Federal Energy Regulatory Commission
Division of Dam Safety and Inspections

GUIDELINES FOR DRILLING
IN AND NEAR EMBANKMENT DAMS
AND THEIR FOUNDATIONS

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1.0 INTRODUCTION/PURPOSE

1.1 Objective

The primary purpose of this document is to provide guidance for drilling in and near embankment dams and their foundations. Of special emphasis is the prevention of damage to the embankment, structures, and their foundations from hydraulic fracturing, heave, erosion, filter/drain contamination, or other mechanisms during drilling-related activities.

The need for any investigation (drilling, testing, etc.) at a dam site should have been presented to and accepted by FERC prior to developing an investigation program requiring drilling activities in or adjacent to a dam. In addition, it should have been demonstrated that any potential damage to the structure created by the drilling and associated processes is outweighed by the need for the drilling data. It is not the purpose of this document to provide an all-inclusive guidance or best practices on considerations for the development of a subsurface exploration or investigation program for a dam.

A guiding principle inherent in any potential dam investigation or testing is DO NO HARM. In developing investigation plans it is important to identify the potential risks and develop and implement plans to mitigate, manage, or avoid those risks.

These guidelines are appropriate for FERC-regulated embankment dam or other earthen water retaining structures (levee, canal embankment, etc.) – any earthen structure that's responsible for holding back water or serves to provide direct support to the feature or element that is holding back the water, including its foundation.

Much of the information in Sections 3.0 and 4.0 of these guidelines have been taken from or modified from the following documents:

1. U.S. Army Corps of Engineers, "Drilling in Earth Embankments and Levees", ER 1110-1-1807, Washington, DC, December 31, 2014.

2. Bureau of Reclamation, "Guidelines for Drilling and Sampling in Embankment Dams", Denver, CO, August 2010.

1.2 Scope

Much of the information contained in this guideline has principles and applications to other forms and purposes of investigation, maintenance, construction, modification, or other activity that physically penetrates the dam or foundation, including:

- Test pits/trenches
- Drilling holes/borings and probes

- Dynamic loads/pulses/blasts
- Excavations, including grading/regrading and foundation installations/construction
- Utility installation, including buried conduits, utility vaults, utility poles, etc.
- Concrete removal/demolition
- Drain and relief well cleaning/maintenance
- Toe drain/drainage feature modifications/repair
- Penetrations, including conduits, horizontal drilling activities, etc.
- Grouting or other pressure injection/testing activities
- Removal of large vegetation, trees, and root balls

These apply to any area subject to seepage pressures, stability influences or have the potential to cause harm to the water retaining structure or its foundation.

2.0 BACKGROUND

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 (use of inappropriate drilling methods), improper in-situ sampling techniques, and/or unacceptable methods of completing (backfilling) borings can open seepage paths which could create conditions conducive to internal erosion (piping) and ultimately dam failure. Although not particularly well documented, there are a number of case histories that have highlighted the potential dangers that can happen as the result of improper planning, using improper drilling methods in dams, not having the appropriate drilling equipment and contingency plans, not having knowledgeable field staff present on-site during the drilling operations, and other factors (France, 2002).

There is also some not well publicized guidance on precautions in developing investigation programs, precautions on appropriate drilling methods, and other ‘rules of thumb’ that are important to consider and others that should be avoided.

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 are only 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 and geotextiles at or near the site 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.

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 at times it is preferable 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 the density of the soil. 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.

In 2000, a FEMA-sponsored workshop was convened with a group of experts with respect to dam safety issues associated with seepage through embankments and their foundations (FEMA, 2000). As part of that workshop, the participants offered the following recommendations relative to the investigation and monitoring of seepage problems and concerns:

- Although actual investigation practices vary widely, it was the consensus of the workshop participants that the recommended state-of-the-practice should be that drilling should not be done in the core of an existing embankment dam unless absolutely necessary, and then only with carefully planned precautions and dry drilling (e.g., auger) methods. The risk of hydraulic fracturing is too great to support drilling in the core without appropriate justification.

- It was the consensus of the workshop participants that drilling or test pitting should not be done at the downstream toe of a dam with water stored in the reservoir, without contingency plans and stockpiling of weighted filter materials (e.g., sand and gravel) to be used in the event of a seepage incident. It is also essential that such explorations be completed with the on-site presence of experienced personnel with the knowledge to react appropriately to any seepage incidents that may occur.

- It was the consensus of the workshop participants that they generally advised against installing piezometers in an embankment core, unless there were very compelling reasons for the instruments. The workshop participants felt that, in most cases, piezometers in the core do not provide significant additional understanding of the performance of the dam beyond that which can be obtained from piezometers in the upstream and downstream shells, which are much safer locations for the instruments.

- Piezometers are tools whose careful installation and subsequent data interpretation, in conjunction with other investigative techniques, may provide valuable information in diagnosing seepage conditions. However, the limitations of what the piezometers record must be recognized, and the piezometer data must be used in conjunction with other information (e.g., seepage rates, seepage locations, etc.) to correctly diagnose seepage conditions. Since piping channels in embankments are often relatively long, narrow features, it is highly unlikely that piezometers will be located at exactly the correct locations to provide direct data regarding the piping phenomenon.

3.0 PLANNING/PROJECT INFORMATION

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. A determination of potential consequences if no action is taken should be made. These consequences should include both risk and likelihood for worsening conditions, which could drive up future cost of remediation if required. When and where 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 engineers, geologists, and others with the requisite knowledge and experience in planning and conducting field exploration programs for dams. 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. 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
- Owner and FERC project files
- Supporting Technical Information (STI) document
- Current and past consultant files
- Records of design and construction, including photographs
- Archived records
- Project records at field offices 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
- Location of any seepage cutoff walls, blankets and drainage features and pipes
- Dam foundation geometry and drilling hazards
- Instrumentation and completion requirements

The investigation may also 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).

4.0 DRILLING ACTIVITIES

4.1 General

Drilling into, in close proximity to, or through dams and their foundations may pose significant risk to the structures. Water, compressed air, and various drilling fluids have been used as circulating media while drilling through dams and their foundations. Although these methods have been successful in accomplishing the intended purposes, there have been incidents of damage to embankments and foundations (Sherard, 1973). While using air (including air with foam), there have been reports of loss of circulation with pneumatic fracturing of the embankment as evidenced by connections to other borings and blowouts on embankment slopes. While using water and drilling mud as the circulating medium, there have been similar reports of erosion and/or hydraulic fracturing of the embankment or foundation materials. Conversely, there have been cases where heave, borehole collapse, and significant disturbance have occurred while drilling in granular materials below the groundwater level. This typically has been the result of not using a proper drilling fluid to balance the water pressures in the soil or using high energy systems that induce heave in order to evacuate the cuttings. There is a delicate balance between too much induced fluid pressure that will cause hydraulic fracture and not enough fluid pressure that will result in borehole instability, heave, or significant sample disturbance. Other potential damaging effects include: creating preferential seepage paths due to improper backfilling, inadequate protection of embankment from drilling fluids during foundation rock coring, erosion and widening of cracks, and inadvertently clogging filters or drains with drilling fluid or grout.

All drilling and associated activities that use fluid or other circulation or stabilization media need to be evaluated for the potential to hydraulically fracture the embankment or foundation. These activities include but are not limited to the use of drilling fluids, backfilling borings after completion, backfill grouting of instrumentation, backfill grouting of casings, water testing for permeability, piezometer rehabilitation, etc. The risk will vary with the selected methods and the site conditions. Every drilling operation must be well thought out and must have benefits of successful completion that confidently outweigh the risk of potential negative impacts.

4.2 Drilling Hazards

The following is a brief discussion of some common drilling hazards that must be considered, evaluated, and mitigated for in developing and implementing an exploration program.

4.2.1 Hydraulic Fracturing

Excessive pressures from water, air, drilling fluid, or grout can fracture embankment and foundation materials. Hydraulic fracturing problems have occurred while drilling in embankments as evidenced by reports of loss of fluid circulation, blowouts into nearby borings, seepage of drilling fluids on the face of the embankment, and other similar situations. Hydraulic fracture can occur in both cohesive materials and cohesionless materials, and bedrock. It has been found that in soils, hydraulic fracturing can occur when the borehole pressure exceeds the lowest total confining stress (minimum principal stress, $\sigma 3$) plus some additional strength (Sherard, 1986). The additional strength can be approximated by the undrained shear strength of the soil. The minor principal confining stress ($\sigma 3$) in a normally consolidated soil with a level ground condition is typically the horizontal stress, which can be reasonably estimated. However, the minor principal confining stress in and under an embankment is difficult to determine and can vary significantly from idealized geostatic conditions. Effects from the side slope geometry, piezometric surface, abutment configuration, foundation rock geometry, embedded structures, compaction stress, and settlement history all are significant and can influence in-situ stress conditions. Typical drilling methods that use circulation fluids can quickly create induced fluid pressures that exceed the minimum confining stress. This often occurs when the return path for the fluid clogs or blocks off and the induced fluid pressures quickly increase. The use of non-pressurized stabilizing fluids is preferable, yet in some subsurface conditions, hydraulic fracture can occur under gravity pressure. Low stress zones may exist within and under embankments. It is possible for the confining stress in these locations to be much less than the gravity pressure exerted by a drilling fluid or grout.

Certain embankment locations and conditions have a higher potential for hydraulic fracturing due to geometric configurations that create zones of low confining stress. Sherard 1973 and 1986 are good references that provide a comprehensive evaluation of the issues along with numerous case histories. Locations and conditions where hydraulic fracturing by drilling media is more likely to occur and have the higher potential of damaging the structure include the following:

- Near and over steep abutments that create low confining or tensile stress conditions.
- Adjacent to rock overhangs on abutments.
- Adjacent to buried structures or abrupt foundation geometry change that creates a differential settlement condition and a zone of lower soil stress transfer.
- Adjacent to conduits where narrow zones of soil backfill were placed between the structure and rock face.
- Dam cores that can experience more settlement than the adjacent shells.
- Dams in very narrow valleys. Arching keeps full confining stresses from developing.
- Near abutments where abrupt changes in geometry occur.

- In areas where the embankment is subject to differential settlement due to large differences in thickness of adjacent compressible foundation or embankment soils.

Accurately estimating in-situ embankment stresses can be difficult for the conditions listed above. In some cases, it may be helpful to calculate static stresses including seepage forces within the embankment. The results of such computations can aid in evaluating the maximum applied drilling fluid pressures or static grouting head for borehole backfill. However, with any such computation, judgment is required in applying the results.

Additional references on hydraulic fracturing are included in Appendix A.

4.2.2 Artesian Conditions/Blowout

In situations where the presence of higher fluid pressures in the subsurface materials is suspected, either at the ground surface or at depth, it may be necessary to install a surface casing to control artesian pressures if the pressures are anticipated to be significant and/or derived directly from reservoir head. Surface casing of 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. When the static water level is very near the ground surface or artesian conditions prevail, one should consider elevating the drilling rig on a temporary drill berm to raise the drill hole collar elevation. In extreme cases, the berm should consist of filter zones. 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.

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 identified and 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.

4.2.3 Erosion

The introduction of drilling fluids into cracks, either existing or formed by hydraulic fracture, can potentially cause erosion along the crack walls. This will enlarge the crack and could lead to an increased potential for internal erosion. Existing subsurface cracks are common in many dams and are often the result of differential settlement. The locations most at risk for existing cracks are typically the same areas that have low confining stress and have the highest risk for hydraulic fracture to occur.

4.2.4 Contamination of Filter/Drainage Features

In addition to hydraulic fracturing, the use of drilling fluids can pose a contamination risk for internal drainage features if the drill fluid or sealing grout migrates into and clogs the drain or filter materials. Avoid drilling near drains or seepage blankets that may become contaminated by fluids. If drain penetration is justified, special provisions must be taken to prevent contamination. Special provisions may also be required for protecting the drainage features while backfilling the hole (such as placement of filter material through the zone of the drain or filter and installing lower and upper seals).

4.2.5 Heave and Sample Disturbance

Drilling programs that include performing in-situ tests or undisturbed sampling may require the use of drilling fluid to offset the confining stress relieved by the drilling of the hole. There have been cases where the failure to prevent stress relief or heave of granular soils below the water table have led to invalid in-situ test results and subsequently invalid interpretation of the subsurface conditions. This has occurred for both tests performed in drill holes and test performed in casings installed by methods that did not control heave or disturbance.

BOR (1999) contains methods to deal with heaving sands while drilling and performing Standard Penetration Tests. If high quality undisturbed samples of fine grained soils are required for shear strength testing, then drilling mud may be required to prevent the soil from failing in undrained triaxial extension. See Ladd and DeGroot (2004) for a discussion on clay sample disturbance due to drilling.

Prior to embarking on any drilling activity, the exploration team should consider, at a minimum, these potential drilling hazards and develop the drilling plans to avoid or mitigate these hazards. If the hazards cannot be avoided, then the risks must be evaluated and mitigated in the drilling plan.

4.3 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 (ASTM, 2006). Other good texts on drilling include The Bureau of Reclamations Earth Manual, Part I, Third Edition, Chapter 2 (BOR, 1998), the Australian Drilling Manual (ADI, 1992), and the National Drill Association Drilling Manual (NDI, 1990). Details of these drilling methods are not discussed in-depth in this guide.

Nine major drilling methods are briefly discussed below. Table 1 provides a quick reference to each method. All drilling methods that use air or fluid media have the potential to create hydraulically-induced fractures. 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.

All drilling programs in dams should be designed to minimize the need for any drilling fluid such as air, gas, water, mud, polymers, slurries or any other drilling fluid that could pressurize the borehole soils. If the drilling objective can be performed using dry methods such as augers or sonic drilling they should be employed in lieu of methods that require fluids. If drilling fluids must be used due to the drilling objective or the subsurface conditions, the drilling plan must contain an analysis of the potential to cause damage and a plan that covers the measures that will be used to minimize the risk (see Section 4.8 for additional information). The use of pressurized air or foam should only be considered when drilling in materials that will not transmit pressures to the soil core or other critical features or when the air pressure is reliably isolated from the borehole soils. Drilling in an open graded rockfill shell may be an example of when using air may be appropriate. All drilling programs that propose the use of stabilizing or circulating fluids or other media will require an additional level of review.

1. **Hollow-Stem Auger –** Hollow-stem auguring (HSA) 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 areas where 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, 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, 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 D6151 (ASTM, 2008). Small diameter cores of 3 to 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.

2. **Sonic Drilling** ASTM D6914 (ASTM, 2010) **–** 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. 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 (static water, not under pressure) is required for dry cohesive formations to lubricate the drill stem. The cores, typically 4 to 5 inches 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 (Dustman, et al, 1992). Since there

is uncertainty as to the extent of disturbance to the adjacent foundation material from the vibratory drilling process, sonic drilling should not be used if SPT, undisturbed sampling, and certain in-situ testing are required.

3. **Cable Tool or Churn Drilling** ASTM D5783 (ASTM 2000a) – 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). The drill string is regularly pulled and a bucket-grab tool is inserted to remove/sample the cuttings. Water is often added to the hole to mix the cuttings into slurry. SPTs can be completed below the bottom of the casing. 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 employs continuous circulation of water to bring cuttings to the surface and should not be used in the core of an embankment dam.

4. **Dual Rotation Drilling** ASTM D5781 (ASTM 2000b) – Dual rotation drilling is not a preferred method for drilling in embankment dams, and its use in embankment core material must be approved by FERC prior to use. 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 ahead of the shoe. In those instances when the bit advances ahead of the shoe they should be recorded on the daily drill report and, subsequently, geologic log for future reference. 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 required.

5. **Fluid Rotary Drilling** ASTM D5783 (ASTM 2000c) – Fluid rotary drilling is not a preferred method for drilling in embankment dams, and its use in embankment core material must be approved by FERC prior to use. 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; however, higher viscosities may be necessary where artesian conditions are encountered. Casing is often advanced with the boring. 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 maximum allowable pressure is recommended.

Fluid rotary is the preferred method for SPT testing for liquefaction (see ASTM D6066), 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. Raising and lowering drill bits, sampling tools, and drill rods should be done slowly so as not to induce negative fluid pressures or increase fluid pressures.

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 FERC 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 D5876 (ASTM 2000d) – 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 FERC prior to use. These drilling systems use fluid rotary action to remove the cuttings with the exception that the fluid flows up the annulus between the rods and the borehole 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 (see ASTM D2113 on Diamond Drilling (ASTM 1999)). 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 D5872 (ASTM 2000e) - 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 over-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 D5782 (ASTM 2000f) - 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, possible fracturing, and degradation/opening/erosion of any weak seam exposed along the sides of the borehole. One example of this type is the air track drill.

Table 1 – Drilling 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>None</td><td>Raise and lower auger string slowly when fluid in hole</td></tr>
<tr><td>Sonic/Vibratory</td><td>None</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>
<tr><td rowspan="4">Restricted Drilling Methods</td><td>Dual Rotation</td><td rowspan="4">Approval of drilling method 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 the core of embankment dams. Approval of drilling method required for other areas. Will only be considered in extraordinary circumstances</td><td rowspan="2">Not allowed in or near the core of embankment dams. Approval of drilling method required for other areas. Will only be considered in extraordinary circumstances</td></tr>
<tr><td>Air Rotary</td></tr>
</table>

There are some general procedures that should be followed when using drilling fluids to limit the risk of damage:

- Tools should be sized and designed to minimize the likelihood of the return flow clogging.

- Methods that require the cuttings to flow through a small annulus between the tools or casing and the borehole wall should not be used.

- Fluid discharges from the bit should always be upward, not downward into the formation material or lateral into the sidewalls that could lead to excessive disturbance or erosion.

- Lower and raise drill tools slowly to avoid pressure changes in the drill hole; this is especially important when using tools with restricted annulus space below the groundwater as the pressure changes are more severe and can lead to suction and surging problems.

- Drilling feed rate must be slow enough to avoid crowding the bit and, thus, minimize the chance of inducing fracturing. The bit must be of a design such that pressure buildup is minimized.

- Drilling media properties, pressure, and return should be continuously monitored. A floating needle pressure valve is required to record maximum pressure spikes that can occur instantaneously and are often unnoticed.

- When media circulation is required, a pressure controlled release (“pop off”) valve should be on the pump.

- In some conditions, casing can be advanced ahead of the drilling bit to reduce the risk of hydraulic fracturing by confining the drilling fluids within the casing.

- Great care should be taken during washing of the hole.

- Casing should be pushed or driven and not jetted. Except in special circumstances, casing must precede the drilling.

- When core drilling rock, the embankment or foundation soil above top of rock must be protected and isolated from the circulating drilling fluid. Fractures in the bedrock must be considered as potential flow paths in contact with the overlying soil.

- A pause or suspension in drilling operations (breaks, meals, overnight/weekend, etc.) should not leave the borehole in a critical state that could result in damage to the embankment.

4.4 In-Situ Testing/Sampling

The actual process of advancing the boring is not the only potential hazard that can lead to hydraulic fracturing and other adverse impacts of the drilling, sampling, disturbance, and performance of the structure. Raising and lowering drill rods, casing, or other drill steel too quickly can induce significant positive or negative fluid pressures.

In-situ testing that includes applying hydraulic pressures through static head (falling head or constant head permeability tests) or pressure induced head (packer pressure tests, etc.) can result in excessive hydraulic pressures that could lead to hydraulic fracturing. In-situ testing and sampling methods and procedures must be aware of the potential to create these conditions. The Bureau of Reclamations' *Engineering Geology Field Manual* is an excellent reference to assist in determining applied and total hydraulic fluid pressures from in situ tests (BOR, 1998).

4.5 Hole Completion

All boreholes and other penetrations (including direct push sampling, Cone Penetration Test soundings, Standard Penetration Testing, Becker Penetration Testing, etc.) in and around embankment dams must 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.

All boreholes and similar penetrations in the impervious portions of an embankment dam and their foundations must be backfilled by tremie-placed cement-bentonite grout or bentonite pellets/chips, except when an alternative backfill method compatible with instrument installation is approved. The drilling plan must address the possibility of confined and separate groundwater aquifers and demonstrate safe completion which avoids cross-contamination and leakage. The grout must be designed to obtain strength equal to or greater than the soil or rock. Note that some instrumentation installations may require additional considerations for the grout strength. Gravity grouting techniques should be used for backfilling boreholes.

For borings that penetrate zones with low confining stress it is possible to induce hydraulic fracturing even from gravity pressure alone. When grouting borings in these locations or if significant grout losses are observed, the grout backfilling should be done in stages allowing the grout to set between stages.

For pervious portions of the dam (drainage features, filters, etc.), the borehole must be backfilled by tremie placement of granular materials that are sized to provide drainage without being susceptible to migration through the pervious embankment or foundation materials or segregation during placement.

Lutenegger, et.al. (1995) is a good source for borehole backfill guidelines.

Special procedures and materials may be required for installation of instrumentation in boreholes.

Borehole completion is often not well documented. Recommended inclusions in borehole completion documentation include intervals of various backfilling materials, 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 important and, as in the case of backfill material volumes significantly higher or lower than calculated, may be indicative of conditions significantly different than anticipated.

Below are some general guidelines that can be considered in borehole completion.

- **High Solids Bentonite Grout** - Tremie grouting with high solids bentonite is an acceptable method of completing boreholes in embankment dams. Mixes which yield 20 to 30 percent solids should be used. Stage up tremie grouting methods should be used in the embankment with the casing (i.e. hollow-stem augers, rods, etc.) pulled incrementally to ensure 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.

- **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 to 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). Commonly, the addition of up to 3 percent powdered bentonite by dry mass of cement is used for pumping ease and to reduce shrinkage and cracking after curing – although a myriad of other compounds are also available. 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 percent gypsum or aluminum powder by weight will give the cement expansive properties, which may be advantageous in embankment dams where internal seepage is an issue. As with the bentonite grout, stage up tremie grouting methods should be used in the embankment core with the casing pulled incrementally to ensure borehole wall stability. The grout should always be injected through a tremie pipe to ensure the best possible placement and most thorough borehole completion.

- **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 pellets or chips should not be considered and only tremie 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 borehole bottom without bridging. It is advisable to always place both solid bentonite and grout through a tremie pipe.

- **Instrument Installations** - 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 a minimum of 1 to 2 hours to hydrate prior to placing additional backfill material above the seal. Alternatively, piezometers can be installed in fully grouted holes. While it is possible to place two piezometers in a typical 4-inch inside diameter hollow stem auger 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. Other instrument installations (slope inclinometer casing, geophysical casing, etc.) will require additional considerations.

4.6 Drilling Personnel

Because of the potential to do harm, drilling in a dam should only be performed by experienced and qualified personnel. This includes the lead drill rig operator and the engineer or geologist who is the on-site representative responsible for the drilling program and the safety of the dam. Schedule, budget, and other issues should be considered secondary to the safety and integrity of the structure and those potentially impacted by its compromise.

Drill rig operators must have a minimum of 5 years of experience drilling with the equipment and procedures described in the drilling program. When the drilling plan includes drilling in or in the vicinity of dam or appurtenant structure foundations or abutments or within an embankment dam, the drill rig operators must have demonstrated embankment dam drilling experience clearly indicated in their resume.

All drilling activities must be conducted in the presence of a qualified geotechnical engineer or engineering geologist who will be responsible for maintaining the integrity of the structure and the inspection of the drilling operation. Qualified is by combination of education, training, and experience as indicated in Table 2.

Table 2 – Minimum Qualifications of Responsible On-site Personnel

Factor	**Low Hazard Dams**	**Significant and High Hazard Dams**
Education	Minimum B.S. in Civil Engineering or Geology (or licensed as a professional engineer, professional geologist, or certified engineering geologist)	
Training	Independent study or formal training in the identification and mitigation of drilling hazards in embankment dams	
Experience	Minimum of two years of general drilling experience	Minimum of four years of embankment dam drilling experience

While there are many inspectors with significant years of experience with drill procedures, classifying soils and rock, and in-situ testing methods, they may only have limited knowledge and experience with dams and may be unaware of potential damage to critical dam features caused by certain drilling procedures. Therefore it is critical that a combination of education, training, and experience be demonstrated and clearly shown on the resume of the geotechnical engineer or geologist inspecting the work.

The project manager directing the drilling program must also be an experienced geotechnical engineer that is a licensed professional engineer or a licensed professional geologist or certified engineering geologist with at least ten years' experience in dams-related work.

Both the drill rig operator and the on-site geotechnical engineer/engineering geologist must also be familiar with these guidelines. It is essential that drill rig operators and the geotechnical engineer/engineering geologist be well trained and aware of the causes of and the problems resulting from hydraulic fracturing and artesian conditions and have the equipment, materials, and experience to correct and remediate damage to the embankment and foundation.

4.7 Other Considerations

Emergency Communications - No dam should be drilled or investigated without a thorough review of the Emergency Action Plan (EAP). FERC-regulated dams have EAPs in place. 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.

Monitoring - During drilling operations, the dam embankment should be continuously inspected and monitored using appropriate procedures and instrumentation at the dam site. The proposed monitoring should be used to evaluate any impacts from of the drilling activity and assist in detecting any unanticipated changes. The type of monitoring (piezometer, inclinometers, etc.), frequency of readings, and purpose for monitoring should be carefully considered. If appropriate, threshold limits could be determined for specific drilling scenarios. It may be necessary to perform daily inspections of the dam for a period of time after the drilling operations have concluded.

Reporting - All incidents of damage or potential damage related to drilling and associated activities for dams must be reported. If a sudden loss of drill media occurs during any embankment drilling within the core, drilling must 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, FERC should be notified immediately.

Construction/Remediation Drilling Activities - Drilling activities performed during construction or remediation phases are often overlooked as opposed to drilling that occurs under the traditional exploration phases. There are numerous examples of dams which required remediation after reservoir filling and the embankment or foundation was damaged. 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.

Exemptions - Drilling required for immediate emergency measures where delays required to develop the drilling plans and to obtain the necessary reviews and acceptances would result in unacceptable risk of damage or failure, may be exempted from the requirements to prepare a drilling plan, as approved by the Regional Engineer. Emergency drilling should be appropriately expedited but should follow the general guidelines presented in this guideline.

4.8 Evaluation of Potential Risks

The licensee must thoroughly evaluate the risks associated with the proposed drilling and indicate how they intend to mitigate them. Among other topics, the potential risks of causing hydraulic fracturing of the embankment, as well as the potential risks of causing seepage, instability, or other potential dam safety issues as a result of the proposed drilling program must be evaluated and addressed. The risk evaluation must include an assessment of the potential impact of the drilling operations and the location of the boreholes in relation to areas of the dam that may be more susceptible to hydraulic fracturing, as discussed in Section 4.2.1.

Aside from comparing the planned drilling locations with the areas of the embankment and soil types that are more susceptible to hydraulic fracturing, the proposed drilling procedures must also be evaluated with respect to their likelihood of causing hydraulic fracturing or other dam safety issues. This includes the instrumentation installation procedures, borehole completion/abandonment procedures, and emergency procedures if a potential dam safety issue is identified during the drilling. Special attention should be given to highlighting the specific procedures and contingency plans that will be utilized to protect the dam from potential hydraulic fracturing and other potential risks.

5.0 DRILLING PROGRAM PLAN (DPP)

An approved Drilling Program Plan (DPP) is required for any exploration drilling, instrument installation, or remediation drilling (including grouting) work to occur on an embankment dam, in proximity of the dam in which the drilling methods could pose a risk to the dam, or the dam's foundation and abutments. DPPs shall be prepared and reviewed by experienced geotechnical engineers and/or engineering geologists familiar with subsurface exploration techniques and methods. It is paramount that all existing subsurface information is thoroughly evaluated and understood by the exploration team prior to developing a plan for additional drilling. In order to understand and communicate subsurface conditions and estimate drilling risk, the existing subsurface information must be assimilated into essential plan and section drawings showing proposed drill holes and depths, target sample areas and proposed instrumentation. The DPP must also comply with good environmental practices and comply with site environmental provisions/restrictions, which may need coordination with DHAC and outside agencies.

The DPP must be reviewed and accepted by the FERC Regional Engineer prior to beginning the drilling program. Depending on the particular dam and scope of the project involved, the review process may also require additional coordination with FERC headquarters staff in Washington, D.C. and/or DHAC. As stated in our Annual Letter, this plan must be submitted for our review a minimum of **30 days** prior to beginning the drilling work. However, licensees are encouraged to inform the FERC project engineer of the planned drilling program and begin discussions with him or her regarding the proposed drilling well in advance of this deadline.

In addition, the licensee is encouraged to set up either a face-to-face meeting or conference call with the Regional Engineer and headquarters staff, as appropriate, once the specifics of the proposed drilling program have been developed. Ideally, this meeting should take place as soon as possible but no later than *a minimum of two weeks* prior to submission of the DPP. The purpose of this meeting and early coordination with the FERC project engineer is to ensure that both the licensee and FERC share a common understanding of the requirements of the project and the DPP, and there are no delays associated with FERC's review or potential issues with the plan.

FERC's primary concern in evaluating the licensee's DPP will be ensuring that the planned drilling program will "do no harm" to the existing dam. A thorough, well-organized, and well-developed DPP, including the various items highlighted in these guidelines, will assist FERC in its review by demonstrating that the licensee fully understands the risks associated with the drilling program, and is taking the appropriate measures to mitigate them.

In general, the DPP must include the following information, as a minimum:

1. Name and description of project.

2. Purpose of site disturbing activity.

3. Description of the proposed site exploration activity (drilling, test pitting, etc.). Include plan view showing location of activity (ies), proposed drill hole depths, sampling intervals, insitu testing, and instrument installations.

4. Describe and show anticipated site conditions. Show location of known subsurface conditions and features. Describe subsurface units. Describe understanding of ground water conditions and phreatic surface, including the potential to encounter artesian conditions. Use cross sections and profiles to graphically illustrate.

5. Describe proposed equipment, methods, and processes. For example, for any activity that introduces a fluid in or near the water retaining feature or its foundation, detail how fluid pressures will be measured and monitored. For example, for falling head permeability tests, show how the introduction of a column of water will not cause excess water pressures in the embankment that could lead to hydraulic fracturing. Likewise, for grouting of boreholes, describe how if staged grouting will be required and how the maximum height of grout column will be determined to prevent hydraulic fracturing.

6. Identify project personnel and qualifications/experience, including resumes.

7. Risk identification and mitigation plan. Identify and describe potential risks imposed by site disturbing activities. Identify and describe risk mitigation plan. For example, for any activity at the toe of a water retaining feature, describe the risk mitigation plan should unexpected artesian conditions be encountered.

8. Identify communication plan with names and phone numbers. Include a list of emergency equipment and supplies to have on site (phone/radio, filter materials, grout materials, light plant, etc.).

9. Provide an overall schedule and duration of drilling activities.

Specific requirements for the DPP are included in Appendix B.

6.0 REPORTING REQUIREMENTS

The DPP should provide details on the documentation, logging, and submission of drilling data. The field inspector's boring log should be submitted to FERC within 24 hours after completion of backfilling the boring. When feasible, draft field boring logs should be submitted daily, along with daily work logs. Since there is always a possibility that some changes will need to be made in the field due to the specific subsurface conditions encountered, the DPP should describe how changes and deviations from the approved DPP will be communicated and coordinated with FERC. Also, any significant differences from expected conditions which could be an indication of a potentially serious dam safety issue must be reported immediately to the FERC Regional Engineer.

7.0 REFERENCES

ADI, 1992, "Australian Drilling Manual", Third Edition, Australian Drilling Industry Training Committee, NSW 2113, Australia.

ASTM, 1999, "Standard Practice for Rock Core Drilling and Sampling of Rock for Site Investigations", D2113, West Conshohocken, Pennsylvania.

ASTM, 2000a, "Standard Guide for Use of Cable-Tool Drilling and Sampling Methods for Geoenvironmental Exploration and Installation of Subsurface Water- Quality Monitoring Devices", D5875-95, West Conshohocken, Pennsylvania.

ASTM, 2000b, "Standard Guide for Use of Dual-Wall Reverse-Circulation Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water- Quality Monitoring Devices", D5781-95, West Conshohocken, Pennsylvania.

ASTM, 2000c, "Standard Guide for Use of Direct Rotary Drilling with Water-Based Drilling Fluid for Geoenvironmental Exploration and the Installation of Subsurface Water- Quality Monitoring Devices", D5783-95, West Conshohocken, Pennsylvania.

ASTM, 2000d, “Standard Guide for Use of Direct Rotary Wireline Casing Advancement Drilling Methods for Geoenvironmental Exploration and Installation of Subsurface Water-Quality Monitoring Devices”, D5876-95, West Conshohocken, Pennsylvania.

ASTM, 2000e, “Standard Guide for Use of Casing Advancement Drilling Methods for Geoenvironmental Exploration and Installation of Subsurface Water- Quality Monitoring Devices”, D5872-95, West Conshohocken, Pennsylvania.

ASTM, 2000f, “Standard Guide for Use of Direct Air-Rotary Drilling for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices”, D5782-95, West Conshohocken, Pennsylvania.

ASTM, 2006, “Standard Guide for Selection of Drilling Methods for Environmental Site Characterization”, D6286-98, West Conshohocken, Pennsylvania.

ASTM, 2008, “Standard Practice for Using Hollow-Stem Augers for Geotechnical Exploration and Soil Sampling”, D6151-08, West Conshohocken, Pennsylvania.

ASTM, 2010, “Standard Practice for Sonic Drilling for Site Characterization and the Installation of Subsurface Monitoring Devices”, D6914-04, West Conshohocken, Pennsylvania.

BOR, 2010, “Guidelines for Drilling and Sampling in Embankment Dams”, Bureau of Reclamation, Denver, Colorado.

BOR, 1990, “Earth Manual, Part II”, Third Edition, Bureau of Reclamation, Denver, Colorado.

BOR, 1998, “Earth Manual, Part I”, Third Edition, Bureau of Reclamation, Denver, Colorado.

BOR, 1999, “Standard Penetration Test: Drillers/Operators Guide, Report Number DSO- 98-17,” J. Farrar, Dam Safety Office, Bureau of Reclamation, Denver, Colorado.

Dustman, J.R., R. Davis, and T. Oouthoudt, 1992, “Soil, Bedrock, and Groundwater Sampling Using Rotasonic Drilling Techniques,”, Proccedings of the Sixth National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring, Geophysical Methods, National Ground Water Association, Las Vegas, Nevada.

FEMA, 2000, “Research Needs Workshop: Seepage through Embankment Dams”, Federal Emergency Management Agency, Washington, DC.

France, J.W., 2002, “Two Embankment Dam Seepage Incidents,” Technical Workshop No. 9, Responding to Dam Safety Emergencies, National Dam Safety Program, National Emergency Training Center, Emmitsburg, Maryland.

Ladd, C. C., and D.J DeGroot, 2004 (revised). “Recommended Practice for Soft Ground Site Characterization,” Arthur Casagrande lecture, Proc. 12th Pan-American Conf. on Soil Mech. and Geot. Engineering.

Lutenegger, A.J., D.J. Degroot, C. Mizra and M. Bozozuk, 1995, “Recommended Guidelines for Sealing Geotechnical Exploratory Holes, Report 378,” National Cooperative Highway Research Program, Transportation Research Board, National Academy Press, Washington, DC.

NDA, 1990, “Drillers Manual,” National Drilling Association, accessed at www.ndu4u.com, Brunswick, Ohio.

Schaefer, J.A., D.B. Paul, and D.D. Boyer, 2011, “Safe Grouting Pressures for Dam Remediation”, USSD Annual Meeting, Nashville, Tennessee.

Sherard, J.L., 1973, “Embankment Dam Cracking,” Embankment Dam Engineering, S. Poulos and R. Hirschfeld, Eds., John Wiley and Sons, New York, N.Y., pp. 272-353.

Sherard, J.L., 1986, “Hydraulic Fracturing in Embankment Dams”, ASCE Journal of Geotechnical Engineering, Volume 112, No. 10, pp. 905-927.

USACE, 2014, “Drilling in Earth Embankments and Levees”, ER 1110-1-1807, U.S. Army Corps of Engineers, Washington, DC.

APPENDIX A

ADDITIONAL HYDRAULIC FRACTURING REFERENCES

Albritton, J., Jackson, L., and Bangert, R., "Foundation Grouting Practices at Corps of Engineers Dams", Technical Report GL-84-13, US Army Corps of Engineers, October 1984.

Alfaro, M.C., and Wong, C.K., "Laboratory studies of fracturing of low-permeability soils", Canadian Geotechnical Journal, 38, 303-315, 2001.

Andersen, K.H., Rawlings, C.G. Lunne, T.A., and By, T.H., "Estimation of hydraulic fracture pressure in clay", Canadian Geotechnical Journal, 31, 817-828, 1994.

Bjerrum, L., Nash, J. K. T. L., Kennard, R.M. & Gibson, R.E., "Hydraulic fracturing in field permeablity testing", Geotechnique, 22, 319-32, 1972.

Bozozuk, M., "Minor principal stress measurements in marine clay with hydraulic fracture tests", Proceedings, Engineering Foundation Conference on Subsurface Exploration for Underground Excavation and Heavy Construction, Henniker, N.H., August 1974.

Bureau of Reclamation, "Engineering Geology Field Manual," Vol I and II, Second Edition, Denver, CO, 1998.

Calcagno, Frank, Jr., USBR, "Hydraulic Fracture Study of the Tiber Spillway Cofferdam", AEG Newsletter 26/4 October 1983.

Casagrande, A. and Covaarrubias, S.W., "Cracking of earth and rockfill dams, tension zones in embankments caused by conduits and cutoff walls", Contract Report S-70-7, U.S. Army Engineer Waterways Experiment Station, July 1970.

Chang, H., "Hydraulic fracturing in particulate materials", Doctoral Thesis, Georgia Institute of Technology, November 2004.

Chen, Yu-jiong, and Zhang, Shu-lu, "Test embankment of fracture grouting", Journal of Geotechnical Engineering, Vol. 115, No. 11, November 1989.

Clough, R.W. and Woodward, R.J. III, "Analysis of embankment stresses and deformations", Journal of Soil Mechanics and Foundations Division, Proceedings of ASCE, Vol. 93, No. SM4, July 1967.

Elwood, D., and Moore, I., "Hydraulic fracture experiments in sand and gravel and approximations for maximum allowable mud pressure", North American Society for Trenchless Technology, No Dig Show, Mar-Apr 2009.

Hamouche, K.K., Leroueil, S., Roy, M., and Lutenegger, A.J., "In situ evaluation of K0 in eastern Canada clays", Canadian Geotechnical Journal, vol 32, pgs 677-688, 1995.

Independent panel to review cause of Teton Dam failure, 1976, Failure of Teton Dam: Report to the U.S. Department of Interior and State of Idaho.

Kulhawy, F.H., and Duncan, J.M., "Stresses and movements in Oroville dam", Journal of Soil Mechanics and Foundations Division, Proceedings of ASCE, Vol. 98, No. SM7, July 1972.

Lo, K.Y. and Kaniaru, K., "Hydraulic fracture in earth and rock-fill dams", Canadian Geotechnical Journal, Vol 27, 496-506, 1990.

McCook, D.K, and Grotrian, K.O., "Using SIGMA/W to predict hydraulic fracture in an earthen embankment", Proceedings: Dam Safety, ASDSO, September 2010.

Mori, A. and Tamura, M., "Hydrofracturing pressure of cohesive soils", Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 27, No. 1, 14-22, Mar 1987.

Schmertmann, J. H., "Measure and use of the insitu lateral stress", The Practice of Foundation Engineer, Department of Civil Engineering, Northwestern University, 1985.

Seed, H.B., and Duncan, J.M., 1981, "The Teton Dam - a retrospective review", Proceedings of the Tenth international Conference on Soil Mechanics and Foundation Engineering, Stockholm, Sweden, June 1981, p. 219-238.

Sherard, J.L., "Loss of water in boreholes in impervious embankment sections", Proceedings, 10th ICOLD Congress, Montreal, Vol. VI, 1970, 377-381.

Sherard, J.L., Decker, R.S. and Ryker, N.L., "Hydraulic fracturing in low dams of dispersive clay," Proceedings of the Specialty Conference on Performance of Earth and Earth-Supported Structures, ASCE, June, 1972, Vol. 1, Part I, pp. 563-590.

Staheli, K., Price, C.G., and Wetter, L., "Effectiveness of hydrofracture prediction for HDD design", North American Society for Trenchless Technology, No Dig Show, May, 2010.

US Army Corps of Engineers, "Foundation completion report Patoka lake dam, Indiana", Appendix E, Analysis of Grouting Effectiveness and Distribution as Observed During Excavation, July 1979.

US Army Corps of Engineers, "Installation of Pipelines Beneath Levees Using Horizontal Directional Drilling, Technical Report CPAR-GL-98-1, April 1998.

Xia, H. and Moore, I.D., "Estimation of Maximum Mud Pressure in Purely Cohesive Material during Directional Drilling, Geomechanics and Geoengineering: An International Journal, Vol. 1, No.1, 3-11. 2006.

Yanagisawa, E. and Panah, A.K., “Two dimensional study of hydraulic fracturing criteria in cohesive soils”, Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 34, No. 1, 1-9, Mar. 1994.

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APPENDIX B

DRILLING PROGRAM PLAN (DPP) OUTLINE FOR DRILLING IN AND NEAR EMBANKMENT DAMS

Drilling in and near embankment dams must subscribe carefully to the “do no harm” philosophy. Dams are not places for standard investigation techniques; they require different drilling procedures because there are significant risks. Incorrect drilling, grouting, or borehole abandonment procedures could lead to damage of the structure by hydrofracturing, erosion, drain contamination or other mechanisms, during drilling operations, instrumentation installation, borehole completion, and borehole abandonment. All design and field personnel need to understand the existing subsurface conditions and potential problems and damage that the drilling could trigger.

An approved Drilling Program Plan (DPP) is required for any exploration drilling or remediation drilling (including grouting) work to occur in or near an embankment dam. DPPs shall be prepared and approved by experienced geotechnical engineers and/or engineering geologists familiar with subsurface exploration techniques and methods.

The following outline describes the basic information that should be developed and included in the DPP that is to be submitted by the licensee. Additional information, discussion, and recommendations on the items presented in Appendix B are provided in the guidelines. It is strongly recommended that the DPP follow the following organizational structure.

1. Purpose

The purpose of the drilling program needs to be clearly defined and summarized in the plan. The DPP should provide sufficient discussion, details, and figures to ensure that the proposed exploration will accomplish its goals and prevent damage to the dam. The need for any investigation (drilling, testing, etc.) at a dam site should have been presented to and accepted by FERC prior to developing a DPP program. In addition, it should have been demonstrate that any potential damage to the structure created by the drilling and associated processes is outweighed by the need for the drilling data.

2. Existing Information

Before preparing a DPP, the licensee or its consultant should review the subsurface, design, and construction information available in the Supporting Technical Information Document (STI) and their files to properly evaluate the risks associated with the proposed drilling program. The information review typically includes, but is not limited to:

- Subsurface profiles and piezometric conditions;
- Geologic mapping, logs, and reports portraying information from previous investigations and construction;
- Foundation reports;
- Embankment construction reports;

- As-built drawings;
- Archived records;
- Construction reports;
- Construction photos;
- Instrumentation plans; and
- Available laboratory analyses.

Based on this review, a summary of the existing information should be included in the DPP.

3. Essential Geologic and Engineering Drawings

The DPP should include a complete set of drawings depicting the current subsurface conditions. This detailed set of foundation and embankment drawings typically requires a plan drawing showing all previous subsurface investigation locations, profile drawings, and sections of the embankment in the areas of proposed exploration. The sections should be drawn to scale (no vertical exaggeration) and should show the locations and depths of the proposed borings along with all available factual information and appropriate geologic or engineering interpretations. The information on the plan, profile and sections should be detailed, include all available data significant to the planned explorations, and be supplemented by additional discussion in the text of the DPP, as appropriate. At a minimum, the following information should be included, as applicable:

- Embankment zones, including added berms, filters, blankets, and drains;
- Estimated extent of any other zones of interest;
- Details of subsurface material classifications, including relevant laboratory test results such as Atterberg Limits, grain size analyses, and dispersivity test results, as applicable;
- Geologic contacts and continuity supported by all nearby drilling and sampling details;
- Contours of the top of rock or any other layer of particular interest;
- Piezometer locations showing screened influence zones and recorded piezometric levels tied to the reservoir water level. Whether or not the dam includes active piezometers, the estimated phreatic surface through the embankment should be clearly shown on all relevant cross-section drawings included in the DPP. In addition, the basis for determination of the estimated phreatic surface should be clearly described in the DPP.
- Inclinometer locations showing any shear zones or areas of deformation;
- Standard Penetration Test (SPT) blow counts or other in-situ test results;
- Geophysical data, where useful (e.g. downhole and/or crosshole shear wave velocity profiles);
- Seepage areas tied to geologic units; and
- Location of all structures, including seepage control features, outlet works, etc.

4. Drilling Scope and Methodology

The plan should thoroughly describe the scope and methods that will be used for the drilling program. At a minimum, the following information should be included:

- Number, location, depth, diameter, and inclination of the proposed borings;
- Drilling and sampling methods, including a description of the drilling equipment to be used (e.g. track-mounted vs. truck-mounted drill rig). The DPP should include justification for the proposed methods and equipment based on the expected subsurface conditions. In particular, if any drilling fluids will be used to advance the borings, the DPP must include a detailed explanation of why these procedures must be used, how the potential for hydraulic fracturing will be mitigated, and how continuous monitoring of the fluid pressures will be accomplished during the drilling. The allowable fluid pressures so as to prevent hydraulic fracturing should be included in the DPP, along with supporting calculations, as appropriate.
- List of ASTM standards and methods that will be followed to perform the drilling.
- Anticipated materials to be drilled and sampled;
- Required sample types (disturbed or undisturbed), sizes, and anticipated depths;
- Procedures for identifying underground utilities, and other surface or subsurface obstacles prior to the drilling; and
- Site Access and accessibility of the boring locations (see paragraph 11). .

5. Field and Laboratory Testing Program

The DPP should provide information on the proposed testing program, which should include both field and laboratory testing. A detailed description of the in-situ testing proposed at each boring should be provided, including the type, location (depth), and specific testing method(s) (i.e. ASTM standards, etc.) to be used. The plan should also describe the anticipated laboratory testing program.

6. Instrumentation Installation

If instrumentation is being installed in one or more borings, the materials, location, and procedures that will be used to construct and install the proposed instrument should be described in the DPP. Appropriate figures including installation details for the instruments should also be drafted and included in the plan. For piezometers and monitoring wells, these details should include the following items, at a minimum:

- Installation depth;
- Pipe material type, length, and diameter, as well as the methods that will be used to centralize the pipe;
- Depth of screened interval and the slotted screen size;
- Type, gradation, depth range, and annular thickness of the filter/drain pack material. The DPP must demonstrate that the proposed filter/drain pack material will adequately meet filter and drainage compatibility criteria with both the surrounding embankment soils and the slotted screen size of the piezometers/wells.
- Type, mixture, depth range, and annular thickness of the bentonite or cement grout seal, as applicable;
- Procedures for monument installation or other near-surface (i.e. within the upper five feet) abandonment methods, as applicable; and
- Procedures for developing the piezometers/wells. In particular, if water or air pressures

will be introduced, the DPP must include reasons why these pressures must be used in order to develop the piezometer/well and indicate how this will be implemented so as to avoid causing any damage to the piezometer/well or surrounding embankment. The DPP must indicate how continuous monitoring of the fluid pressures will be accomplished during the development process, state an allowable fluid pressure that will not be exceeded, and include supporting calculations, as appropriate.

7. Monitoring

The DPP should provide details on any proposed monitoring and evaluation of the drilling activity. The plan should describe the type of monitoring (piezometer, inclinometers, etc.), frequency, and purpose for monitoring. If appropriate, threshold limits could be determined for specific drilling scenarios.

8. Emergency Procedures

A discussion should be provided as to what materials and methods will be used to prevent damage to the dam should problems such as loss of drilling fluids, artesian pressures or seepage be encountered during the explorations. The plan should include an emergency contact list and personnel notification flow chart.

9. Borehole Completion

All boreholes in and around embankment dams should be sealed after completion. Completing a borehole by backfilling with drill cuttings is <u>not acceptable</u>. The proposed materials (grout mix) and field procedures that will be used to backfill the borehole should be described in the DPP, along with the estimated quantities required to backfill the borehole. Additional information on backfilling of boreholes is provided in the guidance.

10. Personnel Experience

The DPP should clearly indicate the specific personnel that will be on site either performing or observing the drilling work, and their respective roles and responsibilities. Resumes for all of the relevant project personnel (including the project manager, field geologist/engineer, and lead driller) should be included in the DPP or submitted prior to start of work. The level of experiences required for each of the specific personnel performing the work is described in the guidelines.

11. Site Access, and Environmental Consideration

The DPP should include information on the proposed procedures to access the boring locations, which may include details for constructing and maintaining access roads and for mitigating any adverse impacts that might be caused by its construction. The DPP, if applicable, should address any adverse impact to the embankment stability or seepage from the construction of access roads within the footprint of the dam. For access roads which will be constructed through areas of previously undisturbed ground, additional consultation with FERC's Division of Hydropower

Administration and Compliance (DHAC) will be required prior to FERC approval of the DPP. The DPP should describe the procedures for identifying underground utilities, and other surface or subsurface obstacles prior to the drilling.

12. Documentation and Coordination

The DPP should provide details on the documentation, logging, and submission of drilling data. Since there is always a possibility that some changes will need to be made in the field due to the specific subsurface conditions encountered, the DPP should describe how changes and deviations from the approved DPP will be communicated and coordinated with FERC. Also, any significant differences from expected conditions which could be an indication of a potentially serious dam safety issue must be reported immediately to the FERC Regional Engineer.

In addition, the DPP should include an overall schedule and duration of drilling activities.

13. Evaluation of Potential Risks

The DPP must document the licensees' assessment of the risks associated with the proposed drilling and indicate how they intend to avoid or mitigate them. Among other topics, this section should address the risks of causing hydraulic fracturing of the embankment, as well as the risks of causing erosion, blowout, contamination of drainage materials, or other potential dam safety issues as a result of the proposed drilling program. The DPP should also outline the nearby instruments whose behavior will be monitored during the investigation, their expected response, and contingency plans for unexpected response.