep the hole full of fluid during the test to stabilize sands. Since drilling fluid is being used, this method has a high potential for hydraulic fracturing.

6. **Becker Drilling/Penetration Testing –** Becker drilling is not a preferred method for drilling in embankment dams, and its use in embankment core material must be approved by the exploration team prior to use. Becker drilling may be one of two methods. The closed bit system advances a closed bit by means of hammering with a double acting diesel hammer. This method frequently is used in coarser grained material where SPT data likely would be invalid. The open bit method advances an open bit by using of the double acting diesel hammer. In this method, disturbed samples may be collected. High-pressure air is forced down the outer annulus of the dual casing system and returned up the inner casing. The returning air carries soil cutting up to the ground surface. Open bit Becker drilling is prohibited when drilling in or near the core section of an embankment dam.

7. **Wire Line and Casing Advancer** (ASTM D 5876 [14]) **–** Wire line and casing advancer systems are not preferred methods for drilling in embankment dams, and their use in embankment core material must be approved by the exploration team prior to use. These drilling systems use fluid rotary action with the exception that the fluid flows up the annulus between the rods and the hole wall. In all cases, use of clear water as a drilling medium should not be allowed in embankment core material. Fluid pressure must be very low and carefully monitored when this method is used in or near the embankment core. When starting or restarting circulation, pumping should be increased gradually to reduce the occurrence and increase the ability to observe evidence of hydraulic fracturing. A pressure relief valve set to the maximum allowable pressure is recommended. Since fluid is circulated up the annulus between the soil and drill rod, there is increased chance of blocking circulation and possible fracturing. The drill rods act as casing and are equipped with a cutting bit. Either a core barrel or cleanout bit lock into the lead section of the drill rods and is latched by wire line. This results in rapid drilling and reduced

rod trip time during coring operations. Some wire line drilling systems have soil core barrels, but their success is limited. Wire line diamond drilling is the primary method of rock core drilling (ASTM D 2113 on Diamond Drilling [15]). Reclamation does extensive rock coring and water testing with these systems. Typically, augers, casing, or other methods are used to set a protective casing through the embankment and foundation soils; and then fluid rotary drilling is used to core and water test the foundation rock.

8. **Drill Through/Drive Casing Advancer** (ASTM D 5872 [16]) Drill through/drive casing advancers are not preferred methods for drilling in embankment dams and their use in embankment core material should not be considered. The drills have a casing driver (hammer) and a rotary rock bit or down hole hammer that may be rotated through the casing hammer. Down The Hole hammers (DTH) and air are used in coarse boulders deposits and hard rock while rock bits and fluids might be used in dirtier gravel cobble soils. One version of DTH, known as ODEX, has a swing out bit which reams the hole for the casing. Air flow to circulate cuttings has to be rather high, but can be reduced by introduction of foam. To minimize fracturing when drilling with air, the drill bit should be held just inside the casing so a protective seal remains at the bottom of the casing. This practice is not possible when using ODEX, which requires the bit to advance before the casing.

9. **Air Rotary** (ASTM D 5782 [17]) - Air rotary is not a preferred method for drilling in embankment dams; and its use should not be considered in embankment core material. This class of drilling is very similar to drill through drive casing systems except the hole may be left open (uncased) exposing the complete borehole wall to air flow. Without the protection casing provides, the possibility exists for circulation blockage and possible fracturing. One example of this type is the air track drill.

Table 1. – Driling in Embankment Dams – Drilling Methods

<table>
<tr><th></th><th>Drilling Methods</th><th>Restriction</th><th>Recommendations</th></tr>
<tr><td rowspan="3">Preferred Drilling Methods</td><td>Auger</td><td rowspan="2">None</td><td>Raise and lower auger string slowly when fluid in hole</td></tr>
<tr><td>Sonic/Vibratory</td><td>Core not suitable for higher level laboratory testing</td></tr>
<tr><td>Cable Tool/Churn</td><td>Chop and drive variation not allowed</td><td>Samples are of cuttings and are highly disturbed</td></tr>
</table>

Table 1. – Driling in Embankment Dams – Drilling Methods (continued)

<table>
<tr><th></th><th>Drilling Methods</th><th>Restriction</th><th>Recommendations</th></tr>
<tr><td rowspan="4">Restricted Drilling Methods</td><td>Dual Rotation</td><td rowspan="4">Approval of exploration team required

Clear water as drilling media not allowed

Fluid pressure must be very low

Bit must not be advanced beyond shoe

Open bit methods are not allowed</td><td rowspan="4">Monitor fluid pressure closely

Use pressure relief valves to cap fluid pressure

Increase pump pressure gradually

Monitor fluid viscosity closely</td></tr>
<tr><td>Fluid Rotary</td></tr>
<tr><td>Becker</td></tr>
<tr><td>Wireline/Casing Advancers</td></tr>
<tr><td rowspan="2">Prohibited Drilling Methods</td><td>Drill Through/Drive Casing Advancers</td><td rowspan="2">Not allowed in or near core of embankment dams</td><td rowspan="2">Not allowed in or near core of embankment dams</td></tr>
<tr><td>Air Rotary</td></tr>
</table>

VI. Drilling Practices

Drilling personnel are responsible for controlling and monitoring drill media pressure, drill media circulation loss, and penetration rate to assure that the drilling operation minimizes the possibility for hydraulic fracturing. All drilling should be accompanied by a field geologist or engineer responsible for EAP, Health and Safety Plan's (HASP), and any emergency contacts required.

If a sudden loss of drill media occurs during any embankment drilling within the core, drilling should be stopped immediately. Action should be taken to stop the loss of drill fluid. The reason for loss should be determined; and if hydraulic fracturing may have been the reason for the fluid loss, the regional office and the Technical Service Center (TSC) principal designer and principal geologist should be notified immediately.

Any drilling into the impervious core of an embankment dam should be performed by experienced drill crews that employ methods and procedures that minimize the potential for hydraulic fracturing. It is essential that drillers be well-trained and aware of the causes of and the problems resulting from hydraulic fracturing. Below is a listing of drilling considerations:

- Auguring, churn drilling, or sonic drilling should be used whenever possible.
- When media circulation is required, a pressure controlled release ("pop off") valve should be on the pump.
- Constantly monitor media return.
- The bit diameter should be of a design that pressure buildup does not occur.
- Great care should be taken during washing of the hole.
- Add and withdraw drill tools slowly to avoid pressure changes in the drill hole.
- Casing should be pushed or driven and not jetted.
- Drilling feed rate must be slow enough to avoid crowding the bit and, thus, minimize the chance of inducing fracturing.
- Casing must precede the drilling.
- Constant inspection/monitoring of the drilling operation is required.

Certain embankment locations and conditions have a higher potential for hydraulic fracturing, and improper drilling procedures or methods will increase the potential for fracturing. Site locations and conditions where fracturing by drilling media are most likely to occur and has the highest risk of damaging the structure include the following:

- In or near cutoff trenches or cutoff walls (Figures 1 and 2).
- Near structures or conduits within embankments (Figure 2).
- Impervious Zone 1 core with slopes steeper than 0.5H:1V (Figure 3).
- Thin Zone 1 core (Figure 3).
- Upstream inclined Zone 1 core (Figure 3).
- Near abutments where abrupt changes in slopes (shoulders) occur (Figures 1 and 7).

- In areas where the embankment is subject to transverse differential settlement due to large changes in thickness of compressible foundation soils (Figures 2, 5, 6, and 7).
- Near abutments steeper than O.5H:1V (Figure 8).
- Impervious zones consisting of silt and mixtures of fine sand and silt (e.g., low plasticity soils that are more easily fractured).
- Drilling in or through grout curtains.
- Near areas softened or weakened by seepage.
- In locations in compacted fill of known defects.

Drill holes in embankments always require sealing after completion. In addition to hydraulic fracturing, fluid rotary drilling also can pose a contamination risk for internal drainage features if the drill fluid or sealing grout can migrate into the drain materials. Avoid drilling near drains or seepage blankets that could be contaminated by fluids. If a drain must be penetrated, special provisions should be taken to prevent contamination, and special provisions might be required for borehole sealing.

Remediation drilling activities are often overlooked as opposed to drilling that occurs under the Field Exploration Request (FER) process. There are numerous examples of Reclamation dams which required remediation after filling, and the embankment or foundation was damaged (Fontenelle). Many of these dams required remedial grouting immediately after construction, and the grouting contractor used air drilling, rapidly resulting in fracturing of blankets and foundations. Jet grouting contractors drill holes with very high air/fluid pressures at rapid rates. Contractors want to drill fast, but drilling fast may cause blockage and loss of the circulating fluid and hydraulic fracturing. It is imperative that, for remediation construction projects,and instrumentation installation contracts, project geologists and engineers identify drilling methods and confirm they are appropriately screened to avoid damage to the dam or foundation. If there is concern, a team should be formed to review the drilling methods and ensure the contract documents have appropriate provisions to avoid damage to the dam and foundation.

VII. Hole Completion

A. General

All boreholes in and around embankment dams will be sealed after completion. Completing a borehole by backfilling with drill cuttings is not acceptable. There are a variety of acceptable methods to complete a borehole in an embankment dam. Hole completion is often not given the consideration it deserves, and many times are not well documented. Recommended inclusions in borehole completion documentation include intervals of various backfilling material, calculated volume of material necessary to fill each interval, and actual volume of material required to fill each interval. Detailed records of borehole completion are vital and, as in the case of backfill material volumes significantly higher or lower than calculated, may be indicatative of conditions significantly different than anticipated. *Recommended Guidelines for Sealing Geotechnical Explorations Holes, Report 178* is a good source for borehole backfill guidelines [18].

B. High Solids Bentonite Grout

Tremmie grouting with high solids bentonite is an acceptable method of completing boreholes in embankment dams. Mixes which yield 20 to 30% solids should be used. Stage up tremmie grouting methods should be used in the embankment core with the casing (i.e. hollow-stem augers, rods, etc) pulled incrementally to insure hole wall stability. The bentonite slurry should always be injected through a tremie pipe to ensure the best possible placement and most thorough borehole completion.

C. Neat Cement Grout

Neat cement grout is another acceptable method of completing boreholes in embankment dams. The best results are achieved when the mix consists of 5-7 gallons of water to one sack, 94 lbs of Type I or Type II Portland cement (using higher water contents may result in excessive shrinkage, cracking, and bleed water). The addition of up to 3% powdered bentonite by dry mass of cement is recommended for pumping ease and to reduce shrinkage and cracking after curing. As with the bentonite grout, stage up tremmie grouting methods should be used in the embankment core with the casing pulled incrementally to ensure hole wall stability. The grout should always be injected through a tremie pipe to ensure the best possible placement and most thorough borehole completion. Additives such as calcium chloride or carboxylic acid can be used to control set times, but shrinkage factor must be considered. Using type K cement or adding up to

1% gypsum or aluminum powder will give the cement expansive properties, which may be advantageous in embankment dams where internal seepage is an issue.

D. Bentonite Pellets or Chips

The use of bentonite pellets or chips may be an acceptable method of completing boreholes in embankment dams. However, there are some conditions under which bentonite bellets or chips should not be considered and only tremmie grouting is acceptable. Bentonite pellets or chips, including those treated to retard or delay flocculation, should not be used in cases where there is a chance the depth of water in the hole could slow the bentonite fall and allow flocculation prior to the bentonite reaching hole bottom. Additionally, even in a dry hole, there must be adequate annular space available to allow the bentonite to fall to the hole bottom without bridging. It is advisable to always place both solid bentonite and grout through a tremmie pipe.

Instrumentation installations require special completions. For piezometers sand packs are placed in the influence zone, and a bentonite seal is placed above the sand pack to prevent any contamination of the sand pack from sealing materials placed above it. The bentonite seal is typically bentonite pellets. A common error in placing the seal is not allowing bentonite time to hydrate. Pellets should be allowed 1-2 hours to hydrate prior to placing the seal. Reclamation typically uses small diameter (1-inch) porous tube piezometers. While it is possible to place two piezometers in a typical 4-inch inside diameter HSA or casing, only one piezometer is recommended, and no more than two instruments should be allowed in a single boring. Difficulty in providing a good seal between multiple riser pipes may result in communication between influence zones.

E. Geophysical Cross Hole Shear-Wave

After drilling is completed, the borings should be cased with 4-inch ID schedule-40 polyvinyl chloride (PVC) pipe (flush joint). Before inserting the 4-inch PVC pipe, the bottom of the pipe is closed with either a cap or should have a one-way ball-check capable of accommodating $1^1/_2$-inch (3.81 cm) OD grout pipe. The 4-inch PVC casing is filled with water and then grouted in place for the entire length of the borehole by inserting a $1^1/_2$-inch (3.81 cm) pipe through the center of the casing contacting the one-way valve fixed to the end cap or by a small diameter grout tube inserted to the bottom of the borehole between the casing and the borehole sidewall. The portion of the boring that penetrates rock should be grouted with a conventional Portland cement that will harden to a density of about 140 lb/ft^3 (2.34 g/cm^3). The portion of the boring in contact with embankment materials, soils, sands, or gravels is grouted with a mixture that minimizes grout penetration into the surrounding medium and yet achieves a good bond between the outside of the casing and the unconsolidated materials. Pump the grout using a conventional, circulating pump capable of moving the grout through the grout pipe to the bottom of the casing upward from the bottom of the borehole. Using this procedure, the annular space between the sidewall of the borehole and the casing will be filled from bottom to top. Water or mud and debris should be displaced with minimum sidewall disturbance resulting in good sidewall casing contact.

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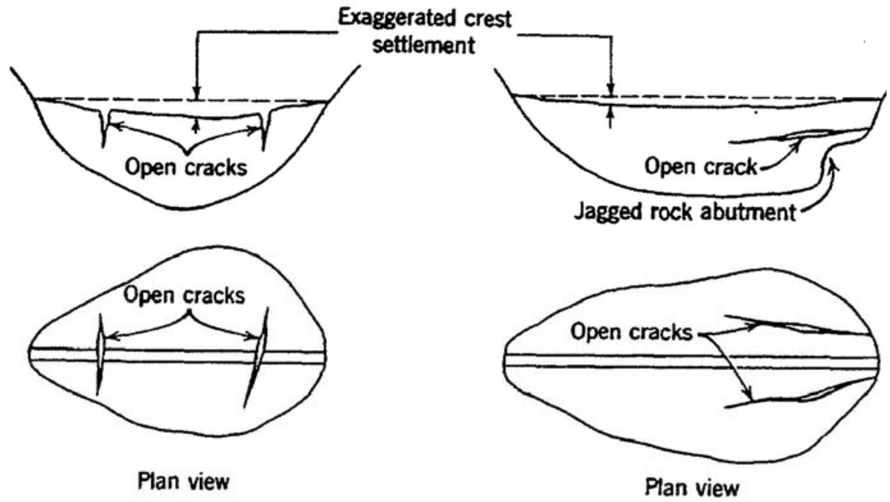


Figure 1A. – Typical transverse differential settlement cracks

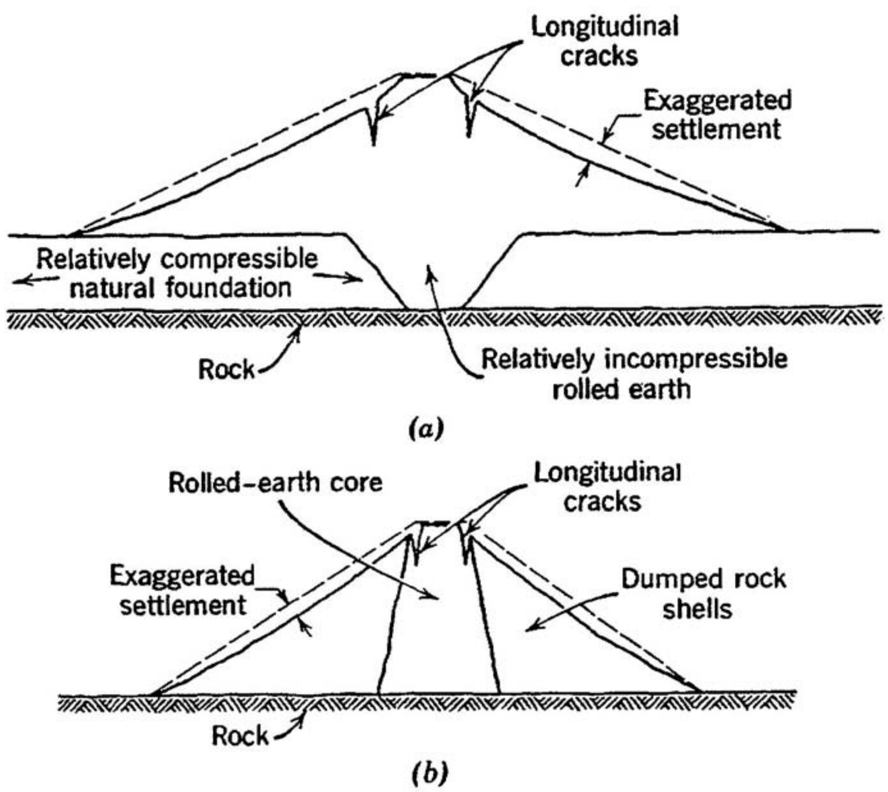


Figure 1B. – Longitudinal cracks. (a) Cracking caused by differential foundation settlement. (b) Cracking caused by differential settlement between embankment sections of dumped rock and rolled earth.

Figure 1. – Examples of Dam Cracking.

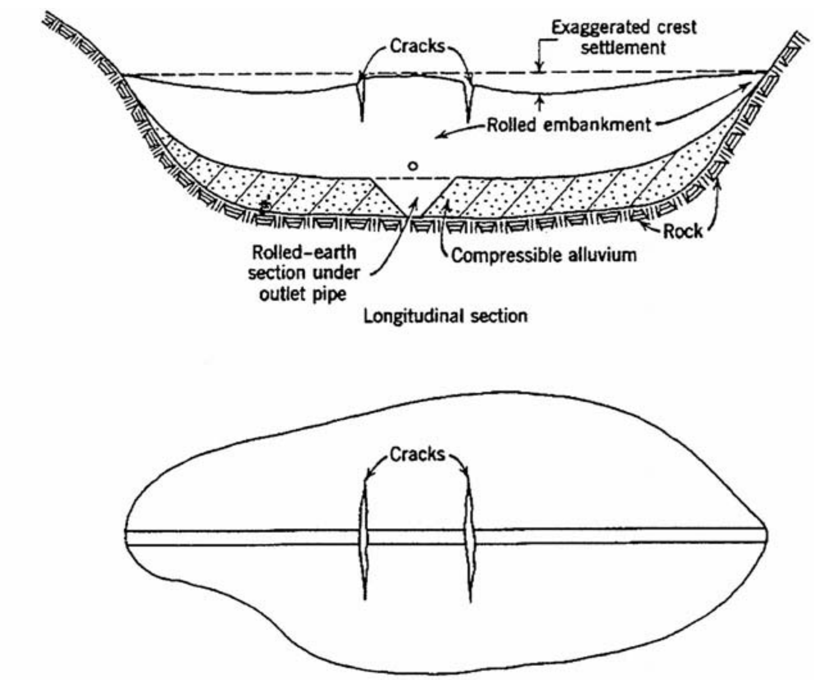


Figure 2A. – Cracking due to differential settlement between natural foundation soil and rolled-earth support under outlet pipe (or other discontinuity in the foundation).

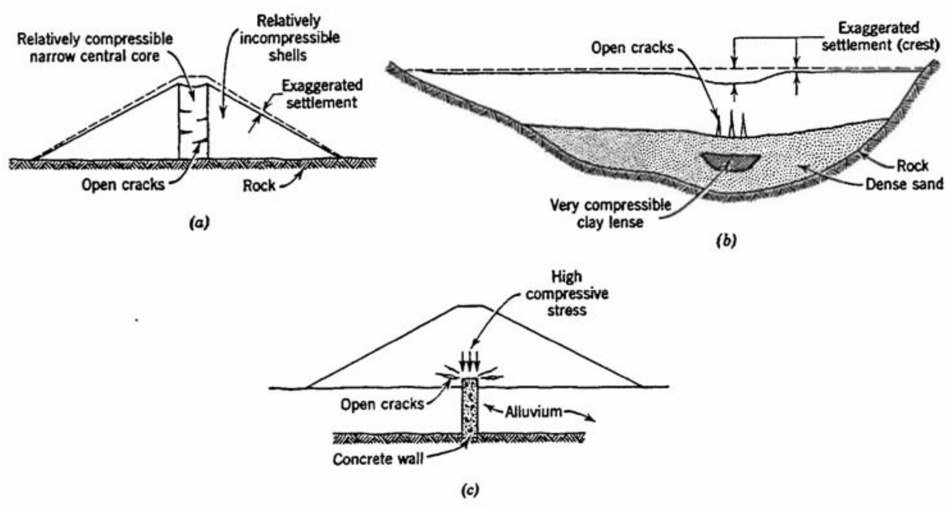
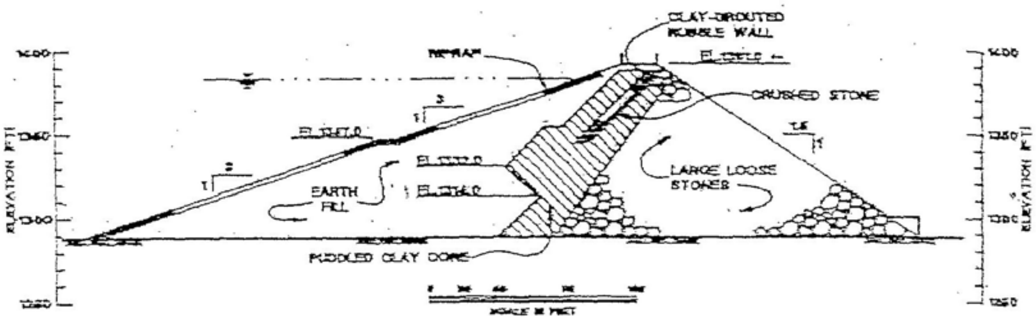


Figure 2B. – Internal embankment cracking.

Figure 2. – Additional Examples of Dam Cracking.



Archives Cross Section of Elmer Thomas Dam

Figure 3. – Example of a Dam with Thin Inclined Impervious Core – An Actual Drilling Incident Occurred on This Dam (France ASDSO).

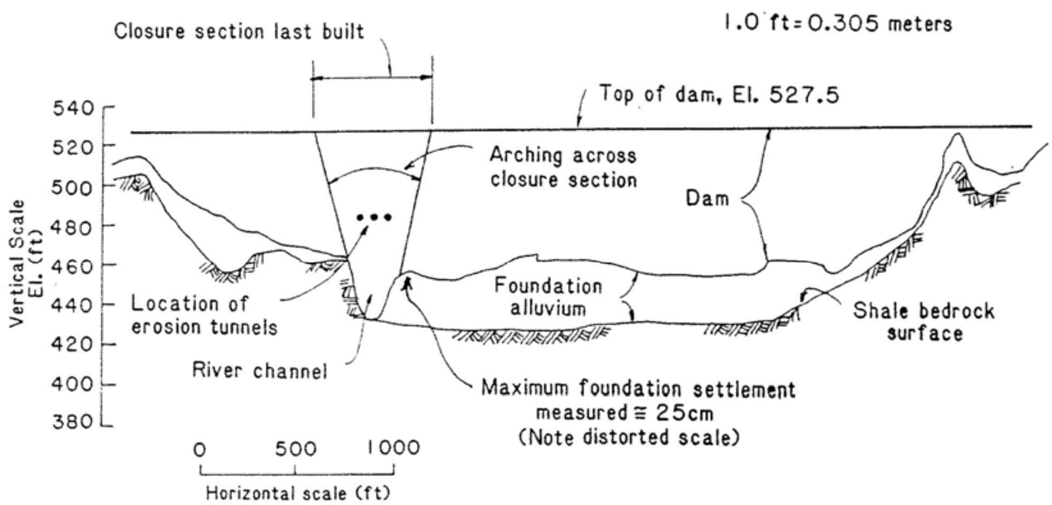


Figure 4. – Examples of Cracking Along a River Channel (Sherard).

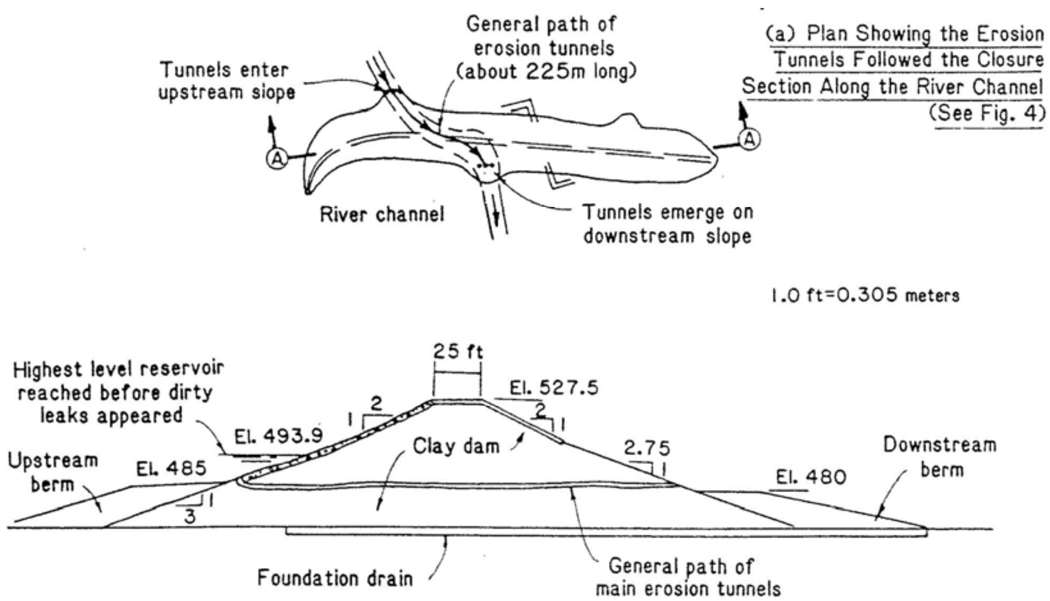


Figure 5. – Example of Dam Cracking Along a River Channel - (Sherard).

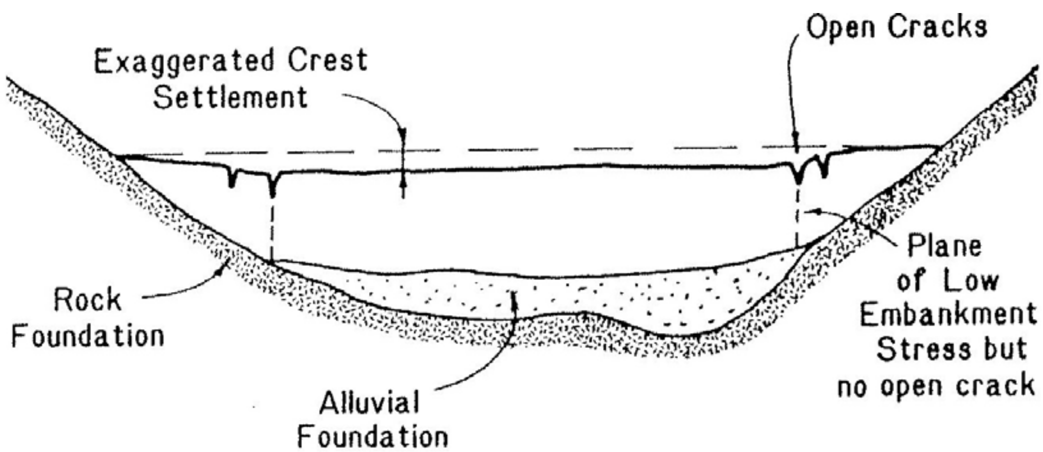
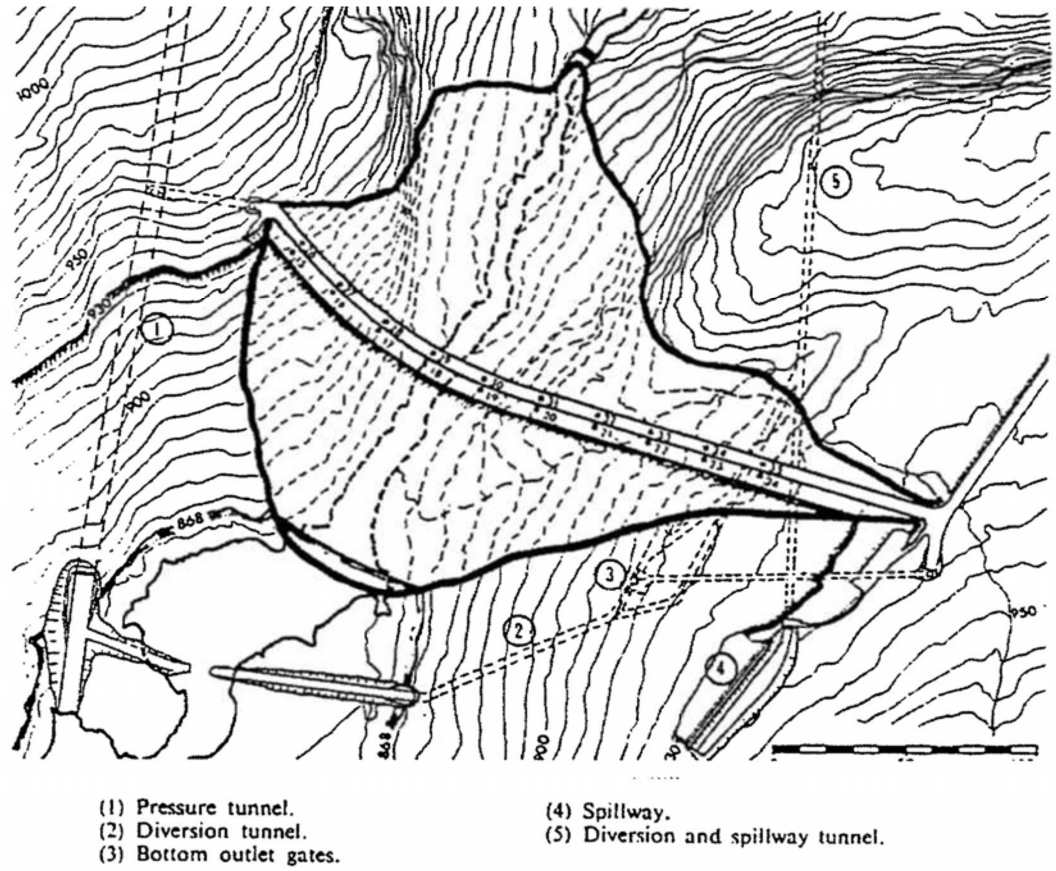
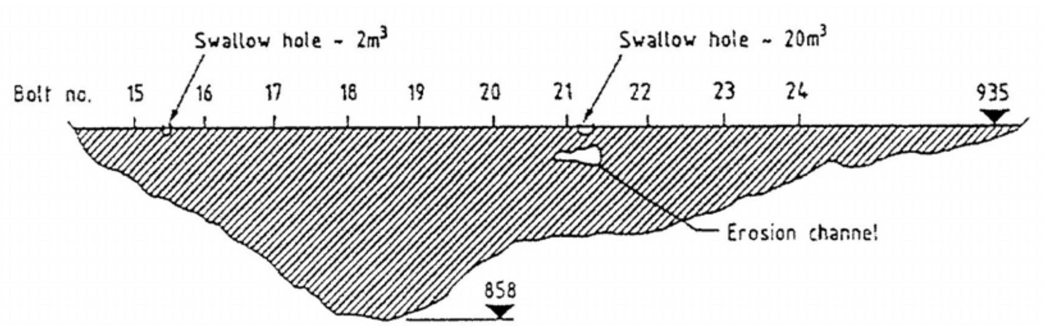


Figure 6. – Example of Dam Cracking from Differential Settlement (Sherard).



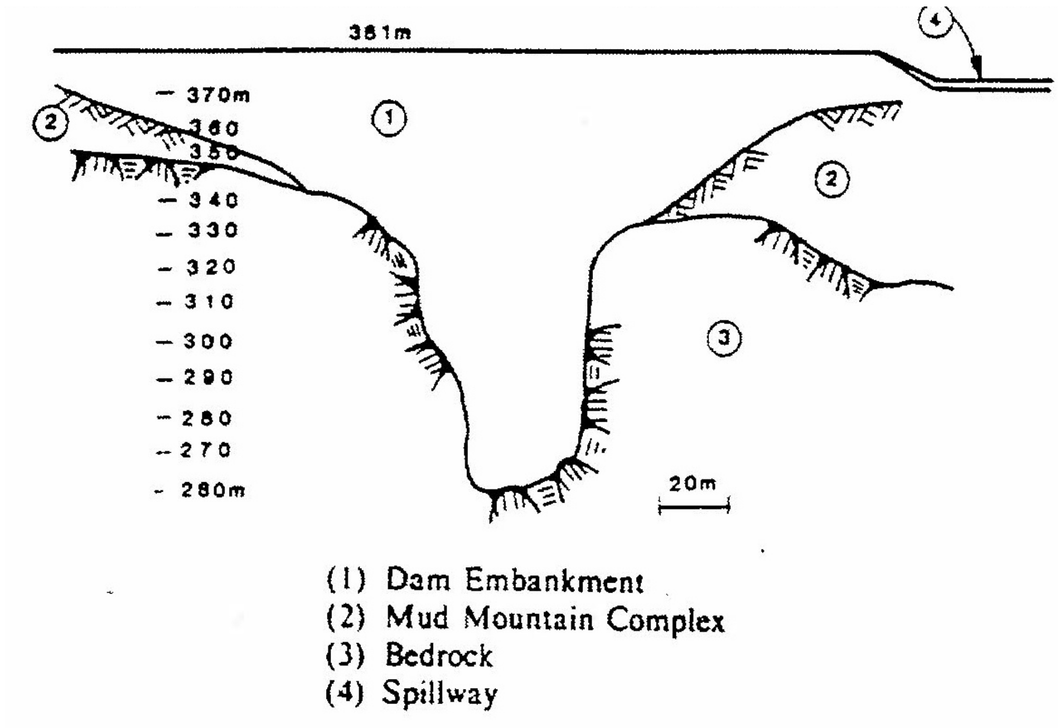
(a) Plan



(b) Valley cross section

Details of Viddalsvatn Dam (vested, 1976; and Kjaernsli, et al.)

Figure 7. – Example of a Dam with Cracking Due to Rock Knob – This Dam Had an Actual Piping Incident (Fell).



Mud Mountain Dan – Valley cross section (Graybeal 1988).

Figure 8. – Extreme Examples of a Dam with Steep, Almost Vertical Abutments – 1 Million Gallons of Slurry Were Lost in a Slurry Wall Failure (Fell).