

Appendix to Chapter 7

GEOTECHNICAL ULTIMATE STRENGTH DESIGN OF FOUNDATIONS AND FOUNDATION LOAD-DEFORMATION MODELING

PREFACE: This appendix introduces ultimate strength design (USD) procedures for the geotechnical design of foundations for trial use and evaluation by design professionals prior to adoption into a subsequent edition of the *Provisions*. Similarly, the appendix also introduces criteria for the modeling of load-deformation characteristics of the foundation-soil system (foundation stiffness) for those analysis procedures in Chapter 5 that permit the use of realistic assumptions for foundation stiffness rather than the assumption of a fixed base.

Current practice for geotechnical foundation design is based on allowable stresses with allowable foundation load capacities for dead plus live loads based on limiting long-term static settlements and providing a large factor of safety. In current practice, allowable soil stresses for dead plus live loads are typically increased by one-third for load combinations that include wind or seismic forces. The allowable stresses for dead plus live loads are often far below ultimate soil capacity. This *Provisions* appendix and the associated *Commentary* appendix provide criteria and guidance for the direct use of ultimate foundation load capacity for load combinations that include seismic forces. The acceptance criteria covers both the analyses for fixed-base assumptions and analyses for linear and nonlinear modeling of foundation stiffness for flexible-base assumptions.

Although USD for foundations has not previously been included in design provisions for new buildings, the same basic principles used in this appendix have been adapted to generate guidelines for the seismic evaluation and retrofit design of existing buildings (FEMA 273, FEMA 356, and ATC 40). The criteria and procedures presented herein for the nonlinear modeling of foundation stiffness, combining a linear or multilinear stiffness and a limiting load capacity based on ultimate soil strength, are essentially the same as those presented in the FEMA and ATC publications identified above.

With respect to the adoption of USD procedures for geotechnical foundation design, the primary issue considered by the Provision Update Committee and the BSSC member organizations has been the impact of the proposed USD procedures on the size of foundations and consequent effect on the potential for foundation rocking and building performance. TS3 has conducted a limited number of design examples, a synopsis of which is presented at the end of the Commentary for the Appendix to Chapter 7. The example results illustrate the expected effects of the methodology, in that relative foundation sizes from USD vs ASD are related to the factor of safety on load capacity under vertical dead plus live loads. When factors of safety are high, smaller foundations result from USD, but when factors of safety are low, it is possible that foundations may be larger using USD. Additional examples, including nonlinear dynamic analyses incorporating nonlinear load-deformation models for foundation soil stiffness and capacity, are warranted to further evaluate and possibly refine the methodology and criteria. It is hoped that trial usage of the methodologies presented herein will allow the necessary consensus to be developed to permit later incorporation into the *Provisions*. Please direct feed-back on this appendix and its commentary to the BSSC.

A7.1 GENERAL

A7.1.1 Scope. This appendix includes only those foundation requirements that are specifically related to seismic resistant construction. It assumes compliance with all other basic requirements which include, but are not limited to, requirements for the extent of the foundation investigation, fills to be present or to be placed in the area of the structure, slope stability, subsurface drainage, settlement

control, and soil bearing and lateral soil pressure recommendations for loads acting without seismic forces.

A7.1.2 Definitions

Allowable foundation load capacity: See Sec. A 7.2.2.

Ultimate foundation load capacity: See Sec. A 7.2.2.

A7.1.3 Notation

Q_{as} Allowable foundation load capacity.

Q_{us} Ultimate foundation load capacity.

ϕ The strength reduction, capacity reduction, or resistance factor.

A7.2 GENERAL DESIGN REQUIREMENTS

The resisting capacities of the foundations, subjected to the load combinations prescribed elsewhere in these *Provisions*, shall meet the requirements of this appendix.

A7.2.1 Foundation components. The strength and detailing of foundation components under seismic loading conditions, including foundation elements and attachments of the foundation elements to the superstructure, shall comply with the requirements of Chapters 8, 9, 10, 11, or 12, unless otherwise specified in this chapter. The strength of foundation components shall not be less than that required for load combinations that do not include seismic load effects.

A7.2.2. Foundation load capacities. The vertical capacity of foundations (footings, piles, piers, mats or caissons) as limited by the soil shall be sufficient to support the structure for all prescribed load combinations without seismic forces, taking into account the settlement that the structure can withstand while providing an adequate factor of safety against failure. Such capacities are defined as allowable foundation load capacities, Q_{as} . For load combinations including seismic load effects as specified in Sec. 4.2.2, vertical, lateral, and rocking load capacities of foundations as limited by the soil shall be sufficient to resist loads with acceptable deformations, considering the short duration of loading, the dynamic properties of the soil, and the ultimate load capacities, Q_{us} , of the foundations under vertical, lateral, and rocking loading.

A7.2.2.1 Determination of ultimate foundation load capacities. Ultimate foundation load capacities shall be determined by a qualified geotechnical engineer based on geotechnical site investigations that include field and laboratory testing to determine soil classification and soil strength parameters, and/or capacities based on insitu testing of prototype foundations. For competent soils that do not undergo strength degradation under seismic loading, strength parameters for static loading conditions shall be used to compute ultimate load capacities for seismic design. For sensitive cohesive soils or saturated cohesionless soils, the potential for earthquake induced strength degradation shall be considered.

Ultimate foundation load capacities, Q_{us} , under vertical, lateral, and rocking loading shall be determined using accepted foundation design procedures and principles of plastic analysis. Calculated ultimate load capacities, Q_{us} , shall be best-estimated values using soil properties that are representative average values for individual foundations. Best-estimated values of Q_{us} shall be reduced by resistance factors (ϕ) to reflect uncertainties in site conditions and in the reliability of analysis methods. The factored foundation load capacity, ϕQ_{us} , shall then be used to check acceptance criteria, and as the foundation capacity in foundation nonlinear load-deformation models.

If ultimate foundation load capacities are determined based on geotechnical site investigations including laboratory or in-situ tests, ϕ -factors equal to 0.8 for cohesive soils and 0.7 for cohesionless soils shall be used for vertical, lateral, and rocking resistance for all foundation types. If ultimate

foundation load capacities are determined based on full-scale field-testing of prototype foundations, ϕ -factors equal to 1.0 for cohesive soils and 0.9 for cohesionless soils are permitted.

A7.2.2.2 Acceptance criteria. For linear analysis procedures (Sec. 5.2, 5.3, and 5.4), factored foundation load capacities, ϕQ_{us} , shall not be exceeded for load combinations that include seismic load effects.

For the nonlinear response history procedure (Sec. 5.5) and the nonlinear static procedure (Appendix to Chapter 5), if the factored foundation load capacity, ϕQ_{us} , is reached during seismic loading, the potential significance of associated transient and permanent foundation displacements shall be evaluated. Foundation displacements are acceptable if they do not impair the continuing function of Seismic Use Group III structures or the life safety of any structure.

For nonlinear analysis procedures, an additional evaluation of structural behavior shall be performed to check potential changes in structural ductility demands due to higher than anticipated foundation capacity. For this additional evaluation, values of Q_{us} shall be increased by the factor $1/\phi$.

A7.2.3 Foundation load-deformation modeling. Where permitted for the analysis procedures in Chapter 5 and the Appendix to Chapter 5, the load-deformation characteristics of the foundation-soil system (foundation stiffness), if included in the analysis, shall be modeled in accordance with the requirements of this section. For linear analysis methods, the linear load-deformation behavior of foundations shall be represented by an equivalent linear stiffness using soil properties that are compatible with the soil strain levels associated with the design earthquake motion. The strain-compatible shear modulus, G , and the associated strain-compatible shear wave velocity, v_s , needed for the evaluation of equivalent linear stiffness shall be determined using the criteria in Sec. 5.6.2.1.1 or based on a site-specific study. Parametric variations of not less than 50 percent increase and decrease in stiffness shall be incorporated in dynamic analyses unless smaller variations can be justified based on field measurements of dynamic soil properties or direct measurements of dynamic foundation stiffness.

For nonlinear analysis methods, the nonlinear load-deformation behavior of the foundation-soil system may be represented by a bilinear or multilinear curve having an initial equivalent linear stiffness and a limiting foundation capacity. The initial equivalent linear stiffness shall be determined as described above for linear analysis methods. The limiting foundation capacity shall be taken as the factored foundation load capacity, ϕQ_{us} . Parametric variations in analyses shall include: (1) a reduction in stiffness of 50 percent combined with a limiting foundation capacity, ϕQ_{us} , and (2) an increase in stiffness of 50 percent combined with a limiting foundation capacity equal to Q_{us} increased by a factor $1/\phi$.

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