# NEW MEXICO OFFICE OF THE STATE ENGINEER
## Dam Safety Bureau
### Geotechnical Investigation and Analyses for Dams
### August 15, 2008

An adequate assessment of geologic and geotechnical conditions of the proposed site is imperative for a safe dam design and construction. Over 50 percent of all dam failures in the USA can be linked to geologic and geotechnical problems according to information provided by the Association of State Dam Safety Officials (ASDSO). The geologic and geotechnical problems range from foundation defects caused by inadequate investigation to internal erosion through the embankment (piping). Each dam site may have its own unique set of geologic and geotechnical challenges. Similarly, the design requirements are different for dams of different size, purpose and hazard potential classification. Therefore, the Office of the State Engineer (OSE) requires the geotechnical investigation and analyses to be site and project specific to address the complexity of site conditions and design requirements of the proposed dam project.

Geotechnical investigation and analyses requirements for dams are cited in the Rules and Regulations Governing Dam Design, Construction and Dam Safety, which were filed with the New Mexico State Record Center as Title 19, Chapter 25, Part 12 of the New Mexico Administrative Code (19.25.12 NMAC). Subsection C.10 of 19.25.12.11 NMAC states that the scope of the geotechnical investigation for a dam is dependent on the following:

- Hazard potential classification
- Size
- Anticipated materials and construction methods
- Site geology and seismicity
- Anticipated soil strata
- Other site-specific conditions

Slope stability analyses are required for all dams regardless of the hazard potential classification. Low hazard dams up to 25 feet high with upstream slope no steeper than 3H:1V and the downstream slope no steeper than 2H:1V are exempt from this requirement. There are a number of other requirements for the geotechnical investigation and analyses, as provided below, that are required only for the dams classified as “significant” or “high” hazard potential. Please refer to Subsection C of 19.25.12.11 NMAC for detailed information.

- Detailed geological assessment
- Detailed seepage analysis through the dam embankment – This analysis is exempt for flood control dams. However, the seepage through the foundation must be adequately analyzed and addressed regardless of the hazard potential classification.
- Detailed seismic design and analyses

It is obvious from above that the size of the dam and its hazard potential classification must be decided before planning a geotechnical investigation. A preliminary study and/or site reconnaissance of the proposed dam location can be very helpful in planning the geotechnical investigation. The geotechnical investigation must be objective. Objectives of the investigation must be decided in consultation with the design engineer and must include the design assumptions to be supported and design parameters required for the dam project.

Development of extraneous information should be avoided. In addition, the investigation should include a plan to go back and perform additional exploration and tests, if necessary, to support the design. If the firm responsible for the geotechnical investigation is different from the firm responsible for the design and construction of the project, there must be good coordination between the firms to ensure any changes in the proposed design and construction method is addressed in the geotechnical investigation.

**Geotechnical Investigation**

A document that may serve as guidance and a checklist in planning a geotechnical investigation is the ASTM Standard D420, Standard Guide to Site Characterization for Engineering Design and Construction Purposes. This document covers all aspects of site investigation from reconnaissance of the project area, exploration plan, equipments, methods, testing, classification of soil to report preparation. The geotechnical investigation program must include the number and location of boreholes and test pits, type and depth of borehole, sample collection methods, frequency of standard penetration tests (SPT) and other borehole tests, field tests and laboratory tests to be performed and so forth. It is recommended that the geotechnical investigation program be submitted to the OSE Dam Safety Bureau for review even though it is not required by the OSE rules and regulations. Depending on the workload at hand, OSE may review and provide feedback.

The geotechnical investigation program involving boreholes on existing dam embankments and appurtenances must be reviewed and approved by the OSE before undertaking such investigations. A geotechnical investigation plan containing objectives of the proposed investigation, borehole layout, borehole size and depth, drilling equipment and method, field tests, sample collection and laboratory tests must be submitted to the OSE Dam Safety Bureau for review and approval. The proposed geotechnical investigation plan must include a mitigation plan to address any emergency situation that may be caused by the investigation and must identify the engineer supervising the investigation at the site.

A geotechnical investigation must consider the following, where applicable:

1. Boreholes: Test borings must be located in the footprint of the embankment, spillway excavation and appurtenant structures. Boreholes must extend to sound bedrock or at least to the depth equal to the height of the dam. When the boreholes are extended to bedrock, coring of the bedrock must be performed following ASTM Standard D2113 to assess its quality and characteristics. The borehole logs must record the depths of any problems such as borehole instability (cave in, squeezing hole, flowing sands), cobbles, lost drilling fluid, lost ground, obstruction, fluid return color changes and equipment problems, and a discussion of the problem must be provided in the geotechnical report. The geotechnical report must provide details of the drilling method, drilling fluid, size of boreholes and the ground elevations at the top of the boreholes.

2. Test Pits or Trenches: Supplemental test pits or trenches must be located appropriately to provide visual inspection of soil layers, measurement of bedrock orientation and collection of bulk samples. Test pits and trenches must be logged. Collection of block samples must be performed according to ASTM Standard D7015. The geotechnical

report must provide details of the method used for excavating test pits and the test pit logs must record any excavation problem observed such as instability of cut (sloughing, caving, etc.), depth of refusal, difficulty of excavating, etc.

3. Field Tests:
   a. Standard Penetration Tests (SPT): The standard penetration test must follow ASTM Standard D1586. Standard penetration resistance (SPT N or N value) is the number of blows of a 140 lbm hammer falling 30 in. required to produce 1-foot of penetration of a specified (standard) 2-in. outside diameter, $1^{3}/_{8}$-in. inside diameter sampler into soil, after an initial 0.5 feet seating. A penetration test that does not meet these requirements is not a SPT and the penetration resistance must not be reported as a SPT N-value or N-value and care must be taken with its use for correlating soil properties. Published correlations for SPT N-value cannot be used for non-SPT blow count numbers. If SPT N-values are used for the assessment of liquefaction potential, the SPT N-values must be normalized according to ASTM Standard D6066.

   b. Cone Penetration Tests (CPT): CPT tests must be performed and results provided according to ASTM Standard D5778. Electronic data must be provided on a CD along with CPT logs and interpretations. CPT tests can be used to supplement site characterization.

   c. Geophysical Investigation: Geophysical survey methods may be used to supplement borehole and outcrop data and to interpret soil profile between boreholes. They can be used to plan borehole locations. ASTM Standards D6429 and D5753 provide guidance on planning and selection of geophysical methods. ASTM Standard D5777 provides guidance on test procedures and interpretation of the seismic refraction method. ASTM Standard D4428/D4428M provides test methods and interpretation of the crosshole seismic test. The geotechnical report must explain the test method and interpretation of the test results.

   d. Field Permeability Test: If a field permeability test is performed, details of the test method, calculations and interpretation must be included along with the results.

   e. Measurement of Water Level in Boreholes: Water level must be measured in boreholes and test pits and shown accordingly on logs of the boreholes and test pits. The water level must be recorded during drilling and after the ground water table is stabilized. Both water levels must be provided on borehole logs along with the time of measurement. Elevation of the water table must be established based on the project datum and shown on the ground profile of the dam site.

   f. Field tests with equipment such as pocket penetrometer and torvane are not acceptable for deriving design parameters. Equipment used in the geotechnical investigation must be used appropriately in accordance with ASTM standards.

4. Sample Collection for Laboratory Testing:
   a. The sample collection program must be designed to meet the requirements of the laboratory tests planned for the project. Some laboratory tests require relatively undisturbed samples while others can use disturbed samples so long as the properties of the sample is preserved. Sample collection, preservation, transportation and handling must be described in the geotechnical report. ASTM Standards D4220 and D5079 must be followed to prevent samples from experiencing excessive disturbance during transportation and handling.

   b. Disturbance of samples inherent to sampling techniques must be recognized. Soil samples that are obtained by driving samplers with a hammer such as the standard penetration test (ASTM Standard D1586) and penetration of samplers lined with rings (ASTM Standard D3550) are considered highly disturbed. This must be recognized when interpreting and presenting results from laboratory tests based on these samples. If the soil samples for the laboratory tests were reconstituted in the laboratory, the method of sample preparation must be explained in detail.

   c. Samples collected by a Thin-Walled Tube Sampler (ASTM Standard D1587) and other samplers specifically designed to minimize disturbance during sample collection process are recognized as undisturbed samples. Description of the sampler and sample collection method must be provided.

   d. For block samples, the method of collection, preservation, transportation and handling must be described in the geotechnical report. If the method complies with ASTM standard D7015, the block samples will be considered undisturbed.

   e. Rock samples must be collected following the procedures outlined in ASTM Standard D2113. Rock Quality Designation (RQD) determination of rock core must follow ASTM Standard D6032.

5. Soil Classification:
   a. Soil classification must follow the Unified Soil Classification System as provided in ASTM Standard D2487.

   b. Rock-mass classification must follow ASTM Standard D5878. A discussion must be provided on the selection of the classification system.

6. Laboratory Tests:
   a. Consistency tests (Atterberg Limits) for fine-grained soil and sieve analysis for coarse-grained soil are the basic tests required for classification of soil and must be performed. Determination of density, water content and specific gravity is also required. Selection of other laboratory tests must be based on the requirements of the design project. A laboratory testing program must be developed while planning for the site investigation since it may dictate the selection of a boring method and sample

collection. Limitations of the laboratory tests must be recognized in the laboratory testing program. Laboratory tests must follow appropriate ASTM standards.

b. Strength Testing:
   i. Direct Shear Test (Consolidated Drained Shear Test): The direct shear test is one of the most popular shear strength tests as it provides relatively rapid determination of shear strength parameters and is less expensive to perform. However, the limitations of the test are often not recognized and/or the test method is not followed appropriately on many occasions making the test results of little value. ASTM Standard D3080 provides the test methodology and discusses specimen requirements, selection of appropriate shearing rate and presentation of the results. This standard must be followed to obtain credible shear strength parameters. **The direct shear test is not recommended on clayey soils.** Triaxial shear tests provide more accurate results for the clayey soils. The normal stress applied to the sample must represent the stress that the soil will be subjected to after construction. Soil samples must be consistent in unit weight and relative density (void ratio) since the strength of the soil varies with relative density.

   ii. Unconfined Compression Test (UC Test): The unconfined compression test can be used to estimate the undrained shear strength of saturated, fine-grained foundation materials. The UC Test is applicable only for cohesive soils which will not expel or bleed water during the loading portion of the test and which will retain intrinsic strength after removal of confining pressures, such as clays or cemented soils. Dry and crumbly soils, fissured or varved soils, silts, peats, and sands cannot be tested with this method to obtain valid unconfined compression strength values. The test must follow ASTM Standard D2166. This test generally provides conservative strength parameters for the end-of-construction loading condition.

   iii. Unconsolidated-Undrained Triaxial Compression Test (UU Test or Q Test): The UU Test is suitable for saturated fine-grained soils. The sample is not consolidated prior to testing and the water content of the soil is not allowed to change either prior to or during testing. This test method removes some of the limitations of the UC Test and is applicable to a wider range of fine-grained soils. ASTM Standard D2850 provides methodology for the UU Test. It is recommended that the UU Test on embankment soils be performed on samples remolded at the higher water content likely to be encountered during fill placement to represent the lowest embankment fill shear strength. Descriptions must be provided about the source and preparation of the sample. The degree of saturation of the sample must be calculated and provided with the result. The reporting guideline provided by ASTM Standard D2850 must be followed. This test provides shear strength parameters suitable for the end-of-construction loading condition (total stress analysis).

iv. Consolidated-Undrained Triaxial Compression Test with Pore Pressure Measurement (CU Test or R Test): For the consolidated undrained test, the sample is saturated and consolidated under confining pressures that approximate field conditions. Pore water pressure during the test is measured to determine effective stress parameters. The consolidated undrained test can be performed on saturated impervious or semi-impervious soils and simulates the soil conditions experienced during steady-state seepage and rapid drawdown. ASTM Standard D4767 provides the test method for consolidated undrained triaxial compression test for cohesive soils.

v. Consolidated-Drained Triaxial Compression Test (CD Test or S Test): The CD Test is similar to CU Test except the shear stress is applied slowly to allow dissipation of excess pore pressure during the shearing process. Pore pressure measurements are not required. This test is suitable for free-draining soils and provides effective stress parameters. The test can also be performed on relatively impervious soils to model strength of the embankment materials above the phreatic line.

c. One-Dimensional Consolidation Test (Oedometer Test): Oedometer tests are performed on clayey soils to obtain consolidation parameters required for the estimation of consolidation settlement. Undisturbed soil samples are required for this test. The test specimen must be fully saturated. ASTM Standards D2435 and D4186 provide the test methods, analysis and reporting of results. If the oedometer is used for evaluating collapse potential of soils, follow ASTM Standard D5333.

d. Permeability Test: The sample preparation and the test method of the permeability test must be discussed in the report. ASTM Standard D2434 provides the methodology for the constant head test on granular soils. If the falling head test is used, it must be stated as such in the report. Relative density of the granular soil specimen must be reported with the result.

e. Dispersibility Test: ASTM Standards D4647 and D4221 provide methods of evaluating dispersive properties of clay soils. A description of the sample preparation and test method must be included in the report along with the discussion of the results.

f. Collapse Potential Test: ASTM Standard D5333 provides the methodology for evaluating collapse potential of soils. This standard must be followed for the test and interpretation of the results.

g. Compaction Tests: ASTM Standards D698 and D1557 provide methods for the Standard Proctor and Modified Proctor, respectively, for the laboratory evaluation of compaction characteristics of soils containing up to 30 percent coarse materials by weight retained on the ¾-inch sieve. If the soil contains over 5 percent coarse particles retained on the ¾-inch sieve and the coarse particles are not included in the Proctor tests, it must be mentioned in the test results and a correction for the oversize particles must be suggested as provided in ASTM Standard D4718. The compaction curves must show all the data points along with the interpreted curve. The 100-percent saturation curve (zero air voids curve) must also be shown on the graph with the compaction curve. The sample preparation and test method must also be explained.

If the soil contains more than 30 percent oversize particles retained on the ¾-inch sieve or the soil particles break during the compaction test changing gradation significantly compared to the field compaction, or the soil is gap graded, concurrence must be obtained in advance from the OSE Dam Safety Bureau on the approach and the method to be used for the compaction evaluation of such soils.

7. Geotechnical Investigation Report: The site investigation report must include, but not be limited to, the following:
   a. A topographic map of the dam site showing locations of boreholes, test pits, trenches, CPT, geophysical tests and other field tests with the footprint of the proposed dam, spillway and other appurtenant structures.

   b. Logs of boreholes and test pits. ASTM Standard D5434 may be used as guidance and a checklist. Ground elevation of the borehole, test pits and CPT locations must be provided based on the datum established for the project. Also, provide a record of any problems such as borehole instability (cave in, squeezing hole, flowing sands), cobbles, lost drilling fluid, lost ground, obstruction, fluid return color changes, and equipment problems in the logs.

   c. Details of the drilling method, drill rig, drilling fluid, sample collection method, measurement of water table etc.

   d. Details of the field tests such as SPT, CPT, geophysical testing and permeability including description of equipments and test methods along with calculations, discussion and interpretation of results.

   e. Details of the laboratory tests including descriptions of equipments, sample preparation, test methods, calculations and a discussion of the results. ASTM standards provide guidelines on reporting individual tests. Following those guidelines will suffice in reporting the laboratory and field tests.

   f. Locations of borrow material with properties based on the field and laboratory tests.

   g. Subsurface ground profiles based on borehole and test pit logs, field and laboratory tests. At least one profile must be shown along the dam axis and spillway.

   h. Discussion of site conditions based on the investigation, any design challenges, possible and recommended solutions. Discussion must include, if warranted, recommendation for any further investigation or analysis.

i. Recommended design parameters in a tabular form based on the objectives of the investigation and requirements of the design. The design parameters must be based on the investigation. Setting aside the results from the investigation and using design parameters from published literature and textbooks is not acceptable. Published correlations, however, can be used to verify reasonableness of the field and laboratory test results. Also in special circumstances where the testing of the material is recognized to be difficult, use of design parameters based on literature review may be allowed, but adequate justification must be provided in the report.

**Geotechnical Analyses**
Geotechnical analyses must be performed using the recommended design parameters from the site investigation report. The parameters taken from other sources must be explained and justified.

1. Seepage Analysis
   Steady state seepage analysis is required for significant and high hazard potential dams. Exceptions are made for flood control dams. The seepage analysis can be performed by drawing flow nets or by using computational methods available in various computer programs. Whichever method is used, the selection of input parameters must be discussed and the parameters must be provided in a tabular form. The assumptions used in the analysis including boundary conditions must be discussed. Appropriate consideration must be given to anisotropy. The OSE rules and regulations require that the following must be supported by field and laboratory permeability tests:
   - Horizontal permeability less than 4 times the vertical permeability for constructed embankment
   - Horizontal permeability less than 9 times the vertical permeability for native deposits

   Seepage analysis must be performed both through the embankment and the foundation and abutments. Recommendations must be made for design based on the seepage analysis.

   Reporting: The seepage analysis report must include the following:
   a. List of assumptions and boundary conditions followed by a discussion and justification.

   b. Cross-sections of dam and foundation with flow nets or with finite element mesh if computational method is used for the seepage analysis.

   c. Input parameters in a tabular form followed by a discussion and justification. For seepage analysis by computer, appropriate input and output datasheets are required.

   d. Discussion of the selected methodology for the seepage analysis.

e. Results of the seepage analysis with phreatic lines drawn on the cross-sections of the dam and foundation. Discussion must include exit seepage gradients and estimated seepage quantity.

f. Recommendations for the design of the dam, foundation and seepage collection system.

2. Slope Stability Analysis
The stability of the upstream and downstream slopes of the dam embankment must be analyzed for the most critical or severe loading conditions that may occur during the life of the dam. The OSE rules and regulations require stability analysis for the following loading conditions:
   - End of Construction with minimum F. S. 1.2
   - Steady-State Seepage (Long-Term stability) with minimum F. S. 1.5
   - Operational Drawdown with minimum F. S. 1.5
   - Rapid (or Sudden) Drawdown with minimum F. S. 1.2
   - Earthquake (If pseudostatic analysis is applicable, the minimum F. S. 1.1)

   Justification must be provided if a particular loading condition is not analyzed and/or is considered to be not applicable to the project.

   a. Total Stress Analysis (Undrained Condition) vs. Effective Stress Analysis (Drained Condition) and Selection of Strength Parameters:

      The following definitions of undrained and drained conditions are taken from Duncan and Wright (2005).

      Undrained Condition – the condition under which there is no flow of water into or out of a mass of soil in the length of time that the soil is subjected to some change in load. Changes in the loads on the soil cause changes in the water pressure in the voids, because the water cannot move in or out in response to the tendency for the volume of voids to change.

      Drained Condition – the condition under which water is able to flow into or out of a mass of soil in the length of time that the soil is subjected to some change in load. Under drained conditions, changes in the loads on the soil do not cause changes in the water pressure in the voids in the soil, because the water can move in or out of the soil freely when the volume of voids increases or decreases in response to the changing loads.

      Drained or undrained condition is based on the soil permeability and the loading condition. For fully drained condition, effective stress analysis with effective stress parameters ($c'$, $\phi'$) must be selected. For fully or partially undrained condition, total stress analysis with total stress parameters ($c$, $\phi$) must be selected. USSD (2007) provides a summary of approaches used by various federal and state agencies for selecting type of analysis and strength parameters for various loading conditions.

Table 1 provides guidelines for selecting the type of analysis and strength parameters for the loading conditions required by the OSE rules and regulations. Professional judgment must be used to follow or not to follow these guidelines. Justification must be provided in the geotechnical report for the selected strength parameters and analysis.

**Table 1**
**Recommended Guidelines for Selecting Type of Analysis and Strength Parameters**

| **Loading Condition** | **Type of Analysis** | **Shear Strength Test**[1] |
|---|---|---|
| End of Construction | $k > 10^{-4}$ cm/sec - fully drained, effective stress<br><br>other k – undrained, total stress | CU or CD Test<br><br>UU or UC Test |
| Steady-State Seepage | Drained – effective stress Phreatic Surface[2] with water level at spillway crest for wet dams | CU or CD Test |
| Operational Drawdown | Professional judgment based on how fast the water level drops and if the material will drain quickly enough | CU or CD Test |
| Rapid Drawdown | $k > 10^{-4}$ cm/sec - fully drained, effective stress<br><br>other k – undrained, total stress[3] | CU or CD Test<br><br>CU Test |
| Earthquake (Pseudostatic Analysis)[4] | Undrained, total stress | CU Test |

[1] Consolidated drained direct shear test may be used in place of CD Test for granular soils on small projects. CU Test represents consolidated undrained triaxial compression test with pore water pressure measurement.
[2] Phreatic Surface is established from seepage analysis.
[3] USACE (2003) suggests a three-stage computation.
[4] See Seismic Analysis section for details.

b. Use of Cohesion: Use of cohesion for impervious and semi-pervious fine grained soils is a common practice. A conservative value (lower end value) of cohesion should be used in the analysis. Cohesion value of free draining material is generally not considered.

c. Method of Slope Stability Analysis: Simplified Bishop's Method provides reasonable results for circular slip surface with simple geometry and is not applicable to non-circular slip surface. Janbu's method on the other hand is suitable for planar slip surface and is not applicable to circular slip surface (Krahan 2003). If the analysis is performed using a commercial slope stability software, select the best method from the options available in the software. More advanced methods such as Spencer and

Morgenstern –Price are preferred by the OSE. Provide a justification for the selected method of analysis.

d. Use of Computer Software: Most of the commercial software products such as Slope-w, G-Slope and SLIDE are acceptable. Care must be exercised with the automated searches of slip surface since results frequently bias towards deeper, less conservative solutions. Input variables must be checked since some models may run even with significant geometry or material errors. Results of the computer analysis must be checked for reasonableness with other methods such as chart solutions, spreadsheet calculations or other slope stability programs.

e. Reporting: The slope stability analysis report must include the following:
   i. Geometry of the dam with co-ordinates (or dimensions) and material properties used in the slope stability analysis. The information must be sufficient to permit duplication of the model in other slope stability analysis software products.

   ii. Assumptions made in the analysis, justifications for input parameters, etc.

   iii. Details of the method of analysis and justification for its selection.

   iv. Results in graphical form showing critical slip surface, search boundary etc.

   v. Verification of results with other methods such as chart solutions.

   vi. Final results and conclusions with factors of safety in tabular form.

3. Seismic Analysis
Subsection C.13 of 19.25.12.11 NMAC requires dams classified as high or significant hazard potential to perform seismological investigation of the dam site and analyze seismic stability of the dam and appurtenances. The investigation must include evaluation of liquefaction potential, earthquake-induced sliding and other hazards posed by the design earthquake. The design earthquake for the high hazard potential dams other than the flood control dams is the maximum credible earthquake or an earthquake with a 5000-year return frequency. The design earthquake for the significant hazard potential dams or the high hazard potential flood control dams is an earthquake with 2 percent chance of occurrence in 50 years (approximately 2500-year return frequency).

a. Pseudostatic Analysis: The pseudostatic slope stability analysis is acceptable for the following cases (see Subsection C.13 of 19.25.12.11 NMAC for details):
   i. For peak acceleration at the foundation up to 0.20g if the dam embankment is compacted to at least 95 percent of maximum Standard Proctor density, or at least 90 percent of maximum Modified Proctor density, or at least 70 percent of relative density, and the foundation is not prone to liquefaction.

   ii. For peak acceleration at the foundation up to 0.35g if the dam embankment is compacted to at least 95 percent of maximum Standard Proctor density, or at least

90 percent of maximum Modified Proctor density, and the dam is founded on clayey soil or bedrock and the embankment is constructed of clayey material.

iii. For dams meeting factors of safety requirements for slope stability for all static loading conditions.

iv. For dams meeting freeboard requirements (see Subsection C.15 of 19.25.12.11 NMAC for details)

The acceleration selected for the pseudostatic slope stability analysis must be at least 50 percent of the predicted peak acceleration at the foundation, but in no case less than 0.05g. The analysis must be performed for the steady state seepage condition with water level at the spillway crest for water storage dams. For flood control dams with ungated outlet conduits, the analysis may be performed with an empty reservoir. The factor of safety must be at least 1.1.

b. Deformation Analysis: For dams not meeting the requirements of the pseudostatic analysis, a deformation analysis is required. Since the deformation analysis is not common, guidelines are not available for this analysis. The deformation analysis must be performed by professional engineers experienced in such analyses. The dam must be capable of withstanding the design earthquake without breaching and with at least 3 feet of freeboard remaining after deformation. The analysis must also assess the potential for internal erosion as a result of cracking during deformation.

**References:**

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