CHAPTER IV

EMBANKMENT DAMS

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Embankment Dams

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Appendix 4-A Engineering Data

Chapter IV

Embankment Dams

4-1 Purpose and Scope

4-1.1 General

The guidelines presented in this chapter provide staff engineers with recommended procedures and criteria to be used in reviewing and evaluating the safety of existing and proposed earth and rockfill (embankment) dams. The review performed by staff engineers will be conducted to ensure that all decisions, methods, and procedures performed by licensees/exemptees, or their consultants, are sound regarding dam safety, and to ensure that the Commission's Dam Safety Program objectives as stated in Part 12 of the Commission's Regulations are consistent with accepted. up-to-date state-of the-art procedures (the term licensees also refers to applicants for license where appropriate).

The evaluation of safety of both new and existing embankment dams presents special and unique problems. Existing dams may prove difficult to analyze especially in those instances where the dam was designed before the development of modern design and construction technology or where adequate records are not available. Even for a relatively new dam, where records are extensive. Evaluation can be cumbersome for the following reasons: (a) various levels of completeness of records, (b) different site conditions, (c) varying degrees of quality in design and construction, and (d) differing depth of evaluation required for each dam. The objective set forth in this chapter is to provide systematic procedures for performing staff evaluations.

4-1.2 Depth of Review

The review of existing dams will generally not be as detailed as the procedures involved in the design of new dams. Some critical areas may require detailed review. Primarily, the review is intended to evaluate procedures and methodology of design and analysis to ensure that safe and adequate embankment dams were constructed. The licensee's/exemptee's or its consultant's investigations and evaluations should be examined to determine if all areas of importance were considered and appropriate design criteria have been used.

For proposed dams, the licensee will be required to submit a design report in accordance with the Commission's Regulations. This report will be thoroughly examined to determine if all appropriate design criteria have been met.

During the investigation and evaluation for both proposed and existing dams, important areas to consider are as follows:

- The embankment must be safe against excessive overtopping by wave action especially during pre-inflow design flood conditions.

- The slopes must be stable during all conditions of reservoir operations, including rapid drawdown, if applicable.

- Seepage flow through the embankment, foundation, and abutments must be controlled so that no internal erosion (piping) takes place and there is no sloughing in areas where seepage emerges.

- The embankment must not overstress the foundation.

- Embankment slopes must be acceptably protected against erosion by wave action and from gullying and scour against surface runoff.

- The embankment, foundation, abutments and reservoir rim must be stable and must not develop unacceptable deformations under earth quake conditions. 1/ See Section 4-7 and Reference 36 for seismic design.

Existing dams should be viewed in light of knowledge of studies and reports on similar dams of the same vintage to gain an understanding of probable design and construction methods. For existing dams, an independent analysis of the embankment stability or adequacy need not necessarily be performed by staff. The data presented by the licensee should be reviewed to determine if they appear reasonable and if the latest information has been considered. The criteria used by the licensee or its consultant should be consistent with any changed conditions discovered during onsite examinations such as loadings, seepage, increased pore pressures in the dam or the foundation, erosion, etc.

For proposed dams, an analysis of the stability and adequacy is required unless specifically exempted by the Commission. The methods and procedures used in the evaluation of any embankment should be consistent with the latest, accepted state-of-the-art methods and criteria, and with guidance contained in this chapter of the Guidelines.

4-1.3 References

Criteria and methods of evaluation and analysis used in reviewing licensee's reports should be based on criteria and procedures established in literature published by such agencies as the Corps of Engineers, U. S. Bureau of Reclamation, or other recognized engineering references. Selected references are listed in Section 4-8.

1/ Reference 1, pg. 192

4-2 Sources of Data and Information

To properly evaluate all information and data presented in the licensee's design report, various available FERC reports should also be reviewed. Available reports include:

- Prelicense Inspection Reports of existing dams and/or Site Inspection Reports of proposed damsites
- Operation Reports
- Construction Reports
- Independent Consultant's Safety Inspection Reports

One or more of the above listed reports should be available for licensed projects. If a license has not previously been issued, the staff engineer performing the review should refer to the Prelicense Inspection Report prepared by the staff engineer responsible for the project in the Regional Office.

For existing dams, additional data may be available from the facility owner, previous owners, state or local agency if the facility is a publicly owned project, and from the state agency responsible for dam safety, such as Department of Water Resources, Department of Environmental Resources, Division of Dam Safety or Department of Natural Resources. Also, technical information may be available from Corps of Engineers Phase I Inspection Reports of public or private entities having impounding structures upstream or downstream of the facility.

For proposed dams, the source of information will generally be the licensee and/or its consultants and engineers. For all proposed dams, the licensee will be required to provide staff with those data necessary to evaluate whether the design of the structure is safe and adequate.

Data that may be available from the sources referenced should include:

- Logs of drill holes, test pits, and exploratory trenches
- Site geologic reports
- Site seismicity reports
- Materials exploration and testing reports
- Reservoir area-capacity curves, rim conditions, and drainage basin information

- Dambreak analyses and reports

- Construction reports

- Correspondence that may highlight design changes or problems
- Design drawings and specifications

- Design reports including assumptions used and the reasons therefore

- Inspection records

- Maintenance records

- Aerial photography

- Licensee's reports

- Construction photographs

- Concrete materials and mix design

- As built drawings

4-3 Review of Existing Data

Appendix 4-A is a listing of various engineering data related to the design, construction, and operation of an embankment dam. Prior to review and analysis of existing data, this appendix may be useful in organizing the data as discussed in the U.S. Bureau of Reclamation's "Safety Evaluation of Existing Dams" (SEED) Manual." 2/

The engineer performing the review should examine all data to determine if problem areas have been recognized and, if appropriate methods are proposed for correction. Additionally, the data should be examined to determine if the source of any current conditions or problems, such as seepage, settlement, cracking, etc., are evident from existing data. The methodologies and criteria used in the design should be examined and compared to accepted state-of-the-art procedures and criteria.

2/ Reference 2

Advances in accepted state-of-the-art methodologies may require a reevaluation of the original design or of these guidelines. The SEED Manual discusses in greater detail specific information to look for in the reports and data that may be available.

4-4 Need for Supplemental Information

The objective of reviewing existing data is to be in a position to use as much information as is available to evaluate the structural adequacy of existing or proposed embankment dams. Data and analyses should be the prevalent basis for judgments on dam safety. If potentially hazardous conditions are believed or determined to exist and the existing data are insufficient to resolve the problem, it may be necessary to request supplemental investigations, analyses, or information to complete the evaluation. The information could involve additional visual inspections, measurements, foundation exploration and testing, materials testing, seismic information, hydrologic and hydraulic data. Conditions that may require supplemental information are as follows:

- Significant cracking, settlement or sloughing of an existing embankment and the potential for such in any proposed structure

- Uncontrolled seepage conditions through the embankment, the abutments, or at the toe area, and the potential for such in any proposed structure

- Available data is not adequate to perform accepted state-of-the-art analytical methods that are necessary

- Increase in settlement rate

- Increase in measured seepage

- Rise in internal seepage pressures

4-5 Evaluation of Embankment Dams

The two principal types of embankment dams are earth dams and rock-fill dams, depending on the predominant fill material used.

a. **Earth Dams -** An earth dam is composed of suitable soils obtained from borrow areas or required excavation which are then spread and compacted in layers by mechanical means. Earth dams may be constructed as homogeneous or zoned dams. Zoned dams are generally preferred since zoning permits the use of several different material types in the embankment that may be available from borrow areas or required excavations. Homogeneous embankments are usually not considered except when free-draining materials are not readily available.

Some older dams have been placed by hydraulic means. These hydraulic fill dams frequently contain large masses of loose to very loose soils in them because of the dumping and sluicing of the soils during construction. Adequate soil data (e.g. SPT blow counts, gradation analysis, phreatic surface, etc.) must be available to evaluate the liquefaction potential and stability of these dams.

b. **Rock-fill Dams** 3/ - A rock-fill dam is an embankment composed largely of fragmented rock with an impervious earth core. The core is separated from the shells by a series of transition zones built of properly graded materials. The impervious core may be central or inclined. The core, transition zones, filters, etc. should be evaluated as discussed in Section 4-5.1. In some cases an impervious upstream membrane of concrete, asphalt, or steel plate may exist or be used in lieu of an impervious core.

Rock-fill zones are generally compacted in layers, 12 to 24 inches thick by 10 to 15 ton steel-wheel vibratory rollers. Layer thicknesses of 6 inches up to 36 inches have been also used and may be appropriate. The largest particle diameter generally should not exceed .9 of the compacted layer thickness. Dumping rock-fill and sluicing with water, or dumping in water is generally not acceptable for embankment dam construction today. However, the application of some water before compaction, on dirty rock-fill, and on the zone adjacent to an impervious upstream membrane, to achieve better compaction, is acceptable.

The structural safety of an embankment dam is dependent primarily on the absence of excessive deformations under all conditions of environment and operation, the ability to safely pass flood flows, and the control of seepage to prevent migration of materials and thus preclude adverse effects on stability.

To properly evaluate the stability of an embankment dam, the following areas should be reviewed.

- Embankment zoning and cross section
- Seepage control measures and records
- Deformation, predicted or recorded
- Erosion control measures
- Structural stability analyses

3/ Reference 3, Chapter 1

- Liquefaction potential

- Overtopping potential and the ability to resist overtopping

- Foundation and embankment material properties and strengths

- Erodibility indices

- Adequacy of freeboard

For existing dams, the review should also include summarizing the past behavior of the dam, with attention given to any problem areas noted.

4-5.1 Embankment Zoning

For zoned embankments, the zoning geometry and properties of the materials placed in the zones should be reviewed to determine: (1) the structural design, and (2) the types of internal features such as chimney drains, blanket drains, toe drains, etc., that are proposed or were used to provide for and maintain embankment stability. One should keep in mind that embankment zoning is also established for economic reasons according to the availability of materials. 4/ The embankment zoning should provide an adequate impervious zone, transition zones between the core and the shells, and seepage control zones. Desirable characteristics that these zones should have or provide are as follows:

- In general, the width of the core at the base of cutoff should be equal to, or greater than, 25 per cent of the maximum difference between the maximum reservoir and minimum tailwater elevations. The minimum top width of the core should not be less than 10 feet. 5/ The coefficient of permeability of the core material should preferably be 10^{-4} cm/sec or less. More permeable core material may be acceptable if seepage is still adequately controlled and appropriate factors of safety are still met. 6/

- Transition zones must meet accepted filter criteria, e.g. see References 1, 4, & 5, to protect the adjacent zones from piping. The transition zones should be sufficiently wide to ensure that they

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4/ Reference 1, Chapter 6

5/ Reference 3, pg. 5-3

6/ Reference 1, Chapter 6

are continuous and constructable with a minimum of contamination at the contact. 7/8/ The range of gradation of the transition zones should be limited to avoid segregation of materials during placement.

- Seepage control features within the embankment should be sized adequately to contain all seepage flows. The features should also be sufficiently pervious to ensure that all seepage will be intercepted and controlled without excessive pressure head losses. 9/10/

- Zoning of an embankment that places the more pervious material on each side of the core zone is preferable. This placement improves the stability of the embankment during rapid drawdown conditions and keeps the downstream slope drained for greater effective weight. 11/

Homogeneous dams should also have seepage control features such as chimney drains, blanket drains, etc. including a transition zone between the main embankment material and the drain.. Even if a homogeneous embankment has no specific seepage control features, these embankments must have adequate internal drainage capability to ensure against seepage outbreak on the downstream slopes or abutments. Desirable characteristics listed above also apply to the features of this type of structure. The homogeneous structure is generally more massive and usually has flatter slopes than a zoned embankment of the same height. These characteristics compensate for a tendency toward a higher phreatic line in the homogeneous embankment. They also tend to provide better slope stability during rapid drawdown. 12/

4-5.2 Seepage Control Measures

All embankment dams are subject to some seepage passing through, under, and around them. 13/ If uncontrolled, seepage may be detrimental to the stability of the structure as a result of excessive internal

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7/ Reference 4, pg. 57, 606

8/ Reference 1, Chapter 6

9/ Ibid.

10/ Reference 3, pg. 5-3

11/ Reference 5, pg.7

12/ Reference 1, Chap. 6

13/ Reference 5, pg.1

pore water pressures or by piping. 14/ For existing dams, records or evidence that seepage flows have removed any significant degree of fine grained material must be evaluated. Any such record requires further field investigation.

Seepage should be effectively controlled to preclude structural damage or interference with normal operations.

In the evaluation of seepage reduction or seepage control measures as they pertain to dam safety, one should review and evaluate the following:

- Protective control measures such as relief wells, weighted graded filters, horizontal drains, or chimney drains which prevent seepage forces from endangering the stability of the downstream slope. 15/

- Filters and transition zones designed to prevent movement of soil particles that could clog drains or result in piping. 16/17/

- Drainage blankets, chimney drains, and toe drains designed to ensure that they control and safely discharge seepage for all conditions. The design of these features must also provide sufficient flow capacity to safely control seepage through potential cracks in the embankment impervious zone. 18/

- Contacts of seepage control features with the foundation, abutments, embedded structures, etc., designed to prevent the occurrence of piping and/or hydrofracturing of embankment and/or foundation materials. 19/ If conduits or pipes exist through the embankment, they should be inspected to ensure that they are functional or have been properly sealed.

- Grouting, cut-off trenches, and impervious blankets.

14/ Reference 3, pg. 1-6

15/ Ibid., pg. 1-6, b

16/ Reference 4. pg. 57

17/ Reference 1, pg. 218

18/ Reference 3, pg. 1-6

19/ Reference 1

- Construction records for foundation shaping, treatment and grouting at the contact between the impervious core and foundation.

- Measures such as compaction requirements, seepage collars, placement of special materials, or other similar features to prevent internal erosion from seepage at the interface with concrete structures. 20/21/ If seepage collars are present, special attention should be given to compaction requirements around them. The use of seepage collars is not recommended in new construction.

- For existing embankments, all seepage records compiled during the existence of the structure should be reviewed for significant trends or abnormal changes. The causes of any abnormalities should be determined as accurately as possible.

4-5.3 Deformation, Predicted or Recorded

The type, amount, and rate of deformation of an embankment, either vertical or horizontal movement, must be estimated during the design stage and should be recorded during the operation of the structure. For proposed embankments, the structure should generally be cambered to allow for the estimated settlement during the life of the structure. For existing embankments, any evidence or records of unusual settlement, cracking, or movement should be reviewed to determine whether these conditions are detrimental to the continued safe operation of the structure. Field investigations may be required to determine the causes of these abnormalities. These investigations may involve such items as surveying the structure, installing movement detecting instruments, or excavating test pits for examination. 22/ The embankment history, height, foundation conditions, hazard, etc. are factors to be considered in determining field investigation needs.

As a result of deformation, cracking can develop through the impervious core section below the line of saturation which may result in piping. Adequately sized and graded filter zones located downstream from the impervious core can prevent piping. 23/ Corrective measures or instrumentation may be needed if adequate filter zones do not exist or are not correctly located.

4-5.4 Erosion Control Measures

20/ Ibid.

21/ Reference 3, Chapter 2

22/ Reference 4, Chapter 12

23/ Reference 4, Chapter II

Upstream and downstream slopes, the toe area, groin areas of the abutments, approach and discharge channels, and areas adjacent to concrete structures should be protected against excessive erosion from wave action, surface runoff, and impinging currents. Inadequate erosion protection can result in slope instability. 24/ Some common types of protection used are riprap, gabions, paving (concrete or asphalt), and appropriate vegetative cover.

The slope and toe protection of all embankment dams should be reviewed to determine if the dam is adequately protected against erosive forces. If the slope protection is being continually displaced, heavier protection is required. Additionally, if embankment materials, consisting of silty and sandy soils, are being moved into the slope protection, measures must be taken to correct this condition before erosion becomes detrimental to the embankment. If riprap is required, a bedding layer must be designed according to established filter criteria and placed under the riprap protection. 25/

4-5.5 Structural Stability Analyses

The evaluation of the stability of embankment dams shall be based on the available design information for proposed structures and on design and construction information and records of performance for existing embankments. The Corps of Engineers Guidelines for Safety Inspection of Dams 26/ can be used as a guide in performing the review.

Stability studies and analyses for proposed embankments will be conducted during design in accordance with methods discussed in Section 4-6.8. Quality control testing during construction will be used to confirm that the design values are being achieved. For existing embankments, the initial stability studies and analyses will normally be acceptable if they were performed by approved methodologies. Additional stability analyses should be performed if initial design analyses do not exist or are incomplete, if existing conditions have deteriorated, if hazard potential of the project has increased, if the embankment has been subjected to loading conditions more severe than designed for, if existing analyses are not in agreement with current accepted state-of-the-art methodologies, or if assumed design parameters cannot be satisfactorily justified. Satisfactory behavior of the embankment under loading conditions not expected to be exceeded during the life of the structure should generally be indicative of satisfactory stability, provided adverse changes in the physical condition of the embankment have not occurred. 27/

24/ Reference 3, Chapter 5

25/ Reference 1, Chapter 6

26/ Reference 6

27/ Reference 6, pg. 10

Evidence of any adverse changes which could affect the stability of an embankment may be obtained from visual inspection and observation of available instrumentation data covering such items as changes in pore water pressures, displacements, changes in loading conditions, seepage, etc. Review of maintenance records and related information may also provide a reference to structural behavior data for a particular structure. Should a review of project records indicate possible deficiencies in the stability of an embankment, additional information may be required regarding the foundation and embankment materials. The Corps of Engineers Guidelines for Safety Inspection of Dams 28/ and other available literature 29/30/31/32/ 33/34/35/ can be referred to in establishing the information necessary to determine the condition and material properties of the foundation and embankment.

4-5.6 Potential for Liquefaction

The phenomenon of liquefaction of loose saturated sands, gravels, or silts having a contractive structure may occur when such materials are subjected to shear deformation with high pore water pressures developing, resulting in a loss of resistance to deformation.

The potential for liquefaction in an embankment or its foundation must be evaluated on the basis of empirical knowledge and engineering judgment supplemented by special laboratory tests when necessary. Simplified methods for evaluating soil liquefaction potential are used by Seed and Idriss 36/ and Castro 37/ to relate blow counts values from standard penetration tests to safe, unsafe, and marginal conditions. These empirical charts relate to observations of manifestations of increase of pore pressure under level ground, such as sand boils. The empirical charts should be considered only as a

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28/ Ibid.

29/ Reference 3

30/ Reference 5

31/ Reference 7

32/ Reference 8

33/ Reference 9

34/ Reference 10

35/ Reference 15

36/ Reference 12

37/Reference 13

guide for identifying zones within the dam and its foundation that may require further study. Further discussion of liquefaction is presented in Section 4-7.

4-5.7 Soil Properties

Soil properties including strength and seepage parameters to be used as input data for stability analyses should be realistic and representative of the range and variation that exist in the foundation, abutment, and embankment materials. 38/ For information concerning the characteristics and strengths of foundation and embankment soils and rock, refer to the procedures established in the Corps of Engineers and U.S. Bureau of Reclamation Guidelines, 39/40/41/42/ and other literature. 43/44/45/46/ The selection of the proper input parameters and their correct use in a stability analysis are generally of greater importance than the method of stability analysis used.

4-5.8 Embankment Overtopping Potential

All embankment dams, either proposed or existing, should be evaluated for overtopping potential under the most extreme conditions expected for which the dam is determined to be a hazard to life or property. Chapter 2 of these Guidelines discusses the Spillway Design Flood and provides freeboard criteria. The maximum reservoir elevation determined for the design flood and expected wave runup are conditions that should be considered. However, a less severe storm with lower reservoir elevation but greater wave propagation may result in conditions that are more critical than those produced by the design flood. In general, overtopping of an embankment is not acceptable. However, for existing dams should minor or intermittent overtopping be determined to be a possibility, an evaluation of the acceptability of this condition must be made based on such information as the characteristics of the

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38/ Reference 14

39/ Reference 8

40/ Reference 9

41/ Reference 2

42/ Reference 15

43/Reference 16

44/Reference 4

45/Reference 17

46/Reference 34

flood hydrograph, embankment materials, prevailing wind direction, fetch, slope and crest protection, hazard potential at that time, etc.

4-6 Static Stability Evaluation

4-6.1 General

As discussed in Section 4-1.2, a new, independent stability analysis by staff is not necessarily required for a proposed or existing embankment. Spot checks of analyses may be required to verify that application of the specific analytical approach is correct. The analysis and evaluation of the structural adequacy of an embankment dam by the licensee and/or its consultant should be reviewed based on information formulated by the licensee and information developed by the Regional Office staff from various project inspections and data requests resulting from the licensing or inspection program. For embankment dams, stability analyses should be examined to determine if the criteria used and loading conditions analyzed are appropriate. This review should be based on the above information to determine if the methods of analyses used are based on accepted state-of-the-art and that proper types of failure surfaces have been analyzed (e.g., wedge, circular, or noncircular).

An independent stability analysis should be performed by staff if actual conditions differ from those assumed in the licensee's analysis, if soil parameters are inconsistent with material types, if soil strength parameters or pore water pressures are inconsistent with the method being used, or if the critical failure surfaces do not appear to have been determined.

Staff has several stability programs for computers available. 47/ These programs may be used by staff in reviewing the results of the licensee's analyses. It should, however, be understood that the results obtained by these methods of analyses may not necessarily agree exactly with the licensee's results based on another method; however, it will provide an indication as to the adequacy of the analysis being reviewed. Staff is not limited to the use of these computer programs. Other accepted programs may also be used. The staff should verify that the licensee has checked the analysis by hand calculations for potential critical cases that have marginal factors of safety.

A brief discussion is included in this section of the Engineering Guidelines concerning some methods of stability analysis and why the results obtained from each method may vary to some degree. Additionally, references are listed in Section 4-8 that analyze the various methods of stability analyses in detail. An historical development of methods of stability analyses is presented in Reference 16. 48/

47/ Reference 37 and 38

48/ Reference 16, pp. 323-326

4-6.2 Review Approach

Stability analyses should be reviewed to determine if input data appear appropriate based on a knowledge of the embankment and foundation materials, on pore pressures in the embankment and its foundation, or if the method of analysis chosen by the licensee is being used correctly. The literature provides several publications, textbooks, and other sources of information that discuss in detail the various methods of analyses available. Refer to Section 4-8 for references that can be used in obtaining information for use in reviewing a particular method of stability analysis. 49/50/

A review of the stability analysis presented by the licensee shall include an evaluation and summary of the data used in the analysis and an evaluation to determine if the critical conditions have been investigated. The items to be evaluated include:

- Densities of soils
- Shear strength parameters
- Pore water pressures, estimated or existing
- Loading conditions
- Trial failure surfaces
- Method of analysis

The soil densities and shear strengths to be used for the various loading conditions investigated can be evaluated by studying available laboratory test data and/or comparing data presented to that known for similar materials based on past experiences and on data available from other dams consisting of similar materials and construction methods.

Pore water pressures used in the analysis of the various loading conditions investigated should be reviewed to determine if they are realistic based on available instrumentation data or estimates based on such methods as those proposed by Casagrande 51/ and Carstens and May. 52/

49/ Reference 20

50/ Reference 26

51/ Reference 18

52/ Reference 19

When field explorations and laboratory testing are required to provide additional information concerning the strength characteristics of the embankment materials, the sampling and laboratory testing procedures should be reviewed to determine if they were adequately accomplished and are representative of the conditions analyzed. Corps of Engineers and U.S. Bureau of Reclamation technical guidelines concerning sampling and laboratory testing procedures can be used to complete this review. 53/54/55/

4-6.3 Conditions to be Investigated

An embankment and its foundation are subject to shear stresses imposed by the weight of the embankment and by pool fluctuations, seepage, or earthquake forces. Loading conditions vary from the commencement of construction of the embankment until the time when the embankment has been completed and has a full reservoir pool behind it. The range of loading conditions encompasses the following conditions at various stages from construction through the operational stage of the completed embankment:

- End of Construction
- Sudden drawdown
- Partial pool with steady seepage
- Steady seepage, normal pool
- Earthquake
- Appropriate flood surcharge pool

In all loading cases, the shear strength along any potential failure surface must be defined. The shear strength available to resist failure along any particular failure surface depends on the loading conditions applied.

4-6.4 Shear Strength

53/ Reference 9

54/ Reference 10

55/ Reference 15

Generally, the shear strengths of materials used in stability analyses are determined from laboratory testing procedures which attempt to duplicate the various loading conditions to which the embankment is expected to be subjected. 56/57/58/

From the time construction begins until the reservoir has been filled and a state of steady seepage has been established, three different conditions of drainage will have occurred. Shear strength values used in stability analyses for each condition of drainage are determined from laboratory tests on specimens of the material which are compacted to the density and water content that simulates the conditions anticipated in the dam. 59/ Tests corresponding to the three conditions of drainage are: 60/61/62/63/

- Q or unconsolidated-undrained (UU) test in which no initial consolidation is allowed under the confining pressure and the water content is kept constant during shear.

- R or $\overline{R}$ consolidated-undrained (CU) tests in which consolidation is allowed under initial stress conditions but in which the water content is kept constant during application of shearing stresses. The $\overline{R}$ test is identical to the R test except that pore water pressure measurements are made during the $\overline{R}$ test.

- S or consolidated-drained (CD) test in which consolidation is permitted under the initial stress conditions and also for each increment of loading during shear.

4-6.4.1 Laboratory Testing

Testing procedures for determining the shear strengths of soils to be used in stability analyses, as well as determining other engineering properties of soils, such as density, moisture content, consolidation,

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56/ Reference 11

57/ Reference 16

58/ Reference 20

59/ Reference 16

60/ Reference 11

61/ Reference 10, pp. 328-338

62/ Reference 16

63/ Reference 20

permeability, gradation, etc., can be found in Corps of Engineers and U.S. Bureau of Reclamation manuals. 64/65/ When reviewing-analyses of existing embankments the R, $\overline{R}$, and S shear strength parameters may be considered. In situations where unconsolidated soils may still exist for years after construction a strength envelope between the Q and $\overline{R}$ may be appropriate in evaluating the stability of the embankment dam. For proposed dams, shear strength parameters obtained from the Q test will also be used.

4-6.4.2 Q - Unconsolidated-Undrained Shear Strength

The Q test is performed on specimens of impervious materials under simulated loading conditions expected to occur during construction of embankments and results in an approximation of the end-of-construction shear strength of the material.

4-6.4.3 R and $\overline{R}$ - Consolidated-Undrained Shear Strength

The R and $\overline{R}$ tests apply to conditions in which impervious or semipervious soils that have been fully consolidated under one set of stresses are subjected to a stress change during the test without time for consolidation to take place (soil is sheared without allowing dissipation of pore pressures).

4-6.4.4 S - Consolidated-Drained Shear Strength

The shear strength resulting from an S test is obtained by fully consolidating the soil specimen under the applied confining stress and, when drainage is complete, applying shear stresses slowly enough to allow full drainage to occur during the shearing process under each loading increment.

4-6.5 Types of Stress Analyses

In general there are two types of stress analyses that are used in the evaluation of existing and proposed embankments. These are the total stress analysis and the effective stress analysis. The total stress analysis is used in the design of embankments for loading conditions during construction, rapid drawdown, and earthquake. The effective stress analysis should be used only in cases where the soils behave drained and piezometer data are available. The cases that can be analyzed by the effective stress method are partial pool and steady seepage.

4-6.6 Loading Conditions for Analysis

64/ Reference 10

65/ Reference 15

As outlined in Section 4-6.3, an embankment may be subjected to several loading conditions during its life, ranging from construction to full pool operation. The loading conditions for which an embankment must be analyzed are presented in detail in the following paragraphs.

4-6.6.1 End of Construction Loading Condition

At the end of construction, an embankment dam is still undergoing internal consolidation under its own weight. For homogeneous dams or for zones in dams constructed from impervious materials, pore water pressures will be built up during construction due to the inability of the impervious soil mass to drain rapidly during consolidation.

The shear strength applicable to the impervious dam or zones within the dam during the construction loading condition, is determined by the Q test conducted at field moisture contents and at field confining stresses. The type of stress analysis that applies to this loading condition is the total stress analysis. Because of the difficulty in estimating pore water pressures within the embankment during this stage of loading, an effective stress analysis is not generally used. The analysis may, however, be conducted using pore pressure responses in previously constructed dams that used materials, construction methods, and construction schedules similar to those for the proposed dam. For pervious zones in the embankment where drainage can occur rapidly, S strengths should be used in the analysis.

The end of construction analysis using shear strengths obtained from the Q test as representative of the strength available in the impervious zones of an embankment, represents a lower limit of stability since consolidation is progressing during the course of construction. If there are any serious questions about stability during construction, the only positive method to determine the stability is to install piezometers and evaluate the stability during construction.

4-6.6.2 Sudden Drawdown Loading Condition

In the sudden drawdown loading condition the structure has been subjected to a prolonged high pool during which time a steady seepage condition has been established through the embankment. The soil in the embankment below the phreatic surface is in a completely saturated state and is fully consolidated under the weight of the overlying material. If subsequently the reservoir pool is drawn down faster than pore water can escape, excess pore water pressures develop. Consequently, the reduced factor of safety following a reservoir drawdown is due primarily to the existence of high residual pore water pressures (drawdown pore water pressures) acting inside the upstream slope. 66/ The shear strength is governed by the state of stress developed during consolidation under buoyant weight before drawdown. 67/

The shear strength parameters required for an analysis under this loading condition are obtained from the $\overline{R}$ test. An expression is then determined for relating consolidation pressure to the undrained shear

66/ Reference 16, pg. 370

67/ Reference 20, pg. 26

strength. Laboratory tests are performed under consolidated -undrained conditions, in which the samples are consolidated under stresses corresponding to the conditions immediately preceding the drawdown. 68/69/ If the material being investigated can drain so rapidly as to dissipate practically all the excess pore water pressure as the drawdown progresses, 70/ the drained or S strength is the strength used in the analysis. This type of analysis is referred to as a total stress analysis.

If an effective stress analysis is conducted, one method of measuring the effective stress parameters is to perform consolidated-undrained triaxial tests on the soil with the measurement of pore pressure. This type of test is referred to as an $\overline{R}$ test. The accuracy of this type of analysis rests in how well the pore pressures can be estimated. If $\overline{R}$ tests are run on undisturbed samples retrieved from an existing embankment, results of pore-pressure observations in the field can be used in determining pore pressure coefficients to be used in the $\overline{R}$ testing procedure.

For further discussion on differences between total and effective stress analyses refer to References 4 and 16. Laboratory procedures for the R and $\overline{R}$ tests are discussed in Reference 10.

When conducting a sudden drawdown analysis the Corps of Engineers uses shear strength based on the minimum of the combined R and S envelopes (figure 1). 71/ Shear strengths of free-draining materials where dissipation of pore water pressure can proceed as the reservoir pool is drawn down will be based on the S shear strength envelope of the material.

68/ Reference 4, pg. 258

69/ Reference 20, pp. 23-27

70/ Reference 4, pg. 258

71/ Reference 11

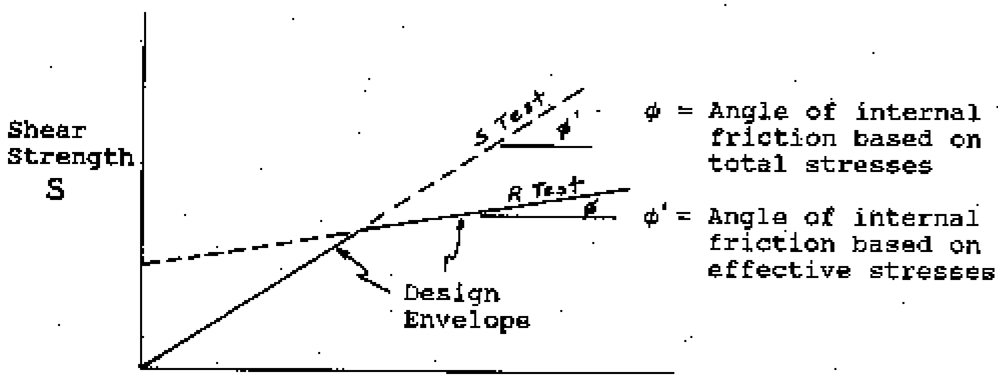

Figure 1

The unit weights of the soils to be used in analyzing the "before drawdown" condition will be the moist weights above the line of saturation and submerged weights below. In analyzing the "after drawdown" condition, moist unit weights will be used for the zone above the original phreatic surface, saturated unit weights will be used within the drawdown zone, and submerged weights will be used below the level of drawdown.

4-6.6.3 Steady Seepage Loading Condition

Steady seepage develops after a reservoir pool has been maintained at a particular elevation (e.g., maximum storage pool) for a sufficient length of time to establish a steady line of saturation through the embankment. The seepage forces which develop in the steady state condition act in a downstream direction. The condition of steady seepage throughout an embankment may be critical for downstream slope stability. 72/ The seepage forces can be conservatively estimated by assuming a horizontal phreatic line through the impervious zone at the elevation of the storage pool intersected by zones of free-draining material. However, high abutment groundwater tables may cause the phreatic surface to be higher in the vicinity of the abutments. In homogeneous impervious embankments, the line of seepage can be estimated by various methods. 73/74/ Examples of estimating the line of seepage through an embankment are given in Reference 5. If sufficient instrumentation is available, piezometer levels in both the embankment and foundation can be reviewed and phreatic surfaces can be developed accordingly.

72/ Reference 11, pg. 19

73/ Reference 18

74/ Reference 19

The pore water pressures which exist within an embankment at any given time are generated as the result of two actions which can be considered independent for practical purposes: (1) gravity seepage flow, and (2) changes in pore volume due to changes in the total stresses. 75/ The full reservoir stability condition is nearly always analyzed using the effective stress method of analysis and the pore water pressures acting are assumed to be those governed by gravity flow through the embankment. 76/

For design purposes, the Corps of Engineers generally uses the shear strength of impervious soils corresponding to a strength envelope midway between the R and S test envelopes when the S strength is greater than the R strength. The S envelope is used when the S strength is less than the R strength (figure 2). The shear strength of freely draining cohesionless soils should be represented by the S test envelopes. 77/

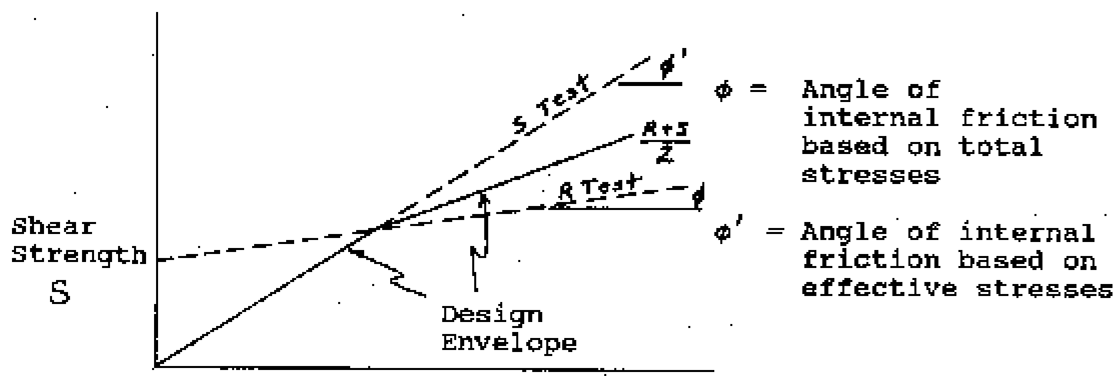

Figure 2

The unit weights to be used in the analysis will be the moist unit weight above the line of saturation and submerged weights below this line.

In the case where a steady seepage condition exists in an embankment, an additional horizontal thrust may be imposed by a surcharge pool up to the probable maximum pool elevation, generally not for a prolonged period of time. Thus the impervious zone would not become saturated above the steady

75/ Reference 16

76/ Ibid.

77/ Reference 11, pg. 18

state condition established under normal reservoir conditions. The shear strengths to be used in the stability analyses should be the same as those used in the steady seepage case with maximum storage pool.

4-6.6.4 Partial Pool Loading Condition

The same information applies to the partial pool loading condition as to the steady seepage loading condition except that the upstream slope is also analyzed. The upstream slope should be analyzed for various pool elevations to determine which pool elevation creates the lowest factor of safety.

4-6.6.5 Earthquake

Evaluations of seismic effects for embankments located in areas of low or negligible seismicity (0.05g or less) may be accomplished using the seismic coefficient in the pseudostatic method of analysis. Seismic coefficients at least as large as shown in figures 6, 6a, 6b, and 6c of Reference 11 shall be employed as applicable. 78/ The pseudostatic method assumes that the earthquake causes additional horizontal forces in the direction of potential failure. This investigation need only be applied to those critical failure surfaces found in analyzing loading conditions without earthquake loading. An analysis of earthquake loading is seldom necessary in conjunction with sudden drawdown stability analysis. However, if earthquake loading is possible during reservoir drawdown associated with a pumped storage project where frequency of drawdown occurs on a daily cycle, earthquake effects during sudden drawdown should be investigated. The selection of shear strengths to be used in the analysis are discussed in Section 4-7.

For embankments located in areas of strong seismicity, a dynamic analysis of embankment stability should be performed based on present state-of-the-art procedures. Refer to Corps of Engineers ER 1110-2-1806, "Earthquake Design and Analysis for Corps of Engineers Dams," for the earthquake loading to be used in dynamic analyses and for guidance in performing seismic evaluations.

In general, an embankment dam should be capable of retaining the reservoir under conditions induced by the maximum credible earthquake where failure would cause loss of life. The following investigations should be accomplished for all proposed and existing embankments, with the exception that existing confirmed "low" hazard potential dams may be exempted from these investigations.

- A seismic stability investigation using a dynamic analysis for proposed and existing dams located in Seismic Zones 3 and 4 of Reference 33.

78/ Reference 11, change 1, dated 17 February 1982

- An evaluation of the liquefaction potential for all dams that have or will have liquefiable materials either in the embankment or foundation.

- A geological and seismological review of existing dams in Seismic Zones 2, 3, and 4 of Reference 33, to locate faults and ascertain the seismic history the of region around the dam and reservoir.

- A seismic stability investigation of existing dams by dynamic analyses, regardless of the seismic zone in which the dam is located where capable faults or recent earthquake epicenters are discovered within a distance where an earthquake could cause significant structural damage.

4-6.7 Factors of Safety

The factor of safety includes a margin of safety to guard against ultimate failure, to avoid unacceptable deformations, and to cover uncertainties associated with the measurement of soil properties or the analysis used. 79/ In selecting a minimum acceptable factor of safety an evaluation should be made on both the degree of conservatism with which assumptions were made in choosing soil strength parameters and pore water pressures, and the influence of the method of analysis which is used.80/ The latter concerns the method of calculation in which side earth forces are considered and how assumptions of directions of side earth forces affect stability analysis results.

A qualitative estimate of the factor of safety can be obtained by examining conditions of equilibrium when incipient failure is postulated, and comparing the strength necessary to maintain limiting equilibrium with the available strength of the soil. 81/

Therefore, the slope stability analysis of soils requires measurements of the shear strength and computation of the shear stress. Appropriate minimum values of factors of safety to be used in the stability analysis of a slope depend primarily on the measurement of strength. Factors influencing the selection of minimum factors of safety include:

- Reliability of laboratory shear strength testing results

- Embankment height

- Storage capacity

79/ Reference 22, pg. 48

80/ Reference 16, pp. 368-371

81/ Reference 23

- Thoroughness of investigations
- Construction quality, construction control of embankment fills
- Judgment based on past experience
- Design conditions being analyzed
- Predictions of pore water pressures used in effective stress analyses

FERC minimum factors of safety are listed in Table 1. Final accepted factors of safety may depend upon the degree of confidence in the engineering data available. In the final analysis, the consequences of a failure with respect to human life. property damage, and impairment of project functions are important considerations in establishing factors of safety for specific investigations.

4-6.8 Static Stability Analysis

Various analytical methods for evaluating the static stability of an embankment dam exist. The method utilized in the licensee's analysis should be consistent with the anticipated mode of failure, dam cross section, and soil test data.

4-6.8.1 Limit Equilibrium

Many methods of stability analyses exist that use the same general approach of employing the "limit equilibrium method" of slope stability analysis. In this type of approach a qualitative estimate of factor of safety can be obtained by examining the conditions of equilibrium when incipient failure is postulated, and comparing the strength necessary to maintain limiting equilibrium with the available strength of the soil. The factor of safety (F.S.) is thus defined as the ratio of the total shear strength available (s) on the failure surface assumed to the total shear stress mobilized T along the failure surface to in order maintain equilibrium. 82/

$$F.S. = \frac{s}{J} \qquad (1)$$

A state of limiting equilibrium exists when the shear strength mobilized is expressed as:

82/ Reference 24

$$J = \frac{1}{F.S.}(s) \qquad (2)$$

F.S. is a factor of safety with respect to shear strength and 1/F.S. is the degree of mobilization of the shear strength. It may be shown that the definition of F.S. given by equation (1) is equivalent to the one used in the Ordinary Method of Slices, where the factor of safety is defined as the ratio of the resisting moment to the over turning moment. 83/

The shear strength of a soil is expressed by the following expression:

$$s = c + F \tan N$$

in which c and N represent the intercept and slope of the Mohr-Coulomb shear diagram and F represents the normal stress on the shear surface. Thus, to determine the shear strength along a potential failure surface the normal stress on the shear surface must be known. In analyzing both force and moment conditions of equilibrium it becomes apparent that the problem of determining the distribution of the normal stress on the shear surface is statically indeterminate, that is, there are more unknowns than there are equations of equilibrium. 84/ An approach to this situation is to make assumptions to reduce the number of unknowns in order that the problem is statically determinate, such as is done in the "limit equilibrium" analysis procedure. Different procedures use different assumptions. Some methods do not satisfy all conditions of equilibrium, such as moment equilibrium or vertical and horizontal force equilibrium. Table 2 shows equilibrium conditions satisfied by various methods of analysis.

Table 2

Equilibrium Conditions Satisfied

Procedure	Overall Moment	Individual Slice Moment	Vertical Force	Horizontal Force
Ordinary Method of Slices	Yes	No	No	No

83/ Reference 25, pg. 784

84/ Reference 25

Bishop's Modified Method	Yes	No	Yes	No
Janbu's Generalized Procedure of Slices	Yes	Yes	Yes	Yes
Spencer's Procedure	Yes	Yes	Yes	Yes
Morgenstern and Price	Yes	Yes	Yes	Yes

Studies have been performed to examine the accuracy of the equilibrium methods of slope stability analysis. 85/86/

4-7 Seismic Stability Evaluationy

Various methods of analyses are available for evaluating the seismic stability of an earth dam. These may be classified as:

- Pseudostatic methods
- Simplified procedures
- Dynamic analyses of embankment stability and deformability

Regardless of the method of analysis, the final evaluation of the seismic safety of the embankment should be based on all pertinent factors involved in the investigation and not solely on the numerical results of the analysis. 87/ References presented in the Corps of Engineers ER 1110-2-1806 can be used in determining the scope of analysis required for properly assessing the seismic stability of an embankment dam.

Table 1 (1)

Loading Condition	Minimum Factor of Safety	Slope to be Analyzed

85/ Reference 25, pp. 783-791

86/ Reference 26, pp. 475-498

87/ Reference 21

End of construction condition	1.3	upstream and downstream
Sudden drawdown from maximum pool	>1.1*	upstream
Sudden drawdown from spillway crest or top of gates	1.2*	upstream
Steady seepage with maximum storage pool	1.5	upstream and downstream
Steady seepage with surcharge pool	1.4	downstream
Earthquake (for steady seepage conditions with seismic loading using the seismic coefficient method)	>1.0	upstream and downstream
Earthquake (for all dynamic analyses using a deformation method)		<2 feet of Newmark-type deformation along the potential failure plane (3)

The degree of safety against ultimate failure may be defined as:

$$\text{Factor of Safety} = \frac{\text{strength}}{\text{stress}}$$

or $$F.S. = \frac{J_f}{J}$$

where F.S. = factor of safety

J_f = shear strength along the trial shear surface

J = equilibrium shear stress along the same trial shear surface

4-7.1 General Approach

- Analyses for earthquake loading should begin with simplified procedures and proceed to more rigorous methods of analyses as a particular situation may warrant. Projects with well compacted embankments and dense foundation soils located in Seismic Zones 1 or 2, 88/ and all confirmed low hazard potential projects, may be evaluated by the pseudostatic method using the seismic coefficient assigned to the seismic zone the project is in.

- In areas of severe and/or frequent seismic loading such as in seismic Zones 3 and 4 or where foundation liquefaction potential exists, more rigorous dynamic methods of analyses will be necessary. 89/ Site specific seismic evaluations will be performed for all projects not covered in the paragraph above. These studies will identify earthquake source areas, the maximum credible earthquake, and the distance from the site of each relevant source area. Potential for fault rupture in the dam foundation and in the reservoir will be assessed. The modes of failure that need to be investigated and the appropriate methodology are described in the following subsections.

4-7.2 Modes of Failure:

a. **Loss of Stability**

The dam becomes unstable as a result of loss in strength in the dam or foundation - Liquefaction Slide - typical examples: Lower San Fernando Dam and Ft. Peck Dam.

b. **Excessive Deformations**

The dam remains stable during and after the earthquake; however, deformations can accumulate. The accumulated deformation needs to be estimated and evaluated with respect to its effects on the likelihood of an uncontrolled release of water from the reservoir.

c. **Other Mechanisms:**

- Overtopping due to seiches

- Movements along a fault passing under the dam

- Landslides in abutments causing direct damage to the dam or due to wave in reservoir (Vaiont dam)

88/ Reference 33

89/ Reference Ibid.

4-7.3 Methods of Analyses

a. Pseudostatic Analysis Procedures

For many years the standard method of evaluating the safety of embankment dams against sliding during earthquakes has been the pseudostatic method of analysis. In using this approach no special consideration has been given to the nature of the slope-forming or foundation materials and if the computed factor of safety was larger than unity, it has generally been concluded that the seismic stability question has been satisfactorily resolved. 90/ In Terzaghi's opinion, depending on the nature of the slope-forming materials, a slope may remain stable if the factor of safety is less than unity or may fail if the factor of safety has been found to be greater than unity based on the pseudostatic approach. 91/ This has been confirmed by embankment performances in recent earthquakes.

In general, therefore, earthquake analyses using the seismic coefficient method may be performed only for structures proposed or existing in Seismic Zones 1 and 2. Seismic coefficients at least as large as shown in the Corps of Engineer ER 1110-2-1806, should be employed in the analysis. 92/ In Zones 3 and 4 and in other zones where the pseudostatic method of analysis does not necessarily evaluate appropriately the safety of an embankment, more sophisticated analyses should be performed.

b. Simplified Analysis

Following a detailed study of embankment dam performance during earthquakes, 93/ Seed observed that the seismic resistance of dams constructed of clayey soils is much higher than that of embankments constructed of saturated sands or other cohesionless soils. Thus for embankments which do not involve saturated cohesionless soils, the pseudostatic method of analysis may still be used; alternatively, methods for evaluating deformations in such dams have been developed. The computed displacements can be compared to allowable displacements to determine the adequacy of the embankment (See 4-7.3.d). Methods for evaluating deformations have been developed by Seed and Newmark. 94/95/

90/ Reference 27, pg. 220

91/ Ibid.

92/ Reference 33

93/ Reference 27, pg. 227

94/ Reference 28

95/ Reference 29

When embankments and/or their foundations are composed of loose sands, silts, or gravels, the pseudostatic method may not be applicable. Therefore, analyses must be performed to determine (a) if liquefaction potential exists and (b) whether such a liquefied condition can lead to failure or excessive deformations of an embankment. There are various simplified methods available for evaluating soil liquefaction potential 96/97/98/ based on empirical correlations between in situ behavior of sands and standard penetration resistance. In addition, methods exist to assess the liquefaction potential of a soil by determining whether the soil is contractive or dilative. 99/100/ Under cyclic loading of sufficient magnitude and duration, a loose saturated sand, silt, or gravel having a contractive structure will develop high pore water pressures, lose a large portion of its resistance to deformation, and flow.

c. **Loss of Stability**

The potential for loss of stability can be analyzed using a conventional stability analysis (Section 4-6) incorporating minimum strength values corresponding to the degree to which pore water pressures are generated in the soils by the earthquake shaking. Where the pore pressure ratio in the soil builds up to a value close to 100%, the soil is considered to have developed a condition of liquefaction.

The determination of those zones where liquefaction or pore pressure build-up will occur must be made using a dynamic analysis to determine the stresses and strains induced in the embankment by the maximum anticipated earthquake motions and a knowledge of the pore pressure generation characteristics of the soils comprising the embankment and its foundation. 101/ In general clayey soils do not appear to develop increases in pore pressure due to earthquake shaking. However cohesion-less soils are highly vulnerable to pore pressure development depending on their relative density and other characteristics which should be considered in the seismic evaluation.

Once the degree of pore pressure build up has been evaluated, and zones of potential liquefaction identified, soil may be assigned strength values for use in a stability analysis as follows:

96/ Reference 29

97/ Reference 30

98/ Reference 13

99/ Reference 31

100/ Reference 32

101/ Reference 27

Soil Type	Saturated	Unsaturated
Impervious (clayey)	S_{up}	S_{up}
Pervious (sands) with r_u = 100%	lower of S_{us} or S_r and S_{ds}	S_{d-u}
Pervious (sands) with r_u <100%	S_{d-u}	S_{d-u}

where: S_{up} = undrained peak strength

S_{us} = undrained steady-state strength

S_{ds} = drained steady state strength

S_r = residual strength of liquefied soil

S_{d-u} = shear strength determined by effective stresses corresponding to induced pore pressure.

For soils which develop a condition of r_u = 100% the value of S_{us} or S_r is likely to control the stability of the slope and appropriate values may be determined as follows:

- Based on empirical information from liquefaction slides in similar soils. There is a general correlation between values of S_r and values of $(Nl)_{60}$, the normalized standard penetration resistance of sands and silty sands, presented in Reference 39. However, it is important to be guided in the choice of values of S_r by empirical information from previous failures involving soils similar to the ones under study.

- Based on laboratory tests using the procedures described in Reference 21. In interpreting the test data it should be noted that values of S_{us} are very sensitive to void ratio changes and thus it is necessary to apply corrections to laboratory measured strengths to obtain in-situ values and for possible void ratio redistribution during the period of earthquake shaking, and to interpret the results conservatively.

If the stability analysis indicates no potential for a liquefaction (flow) failure, then a deformation analysis should be performed.

d. **Deformations**

Deformation computations are applicable only to dams not subject to a liquefaction (stability) failure.

Deformations can be assumed not to be a problem if the dam is well-built (densely compacted) and peak accelerations are 0.2g or less. 102/ If this condition is not satisfied, a deformation analysis should be made. This analysis can he made using the Newmark approach or a simplified Newmark procedure. 103/ The deformation calculated along the failure plane by these methods should not generally exceed 2 feet. Larger deformations may be acceptable depending on available freeboard, ability of the embankment to heal cracks and other considerations.

The basic steps involved in conducting a deformation analysis are as follows:

- Determine the magnitude and source of the earthquake or earthquakes that should be considered
- Determine the time-history or time histories of the ground motion associated with the earthquake or earthquakes
- Determine the yield strength of the embankment and foundation materials
- Determine the dynamic response of embankment and foundation materials
- Predict the extent of structural deformations resulting from earthquake shaking
- If predicted deformations are not tolerable, explore design alternatives that would provide a tolerable response

e. Other Methods of Analysis

Other failure mechanisms identified in Section 4-7.2 require special methods of analysis which would need to be adapted or developed for the special circumstances of the project. Generally dams located over faults that could potentially move during an earthquake should not be permitted unless filter transition zones are provided which are at least twice the maximum potential fault movement both horizontally and vertically.

4-8 References

102/ Reference 8

103/ Reference 4

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4-9 APPENDICES

APPENDIX 4-A

ENGINEERING DATA

APPENDIX 4-A

ENGINEERING DATA

This appendix lists engineering data which should be collected relating to the design, construction, and operation of an embankment dam to be used in establishing the adequacy of embankment structures.

1. **General Project Data**

a. Construction dates.

b. Design of structures.

c. As-built drawings indicating plans, elevations, and sections of embankment and appurtenant structures.

d. Information on any modifications made, if applicable, such as dam raising.

2. **Geotechnical Data**

a. Regional and site seismicity.

b. Foundation data and geological features including logs or borings, geological profiles and cross sections, and reports of foundation treatment.

c. Engineering properties assigned to construction materials and the foundation for design purposes including results of laboratory tests, field permeability tests, construction control tests, and assumed design properties for materials.

3. **Construction History**

a. Construction procedures and methods used.

b. Properties and characteristics of construction materials.

c. How was quality control measured and maintained?

d. Final foundation and embankment reports.

4. **Operation and Maintenance Records**

a. Performance record to date based on instrumentation observations and surveillance reports.

b. Comparison of conditions to which embankment has been subjected, to those assumed in the original design.

c. Remedial measures undertaken during life of project.

d. Known deficiencies and any work underway to correct deficiencies.

5. **Inspection History**

a. Operation inspections reports.

b. Safety inspections reports.