misalignment depend upon the design of the bearings, the configuration of the shaft system, and the distances between the bearings. The influence coefficients indicate the amount by which the loading on a bearing changes per inch (mm) of bearing support displacement. The load on Bearing 2 as a result of shaft misalignment is

$$P_2 = P_2' + (-C_{21})y_1 + (+C_{22})y_2 + (-C_{23})y_3 + (+C_{24})y_4 \quad (7\text{-}3)$$

where

P_2' = calculated loading of Bearing 2 with correctly aligned shaft system in psi (kN/m^2),

C_{2j} = change in loading on Bearing 2 per inch of vertical deflection of Bearing j in psi/in. (kN/m^2/mm), and

y_i = vertical deflection of Bearing i from the position of initial correct shaft alignment in in. (mm).

The influence factor C_{22} will be positive and have the largest value, reflecting the fact that an upward displacement of Bearing 2 strongly increases the load on the same bearing, whereas a downward displacement results in a correspondingly large decrease in load. The negative factors C_{21} and C_{23} denote that upward displacement of Bearings 1 and 3 tends to unload Bearing 2. The value of C_{23} will, of course, be considerably larger than C_{21} because of its proximity to Bearing 2. The effect of other bearing displacements on the loading of Bearing 2 becomes smaller with increasing distance from Bearing 2, so that the factor C_{24} will have the smallest value.

The vertical and horizontal coefficients at each of the bearings are required from the TG manufacturer. After the results of MTM analysis are obtained, the responses are compared to the allowable values given by the TG manufacturer. The units as well as the locations of the required displacements are specified by the TG manufacturer.

Some forms of shaft misalignment can have an adverse effect on the bearing loadings but not increase the bending stresses in the shaft system. It is equally possible for some shaft systems to be vulnerable at particular locations to high bending stresses that do not result in any substantial alteration of the loads on individual shaft bearings. When the combined effect of the foundation deflections is found to exceed the allowable response at a particular point, it should be recognized that a design change at another location can be a feasible solution.

Some TG manufacturers provide one set of influence coefficients to determine the effects of foundation displacement on the bearing loads and a different set of coefficients to investigate the effects on the shaft bending stresses. Other manufacturers combine the effects of bearing loads and shaft stresses into a single set of coefficients. In either case, the static serviceability analysis by the foundation design engineer is the same.

Other Static Serviceability Deflection Criteria. TG manufacturers may also impose other deflection criteria as follows:

1. Differential radial displacement between adjacent bearings;
2. Foundation basemat differential settlements;
3. Relative top surface rotation of specific piers;
4. Relative displacements of any three adjacent foundation supports; and
5. Concrete crack width of top deck girders.

Note that the design of TG foundations is typically governed by stiffness criteria; as such, stress levels in concrete sections and reinforcement are relatively low compared to those in building and other types of structures. Therefore, fatigue from cyclic loading in TG foundations is usually not a concern.

It is essential that the TG foundation design engineer have a correct understanding of all the serviceability criteria, both static and dynamic, imposed by the TG manufacturers. Coordination with the TG manufacturers is the key to a successful design if the foundation design engineer has difficulties meeting certain criteria.

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CHAPTER 8
STRENGTH AND STABILITY DESIGN

8.1 INTRODUCTION

The strength design of TG foundations should follow requirements of the building codes specified in the project design criteria, as well as applicable ACI requirements. However, TG foundations have some unique structural characteristics that require special considerations and details in strength design.

This chapter presents the strength design criteria and procedures for the design of concrete TG foundations. The stability design considerations are also discussed.

8.2 LOAD COMBINATIONS FOR STRENGTH DESIGN

The strength design method should be used to design all structural components of reinforced concrete TG foundations.

Factored load combinations for strength design should follow the applicable building codes. In addition to the general load combinations, special load combinations required or recommended by the TG machine manufacturer should be considered. Loads to be used in load combinations are described in Chapter 4. Section 4.9 discusses load combination considerations for TG foundation designs.

8.3 SEISMIC LOAD AND DUCTILE DESIGN CONSIDERATIONS

Seismic loads are defined by the building code specified in the project civil/structural design criteria. Key seismic design parameters, such as S_{DS}, S_{D1}, soil type, and seismic design category (SDC), are usually provided in this document.

According to Section 11.7 of ASCE 7, TG foundations assigned to SDC A need only comply with the requirements of ASCE 7 Section 1.4. TG equipment systems in SDC A are exempt from seismic design requirements. For TG foundations in SDC B to F, the equivalent lateral force analysis procedure is permitted. The seismic response coefficient C_s and the response modification factor R can be determined based on the following design considerations.

For a rigid TG foundation system with a fundamental period less than 0.06 seconds, it is acceptable to use $C_s = 0.3\ S_{DS}\ I_e$ per Section 15.4.2 of ASCE 7. Note that S_{DS} is the site design response acceleration as determined from Section 11.4.4 of ASCE 7, while I_e is 1.25 for Risk Category III and 1.5 for Risk Category IV, respectively. Some low-profile CTG, axial exhaust, or side exhaust STG with higher soil or pile stiffness may be qualified as rigid foundations for the fundamental horizontal modes.

For TG foundations with a fundamental period not less than 0.06 seconds, the seismic response coefficient C_s can be determined per Sections 12.8.1 and 15.4.1 of ASCE 7. In these procedures, the design engineer needs to select the response modification factor R for the TG foundation, which reflects the capabilities of the structure to absorb and dissipate earthquake energy during such an event.

However, the current practice in selecting an appropriate R-value for seismic design of TG foundations varies, depending on how the structure type classification per ASCE 7 is interpreted, seismic severity, and past experiences of the TG foundation design engineer.

Some practitioners classify the elevated space-frame TG foundations as "nonbuilding structures similar to buildings." The corresponding seismic coefficients, with their usage applicability and limitations, are listed in Table 15.4-1 of ASCE 7. Accordingly, the design engineer can select an R-value of 0.8 from Table 15.4-1, classifying the TG pedestal as an ordinary reinforced concrete moment frame (OMF), to avoid ductile detailing requirements stipulated in ACI 318. However, using an R-value of 0.8 will inevitably result in higher seismic demands on the foundation, which may not necessarily cause reinforcement issues in the superstructure, but will very likely cause lateral pile capacity issues for pile-supported foundations, or soil-bearing capacity issues for soil-supported foundations, or even excessive sliding under high seismic loading. For pile-supported foundations, increasing the number of piles alone may not increase the total lateral capacity sufficiently, because individual pile lateral capacity becomes lower as piles are spaced more closely together. As a result, additional piles with a larger basemat footprint may be required, possibly leading to new interface issues with nearby structures.

To avoid issues described previously, alternatively, the design engineer more intends to select an R-value of 3.0, and follow ACI 318 to meet the seismic detailing requirements for intermediate moment frames (IMF). Note that per ASCE 7, for the OMF and IMF, the structural height limit is NL (no limit) for SDC B and C, and 50 ft for SDC D to F, respectively. However, it is the opinion of this task committee that the 50-ft height limitation is too restrictive for a TG pedestal foundation, whose design is more governed by stiffness and vibration criteria than by seismic strength requirements. If a foundation is proportioned per the rules of thumb on weight ratios, column axial compressive stress range, and h/r ratio, as recommended in Chapter 3, the 50-ft height limitation, can be 60 ft for SDC D to F.

Contrary to the previous practice, other practitioners treat TG foundations as "nonbuilding structures not similar to buildings." Then, per Table 15.4-2 of ASCE 7, an R-value of 1.25 can be selected for "all other self-supporting structures, tanks, or vessels not covered above or by reference standards that are similar to buildings." Or, an R-value of 2.0 can be selected if elevated space-frame TG foundations are treated as "inverted pendulum type structures." A survey of major engineering design firms shows that, in various practices, R-values of 1.0, 1.25, and 2.0 have been used without providing seismic detailing required by ACI 318. Among considerations, one major defense argument for doing so has been that TG foundation designs are governed by stiffness and vibration limits, not by seismic strength requirements. As a result, a TG pedestal foundation is usually oversized, such that its structural responses under seismic loads are more or less elastic than plastic. Therefore the detailing requirements may not be necessary for these oversized structural components.

While acknowledging the fact that different R-values have been used in current practice, this task committee recommends using either $R = 0.8$ or $R = 3.0$, and following the appropriate detailing requirements of ACI 318, since there has not been enough research and evidence to substantiate other R-values. A decision to use other values should be based on careful considerations of specific project engineering requirements, as well as close coordination with local building officials, as required. In this regard, this Committee expects that future ASCE 7 updates will provide clearer provision(s) on nonbuilding foundation structures for large vibrating equipment.

Besides the superstructure, the seismic inertia effect of the TG basemat supporting the superstructure should also be considered. Section 12.2.3.2 of ASCE 7 provides the details for two-stage analysis procedure. A typical TG basemat may be considered as a rigid structure for this purpose, regardless of whether it is above or below grade. ASCE 7 recommends $C_s = 0.3\ S_{DS}\ I_e$

as the lateral seismic coefficient for rigid structures. For the purpose of strength design, both soil-supported and pile-supported foundation mats are treated as rigid structures under the effect of horizontal seismic excitation. In the latter case, the interaction effects between the pile and surrounding soil medium are ignored.

The seismic loads of the TG machines should be determined treating the machines as an integral part of the foundation. TG manufacturers may provide machine seismic loads, which design engineers should verify.

For machine anchorage designs, the design engineer should follow ASCE 7, Chapter 13.

8.4 REDUNDANCY FACTOR (ρ) AND OVERSTRENGTH FACTOR (Ω_o)

In accordance with ASCE 7, Section 12.4, redundancy and overstrength factors must be used to create a new set of design load combinations for all structural members. These provisions are applicable for buildings and nonbuilding structures per ASCE 7, Sections 15.4.1, 15.5.1, and 15.6.

Per ASCE 7, Section 12.3.4, the value of the redundancy factor (ρ) for TG foundations can be taken as 1.0. TG foundations are "nonbuilding structures that are not similar to buildings" for block type foundations, or meet the requirements for moment frames described in ASCE 7, Table 12.3-3, for elevated space frame type foundations.

ASCE 7 indicates that where specifically required, seismic load effects shall be modified to account for system overstrength, as set forth in Section 12.4.3. Per Section 18.3.3 of ACI 318, the overstrength factor Ω_o should be used in the shear reinforcement design of OMF columns. Per Section 18.4 of ACI 318, the Ω_o factor should be used for the shear reinforcement design of IMF columns while a constant factor of 2 should be used for the shear reinforcement design of IMF beams. The Ω_o factor is not required for the axial, flexural, and torsional design. As indicated in Section 18.4 of ACI 318, the objective of the requirements in 18.4.2.3 and 18.4.3.1 is to reduce the risk of failure in shear in beams and columns during an earthquake. For anchorage design, ASCE 7 provides a revised version that gives Ω_o factors for all components in Chapter 13.

8.5 ACCIDENTAL TORSION

ASCE 7, Section 12.8.4.2, requires an accidental torsion to be considered for diaphragms that are not flexible. This requirement accounts for the possible difference between the actual mass locations and those considered in the design.

While the tabletop of an elevated space-frame pedestal foundation may be considered a diaphragm that is not flexible, for a TG foundation all the major masses (e.g., machine weights) are already precisely defined and can be accounted for in a finite element model used for the strength design. Therefore, the accidental torsion defined in ASCE 7 need not be included in the design of TG foundations.

8.6 FE RESULTS FOR STRENGTH DESIGN

TG structural members are sized to satisfy dynamic vibration and static deflection criteria. Therefore, a minimal amount of reinforcement often satisfies the strength requirements. Demands because of load combinations involving seismic loads and/or catastrophic equipment loads govern the reinforcement design of a TG foundation.

Using the static FE model, as described in Chapters 6 and 7, with all applicable design loads and load combinations per building codes as well as the TG machine manufacturer's requirements, the design engineer can perform a static analysis to obtain the design forces for all structural components in a TG foundation.

If beam elements are used to model tabletop members and columns, FE member force outputs (axial force, shear force, moment, and torsion) can be directly used for member designs per ACI 318.

If shell elements are used to model walls and basemat, outputs are usually given in a "per unit length" format (e.g., 300 kip-ft/ft for bending moment in a wall). The design engineer will need to post-process the outputs to obtain the resultant forces along a selected length for reinforcement design. Some computer programs may have tools that help calculate resultant forces at user-defined section cut locations. Also see Section 6.12 for guidelines on averaging FE results.

If solid elements are used to model the whole foundation structure, the outputs are usually stresses, not forces and moments that can be readily used for design. In such cases, the design engineer may have to post-process the stress outputs by doing integrations across the sections of interest to obtain the resultant forces and moments at those sections.

To simplify the design process, enveloping resultant forces and moments can be used for reinforcement design, so long as such an approach does not result in too congested reinforcement arrangements.

8.7 BASEMAT REINFORCEMENT DESIGN

TG foundations have thicker basemats compared to other equipment foundations. The reinforcement design of basemats should follow the applicable ACI requirements. If finite element analysis results are available, the design engineer can obtain the maximum bending moments in both directions, and add the maximum absolute value of the torsional moments to them to determine the required flexural capacity in each direction. The axial force, either tension or compression, in the basemat is typically very small and can be ignored. Some design engineers may add additional reinforcements to resist axial tension.

A simplified approach to design of the basemat is to treat it as a slab supported by the columns and walls, then to use the maximum soil-bearing pressure or maximum pile reactions as input loads to perform hand calculations and determine the maximum moments in the basemat. The flexural reinforcement is provided accordingly.

Typically, no shear reinforcement is necessary in the basemat. Because of its thickness, the basemat concrete provides sufficient shear capacity, larger than the maximum shear demands on the basemat.

A punching shear check should be performed for areas surrounding the columns and piles per ACI 318 provisions.

In foundations thicker than 4 ft (1.2 m), the design engineer may use the minimum reinforcement suggested in ACI 207.2R for mass concrete. Also, Section 7.12.2 of ACI 350 provides an alternative criterion, which states that concrete sections that are at least 24 in. thick may have the minimum shrinkage and temperature reinforcement based on a 12-in. concrete layer at each face. Using this alternative, a typical basemat top (or bottom) reinforcement is 0.5% of the assumed cross section depth (24 in.) in each direction. To minimize concrete cracking in mass concrete, additional minimum spatial steel reinforcement per unit volume of concrete may be required by some turbine manufacturers. More discussion is given in Section 8.11.

8.8 COLUMN, BLOCK, PIER, AND WALL REINFORCEMENT DESIGN

Columns, pedestals, and walls in space-frame pedestal foundations should be designed per the applicable ACI requirements.

The minimum column longitudinal reinforcement should be 0.5% of gross concrete area. Though Section 10.6.1 of ACI 318 requires the minimum longitudinal column reinforcement to be 1% of the gross concrete area, Section 10.3.1 allows the use of a reduction in effective area of up to 50% for the calculation of minimum reinforcement. Therefore, the minimum reinforcement may be as low as 0.5% of the gross area. If the reduced effective area is used for strength calculations and minimum reinforcement, the full gross area should still be used for column stiffness calculations.

The column tie sets should be minimum No. 5 bars with a maximum spacing of 18 in. (450 mm). Tie sets need not go into the tabletop joint for low to moderate seismic zones. For higher seismic zones, ACI 318 seismic detailing requirements should be followed. Note that OMFs do not have special seismic detailing requirements if an R-value of 0.8, 1.25, or 2.0 is used.

All longitudinal bars should be laterally supported by ties unless they are 12 in. (300 mm) or closer along the tie to the next laterally supported bar. Lateral support is provided by the corner of a tie with an included angle of not more than 135 degrees.

As an additional check for columns, it is a good practice to ensure that the amount of reinforcement provides a section moment capacity greater than 1.2 M_{cr}, where M_{cr} is the cracking moment capacity based on the concrete modulus of rupture (f_r). This ensures some levels of ductility within the structure.

8.9 TABLETOP REINFORCEMENT DESIGN

Tabletop members should be designed as "beams" per the applicable ACI requirements.

8.9.1 Shear and Torsion

Flexural members of a TG foundation may be subjected to substantial shear and torsion forces. The longitudinal beams supporting the generator stator and the low-pressure turbine exhaust hoods are usually short and heavily loaded, principally along one edge, resulting in relatively high torsion forces. Combined shear and torsion strength of these members should be evaluated by the procedures of ACI 318, taking into account the effects on strength of simultaneous bending moments and axial forces at the section under investigation.

For beams loaded along their top surface, design sections for shear and torsion are taken at a distance "d" from the face of the support unless the shear at the face of the support is substantially different, as in the case where a heavy load or beam reaction is applied within this distance. In this case, the design section should be taken at the face of the support. The distance "d" is defined as the dimension from the compression face of the concrete to the centroid of the tension reinforcement. Shear reinforcement and torsional reinforcement must meet the requirements of ACI 318. The torsional reinforcement should be in the form of closed stirrups.