Chapter 3
Stability Requirements

3-1. General

The concepts used to develop the structural stability requirements contained in this manual are to establish safety factors or safety provisions for the three prescribed load condition categories of usual, unusual, and extreme such that the risk of a failure is kept to an acceptably low level and such that performance objectives are achieved. The use of three different design-load condition categories permits different safety factors or safety provisions to be assigned to the various load conditions depending on the probability of the load condition occurring during the life of the structure. The load conditions used in the stability analyses are described on a probabilistic basis, except the seismic loads and large flood loads falling into the extreme category may be either probabilistic or deterministic.

3-2. Load Condition Categories

The load conditions that a structure may encounter during its service life are grouped into the load condition categories of usual, unusual, and extreme. Associated with each category is a likelihood that the load condition will be exceeded in a given time period. The load conditions, expressed in probabilistic terms, are provided in Table 3-1. The structural performance and the risk of damage or failure depends not only on the likelihood of the loading condition, but also on the safety factors or the safety provisions used, the degree of conservatism used in selecting the foundation strength parameters and hydrological data, and the degree of conservatism inherent in the methods used for the analysis. No attempt has been made to define the likelihood of damage or failure in probabilistic terms. However, the use of these guidelines in conjunction with other Corps guidance will provide structures with adequate protection against stability failure.

Table 3-1 Load Condition Probabilities

Load Condition Categories	Annual Probability (p)	Return Period (t_r)
Usual	Greater than or equal to 0.10	Less than or equal to 10 years
Unusual	Less than 0.10 but greater than or equal to 0.0033	Greater than 10 years but less than or equal to 300 years
Extreme	Less than 0.0033	Greater than 300 years

- *Usual* loads refer to loads and load conditions, which are related to the primary function of a structure and can be expected to occur frequently during the service life of the structure. A usual event is a common occurrence and the structure is expected to perform in the linearly elastic range.

- *Unusual* loads refer to operating loads and load conditions that are of infrequent occurrence. Construction and maintenance loads, because risks can be controlled by specifying the sequence or duration of activities, and/or by monitoring performance, are also classified as unusual loads. Loads on temporary structures which are used to facilitate project construction, are also classified as unusual. For an unusual event some minor nonlinear behavior is acceptable, but any necessary repairs are expected to be minor.

- *Extreme* loads refer to events, which are highly improbable and can be regarded as emergency conditions. Such events may be associated with major accidents involving impacts or explosions and natural disasters due to earthquakes or flooding which have a frequency of occurrence that greatly exceeds the economic service life of the structure. Extreme loads may also result from the combination of unusual loading events. The structure is expected to accommodate extreme loads without experiencing a catastrophic failure, although structural damage which partially impairs the operational functions are expected, and major rehabilitation or replacement of the structure might be necessary.

Appendix B lists the loading conditions that must be evaluated to ensure the stability of specific structure types. The loading conditions have been taken from other USACE manuals and may have been modified to be consistent with other provisions of this manual. When a loading condition is defined in terms of a return period (for example, the Operational Basis Earthquake is defined as an earthquake with a return period of 144 years), the structural engineer can determine if the load condition is usual, unusual, or extreme by referring directly to Table 3-1. When a load condition is stated in non-probabilistic terms, (for example, pool elevation at the top of closed spillway gates, or water to the top of a flood wall), the return period must be determined to see if that particular load condition is usual, unusual, or extreme. In some cases, the load condition category is specifically designated based on established practice, irrespective of any return period (for example, construction is listed as an unusual loading). The engineer only needs to verify stability for those conditions listed in Appendix B. For example, for the unusual category, it is not necessary to verify stability for a 300 year flood or earthquake if these are not specifically listed in Appendix B. Definitions of common loadings for civil works projects are provided in Chapter 4, including: normal operating, infrequent flood, maximum design flood, probable maximum flood, operational basis earthquake, maximum design earthquake, and maximum credible earthquake.

3-3. Risk-based Analysis for USACE Flood Project Studies

USACE policy now requires the application of risk-based analysis in the formulation of flood-damage-reduction projects. The requirements are briefly discussed in the next paragraph to familiarize the structural engineer with the procedures used by hydrology/hydraulics (H&H) engineers use to develop the degree of protection provided by the project (i.e., dam height, floodwall height). The structural engineer needs to coordinate with the H&H engineers to obtain return periods for the required loading conditions to determine the load condition category from Table 3-1.

Risk-based analysis quantifies the uncertainty in discharge-frequency, elevation (stage)-discharge, and elevation-damage relationships and explicitly incorporates this information into economic and performance analyses of alternatives. The risk-based analysis is used to formulate the type and size of the optimal structural (or nonstructural) plan that will meet the study objectives. USACE policy requires that this plan be identified in every flood-reduction study it conducts. This plan, referred to as the National Economic Development Plan (NED), is the one that maximizes the net economic benefits of all the alternatives evaluated. It may or may not be the recommended plan, based on additional considerations. A residual risk analysis for the NED Plan is next performed to determine the consequences of exceeding project capacity. For any flood-protection project, it is possible that project capacity may be exceeded sometime during its service life. Therefore, the question becomes, “If that capacity is exceeded, what are the impacts, both in terms of economics and the threat to human life?” If the project-induced and/or residual risk is unacceptable, and a design to reduce the risk cannot be developed, other alternatives are further analyzed. Either a larger project, that will ensure sufficient time for evacuation, or a different type of project, with less residual risk, should be selected to reduce the threat to life and property. For a detailed discussion of the H&H requirements, see ER 1105-2-101 and EM 1110-2-1619.

When the type and size of the project have been selected, detailed design begins. The structural engineer, in coordination with the hydrology/hydraulic engineers, may use expected values (best estimates) of discharge-frequency and stage-discharge curves to estimate return periods for the various prescribed structure-dependent hydrostatic load conditions listed in Appendix B. For load conditions with prescribed water elevations, (for example, water to the top of closed spillway gates, or water to the top of a flood wall) the headwater elevation may be used in conjunction with the stage-discharge curve and discharge-frequency curves to estimate the annual probability and return period for the event representing the load condition. For some projects, such as high pools at power projects, other information such as project operating data will also be used in estimating the return period for a prescribed loading condition. The designer then refers to Table 3-1 to determine if each particular load condition is usual, unusual, or extreme.

3-4. Site Information

a. General. A proper stability analysis cannot be performed without knowing the potential planes of weakness beneath the structure, the strength of the materials along potential planes of weakness, uplift forces that occur on the structure or on planes of weakness, the strength of backfill materials, and all loads and load conditions to which the structure may be subjected. Knowledge of geologic formations beneath the structure is also important in defining seepage conditions and uplift pressures. Without adequate foundation explorations and testing, the safety factors provided to assess stability of the structure are meaningless. Preliminary stability analyses are useful to identify design parameters, which require special attention. In some rock foundations there may be many faults, shear zones, and discontinuities that make it impossible to do little more than predict average shear and cohesive strengths of the materials that make up the foundation. Use of lower bound values for foundation shear strength or upper bound values for loads is only acceptable when it can be demonstrated that the added costs to improve the accuracy of the strength and loading data will not lead to significant savings for the structure or foundation. Lower factors of safety are permitted by this manual in cases where there is an abundance of information on the various foundation and structure properties used to establish the strength parameters for the stability analysis. Conversely, higher factors of safety are required when there is only limited information on either foundation or structure properties. Three categories of site information, *well defined, ordinary*, and *limited,* were used in establishing safety requirements.

b. Well-defined site information. This category is restricted to use for existing projects. To qualify as well defined, site information must satisfy the following requirements:

- Available records of construction, operation, and maintenance indicate the structure has met all performance objectives for the load conditions experienced.
- Foundation strengths can be established with a high level of confidence.
- The governing load conditions can be established with a high level of confidence.
- Uplift pressures for design load conditions are known, or can be extrapolated for design load conditions based on measured uplift pressure data.

c. Ordinary site information. This category applies to most new project designs. To qualify as ordinary, site information must satisfy the following requirements:

- Foundation strengths have been established with current USACE explorations and testing procedures.
- Foundation strengths can be established with a high level of confidence.
- The governing load conditions can be established with a high level of confidence.

d. Limited site information. This category applies to those new or existing structures designated as *normal* (*critical* structures can not be designed or evaluated based on *limited* site information), where either of the following are true:

- Foundation strengths are based on limited or inadequate explorations and testing information, or
- Governing load conditions cannot be established with a high level of confidence because of insufficient historical data on stream flow, flood potential, etc.

3-5. Critical Structures

Civil works structures, for the purpose of establishing safety factors or safety provisions for use in stability analyses, are to be designated as either critical or normal. Structures designated as critical are those structures on high hazard projects whose failure will result in loss of life. Loss of life can result directly, due to flooding or indirectly from secondary effects. Loss of life potential should consider the population at risk, the downstream flood wave depth and velocity, and the probability of fatality of individuals within the affected population. Information is provided in Appendix H to help design engineers determine if the structure should be designated critical or normal.

3-6. Existing Structures

The safety factors provided in this manual are based on the assumption that for critical and normal structures, the strength of the materials in the foundation and structure has been conservatively established through explorations and testing. This may not be the case for older existing structures, or, if adequate explorations and testing were performed, the records may not be available. When the stability of an existing structure is in question, a phased, systematic approach to evaluating stability should be performed before any remedial actions are undertaken to improve stability. This systematic evaluation process is described in Chapter 7. The load conditions used to evaluate an existing structure should be carefully checked to make sure that what was considered as a usual load condition for the original design is not, once the probabilities of the load conditions are examined, really an unusual or extreme load condition. Evaluation of existing structures should utilize analytical methods which accurately describe the behavior without introducing excess conservatism. When available, actual uplift pressures can be used as a basis for evaluating the stability of existing structures.

3-7. Factors of Safety for Sliding

Analysis of sliding stability is discussed in detail in Chapter 2 and Chapter 5. A factor of safety is required in sliding analyses to provide a suitable margin of safety between the loads that can cause instability and the strength of the materials along potential failure planes that can be mobilized to prevent instability. The factor of safety for sliding is defined by equation 3-1. The required factors of safety for sliding stability for *critical* structures and for *normal* structures are presented in Tables 3-2 and 3-3, respectively.

$$FS_s = \frac{N \tan\phi + cL}{T} \qquad (3\text{-}1)$$

where

N = force acting normal to the sliding failure plane under the structural wedge.
ϕ = angle of internal friction of the foundation material under the structural wedge.
c = cohesive strength of the foundation material under the structural wedge.
L = length of the structural wedge in contact with the foundation.
T = shear force acting parallel to the base of the structural wedge.

Table 3-2 Required Factors of Safety for Sliding - Critical Structures

	Load Condition Categories		
Site Information Category	**Usual**	**Unusual**	**Extreme**
Well Defined	1.7	1.3	1.1
Ordinary	2.0	1.5*	1.1*
Limited**	-	-	-

*For preliminary seismic analysis without detailed site-specific ground motion, use FS=1.7 for unusual and FS=1.3 for extreme. See further explanation in section 3.11 b.
**Limited site information is not permitted for critical structures

Table 3-3 Required Factors of Safety for Sliding - Normal Structures

	Load Condition Categories		
Site Information Category	**Usual**	**Unusual**	**Extreme**
Well Defined	1.4	1.2	1.1
Ordinary	1.5	1.3	1.1
Limited	3.0	2.6	2.2

3-8. Factors of Safety for Flotation

A factor of safety is required for flotation to provide a suitable margin of safety between the loads that can cause instability and the weights of materials that resist flotation. The flotation factor of safety is defined by equation 3-2. The required factors of safety for *flotation* are presented in Table 3-4. These flotation safety factors apply to both *normal* and *critical* structures and for all site information categories.

$$FS_f = \frac{W_S + W_C + S}{U - W_G} \tag{3-2}$$

where

W_S = weight of the structure, including weights of the fixed equipment and soil above the top surface of the structure. The moist or saturated unit weight should be used for soil above the groundwater table and the submerged unit weight should be used for soil below the groundwater table.
W_C = weight of the water contained within the structure
S = surcharge loads
U = uplift forces acting on the base of the structure
W_G = weight of water above top surface of the structure.

Table 3-4 Required Factors of Safety for Flotation – All Structures

	Load Condition Categories		
Site Information Category	**Usual**	**Unusual**	**Extreme**
All Categories	1.3	1.2	1.1

3-9. Limits on Resultant Location

The factor of safety approach established for sliding and flotation is not appropriate for use in the evaluation of rotational modes of failure. Rotational behavior is evaluated by determining the location of the resultant of all applied forces with respect to the potential failure plane. This location can be determined through static analysis. Limits on the location of the resultant are provided in Table 3-5. The entire base must be in compression for the usual load condition, to maintain full contact between the structure and the foundation, so there is no chance for higher uplift pressures to develop in a crack. This helps ensure linear behavior for common loading conditions. For the unusual load case, higher uplift pressures may develop in a relatively short crack, but this would cause only minor nonlinear behavior. For extreme load conditions on typical civil works projects, a shear or bearing failure will occur before overturning could occur. Therefore, the resultant is permitted to be anywhere within the base, and safety is ensured by the safety factor requirements for sliding and by the limits on allowable bearing stresses.

Table 3-5 Requirements for Location of the Resultant – All Structures

	Load Condition Categories		
Site Information Category	**Usual**	**Unusual**	**Extreme**
All Categories	100% of Base in Compression	75% of Base in Compression	Resultant Within Base

3-10. Allowable Bearing Capacity

Allowable concrete compressive stresses and/or allowable bearing capacity values established by materials engineers and geotechnical engineers are used as the basis for evaluating bearing modes of failure. The allowable bearing capacity value is defined as the maximum pressure that can be permitted on soil or rock giving consideration to all pertinent factors with adequate safety against rupture of the soil or rock mass, or movement of the foundation of such magnitude that the structure is impaired. Bearing failure is related to the relative compressibility of the foundation materials, the loading conditions, the geometry of the structure base, and the strength of the foundation and concrete at the structure-foundation interface. Bearing capacity may be related to the shear capacity of the foundation materials or to the deformability of the foundation. Information on foundation bearing analysis can be found in EM 1110-1-1905 for soils, and EM 1110-1-2908 for rock. Safety against bearing failure is generally expressed in terms of an allowable compressive stress for concrete and an allowable bearing capacity for foundation materials. These allowables include an adjustment, which represents a factor of safety. The allowable compressive stress and allowable bearing capacity values are established by testing performed by materials engineers and geotechnical engineers. Discussion on exploration and testing can be found in Chapter 2. The allowable compressive stress and bearing capacity values established for usual load conditions can be increased for the unusual and extreme load conditions. A 15% increase is permitted for unusual load conditions and a 50% increase is permitted for extreme load conditions.

3-11. Seismic Stability

a. General. Traditionally, the seismic coefficient method has been used to evaluate the stability of structures subjected to earthquake ground motions, but this method fails to take into account the true dynamic characteristics of the structure. There have been cases where structures similar to those used on civil works projects have failed during earthquakes because of a sliding or bearing failure. These failures for the most part are attributable to liquefaction and soil strength degradation in the foundation or backfill materials. Seismic stability analyses should be a performed in phases in accordance with requirements of ER 1110-2-1806. Seismic loads to be used in the first phase analysis are provided in Chapter 5 of this manual. Structures which meet sliding stability factor of safety requirements when evaluated by this procedure are considered to be safe and no additional seismic stability analyses are required. Structures that fail to meet factor of safety requirements when evaluated using this procedure should not be considered unsafe or in need of a stability retrofit. The failure to meet these requirements should only suggest the need for other seismic coefficient and dynamic analyses to fairly assess the demands placed on the structure and foundation during a major earthquake. From these advanced analyses engineers can determine if the displacements and stresses experienced by the structure and foundation will place the structure at risk of a stability failure. In many instances, it is acceptable for sliding and rocking to occur at the base of the structure during extreme earthquake load conditions. Stability in such cases is evaluated using dynamic analysis methods, and performance is ensured by limiting permanent displacements to acceptable levels.

b. Modified Factor of Safety. The factors of safety given in Tables 3-2 include FS=1.5 for unusual and FS = 1.1 for extreme load conditions, for ordinary site information. The ordinary site information and related factor of safety must be used in the seismic coefficient method. These factors of safety are based on use of extreme loads with very low probabilities of being exceeded. When factors of safety for seismic loadings are being calculated using the coefficient method, the MCE loads are usually not based on detailed site-specific seismic data. Since the loads would be based on less precise data, there would be greater probability that the predicted extreme loads could be exceeded, therefore, it is appropriate to use higher factor of safety for such analyses. For such analyses, use a factor of safety of 1.7 for unusual and 1.3 for extreme, as stated in the notes following the above table.

3-12. Mandatory Requirements

For a general discussion on mandatory requirements, see Paragraph 1-5. As stated in that paragraph, certain requirements within this manual are mandatory. The following are mandatory for Chapter 3.

a. Load condition categories. Unless the loading condition category (usual, unusual, extreme) is specifically designated in Appendix B, the return period range limitations specified in Table 3-1 shall be used to establish the correct loading condition designation. When the return period for a particular loading condition can not be established with sufficient accuracy to determine if the loading condition is usual or unusual (or unusual or extreme), the loading condition with the more stringent safety requirements shall be used.

b. Critical structures. In accordance with section 3-5, structures on high hazard projects shall be considered *critical* where failure will result in loss of life; all other structures will be classified as *normal*. In making the determination of critical or normal, the engineer must follow the guidelines in Appendix G.

c. Site information. Structures shall be assigned to one of three site information categories: *well-defined*, *ordinary*, or *limited*. Site information category selection shall be in accordance with the provisions of Paragraph 3-4.

d. Sliding stability. Sliding stability factors of safety shall be equal to, or greater than, the values specified in Tables 3-2 and 3-3. The sliding stability factor of safety shall be determined using Equation 3-1.

e. Flotation stability. Flotation factors of safety shall be equal to, or greater than, the values specified in Table 3-4. The flotation stability factor of safety shall be determined using Equation 3-2.

f. Resultant location. The location of the resultant of all forces acting on the base of the structure shall be within the limits specified in Table 3-5.

g. Bearing pressures. Bearing pressures for *usual* load conditions shall be within allowable limits established by the geologist/geotechnical engineer. Increases in allowable bearing pressures shall not exceed 15% for *unusual* and 50% for *extreme* load conditions, in accordance with the guidance in section 3-10.

h. Loading conditions. As a minimum, the loading conditions provided in Appendix B shall be satisfied in the stability analysis.

i. Loads. Loads shall comply with the mandatory requirements of Chapters 4 and 5.