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SI

International System of Units

Report on Foundations for Static Equipment

Reported by ACI Committee 351



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Report on Foundations for Static Equipment

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Report on Foundations for Static Equipment

Reported by ACI Committee 351

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This document addresses static equipment foundation engineering and construction. It presents various design criteria, methods and procedures of analysis, design, and construction applied to static equipment foundations by industry practitioners. This document should, hopefully, encourage discussion and comparison of ideas.

Keywords: anchorage (structural); bolts, anchor; equipment; forms; formwork (construction); foundation loading; foundations; grout; grouting; pedestals; pile loads; reinforcement; soil pressure; subsurface preparation; tolerances (mechanics).

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Background**

Foundations for static equipment are used in industrial processing and manufacturing facilities throughout the world. Engineers with varying backgrounds are engaged in the analysis, design, and construction of these foundations. They often perform their work with little guidance from building codes, national standards, owner's specifications, or other published information. Because of this lack of consensus standards, most engineers rely on engineering judgment and experience. Some engineering firms and individuals, however, have developed their own standards and specifications as a result of research and development activities, field studies, or many years of engineering or construction experience. Only by sharing and discussing this information can a meaningful consensus on engineering and construction requirements for static equipment foundations be developed.

As used in this document, "state of the art" refers to state of the practice, and encompasses various engineering and construction methodologies.

1.2—Purpose

This document presents various design criteria and methods and procedures of analysis, design, and construction currently being applied to static equipment foundations by industry practitioners. The purpose of this report is to present these various methods and elicit critical discussion from the industry. This report is not intended to be a recommended practice; rather, it is a document that encourages discussion and comparison of ideas.

1.3—Scope

This report is limited in scope to the engineering and construction of static equipment foundations. Static equipment, as used herein, refers to industrial equipment that does not contain significant moving parts, or that has operational

characteristics essentially static in nature. Outlined and discussed herein are the various aspects of the analysis, design, and construction of foundations for equipment, such as vertical vessels, stacks, horizontal vessels, heat exchangers, spherical vessels, machine tools, and electrical equipment such as transformers.

This report does not include foundations for:

- Equipment, such as turbine generators, pumps, blowers, compressors, and presses, which have operational characteristics that are essentially dynamic in nature. ACI 351.3R covers concrete foundations for dynamic equipment;
- Vessels and tanks whose contents structurally bear directly on soil (for example, clarifiers and large-diameter storage tanks);
- Buildings, concrete silos, chimneys, and structures that contain static equipment; or
- Equipment sensitive to external vibration. These foundations are generally isolated from the neighboring dynamic equipment foundations to minimize transmission of vibration from other equipment. These foundations rarely require their own separate foundations and are usually located and supported in buildings. ACI 351.3R provides some guidance, although its scope is for equipment that generates dynamic forces.

The geotechnical engineering aspects of the analysis and design of static equipment foundations discussed herein are limited to general considerations. This report is essentially concerned with the structural analysis, design, and construction of static equipment foundations.

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

A	=	base area of footing, ft ² (m ²)
A_{se}	=	effective cross-sectional area of anchor, in. ² (mm ²)
B	=	width of footing, ft (m)
D	=	edge-to-edge distance of footing in direction of overturning moment, ft (m)
d_{bc}	=	diameter of bolt circle, ft (mm)
d_o	=	nominal bolt diameter, in. (mm)
e	=	M/P , ft (m) (Section 4.4)
e_v	=	M/W , ft (m) (Section 5.5.1)
F	=	maximum bolt force for anchors in circular pattern, kip (kN)
f'_c	=	specified compressive strength of concrete, psi (MPa)
f_y	=	specified yield strength of reinforcement, psi (MPa)
h_{ef}	=	effective embedment depth of anchor, in. (mm)
k_c	=	coefficient for basic concrete breakout strength in tension
L	=	length of footing, ft (m)
M	=	overturning moment applied to footing or pier, ft·kip (kN·m) (Section 4.4)
M_p	=	resisting moment provided by passive lateral soil pressure, ft·kip (kN·m)
M_v	=	moment about the centroidal axes of the foundation, ft·lb (N·m) (Section 5.5.1)

M_x, M_y	=	moments about x and y centroidal axes, respectively, ft·lb (N·m)
M_{xy}	=	twisting moment, ft·kip (kN·m)
N	=	number of bolts
N_b	=	basic concrete breakout strength in tension of single anchor in cracked concrete, lb (N)
n_t	=	reciprocal of the thread pitch, threads per in. (mm)
P	=	vertical load due to weight of concrete and equipment, kip (kN)
Q	=	maximum soil pressure at edge of footing, lb/ft ² (Pa)
SR_1	=	stability ratio for drilled piers with larger length-diameter ratios
SR_2	=	stability ratio for drilled piers with smaller length-diameter ratios
S_x, S_y	=	section moduli of base about x and y centroidal axes, respectively, ft ³ (m ³)
W	=	resultant vertical load, lb (N) (Section 5.5.1)
W'	=	weight of equipment, lb (N) (Section 5.2.2)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided herein complement that resource.

base ring—a horizontal plate, generally fabricated in the shape of a ring, which is attached to the bottom of a vertical vessel, stack, or skirt and bears on the concrete foundation.

belled piers—a drilled pier shaft with an expanded excavation at the bottom.

bundle load—force required to pull tube bundles out of a vessel.

canister-type anchor bolt—anchorage assembly that includes a sleeve, a threaded rod, and means of removing the rod and adjusting rod location, projection, and tension.

davit—a device (small crane) used to lift, lower, support, and swing the access covers and other items away from openings of vessels and tanks.

heat exchanger—equipment used to raise or lower the temperature of a fluid by piping fluid through tubes exposed to blowing air (radiator type) or by piping fluid through tubes in a bath of fluid that is maintained at a different temperature (shell-and-tube type).

hydrotest—filling of tanks or vessels with water to check for leaks and structural integrity.

operating loads—loads applied to the equipment or structure due to nature of operation, liquid loads, internal loads, or pressure.

pad—slab-type foundation support for equipment.

saddle—a horizontal vessel support with a curved top that matches the profile of the vessel and a flat bottom supported by the foundation.

shaft—vertical portion of concrete drilled pier.

shell-and-tube heat exchanger—see **heat exchanger**.

skirt—a vertical vessel support consisting of a vertical plate rolled to match the perimeter of the vessel and located between the vessel and base ring.

sleeve—a device used around an anchor to accommodate adjustment and tensioning of the anchor after the concrete has hardened.

slide plate—a support that allows movement of the equipment relative to the foundation in one or two directions.

stack—a cylindrical vertical vent.

tube bundle—piping in a shell-and-tube heat exchanger that contains the fluid to be heated or cooled.

vessel, horizontal—a cylindrical vessel with a horizontal primary axis typically supported on one fixed support and one sliding support.

vessel, vertical—a cylindrical vessel with a vertical primary axis typically supported on a single support at the base of the vessel. Multiple supports are also used.

CHAPTER 3—FOUNDATION TYPES

3.1—General considerations

The design of foundations for equipment may depend on the following factors:

1. Equipment base configuration such as legs, saddles, solid base, grillage, or multiple support locations;
2. Anticipated loads, such as the equipment static weight, and loads developed during construction, operation, and maintenance;
3. Operational and process requirements, such as accessibility, settlement constraints, temperature effects, and drainage;
4. Construction and maintenance requirements, such as limitations or constraints imposed by construction or maintenance equipment, procedures, or techniques;
5. Site conditions, such as soil characteristics, topography, seismicity, climate, and other environmental effects;
6. Economic factors, such as capital cost, useful or anticipated life, and replacement or repair costs;
7. Regulatory or building code provisions, such as tied pile caps in seismic design categories;
8. Construction considerations; and
9. Environmental requirements, such as secondary containment or special concrete coating requirements.

3.2—Typical foundations

3.2.1 Vertical vessel and stack foundations—For tall vertical vessels and stacks, the plan dimensions of the foundation required to resist gravity loads and lateral wind or seismic forces is usually much larger than the support base of the vessel. Accordingly, the vessel is often connected to a concrete pedestal, smaller than the footing below, with dimensions sufficient to accommodate the anchors and base ring. Operational, maintenance, or other requirements may dictate a larger pedestal. The pedestal is then supported from below by the larger spread footing, mat, or pile cap.

For relatively short vertical vessels and guyed stacks with large bases, light vertical loads, and small overturning moments, the pedestal and footing may have the same plan dimensions. If so, the pedestal and footing are combined into a single soil-supported pedestal.

Individual pedestals are rectangular, circular, square, hexagonal, or octagonal. If the vessel is a circular base, a circular, square, or octagonal pedestal is generally provided.

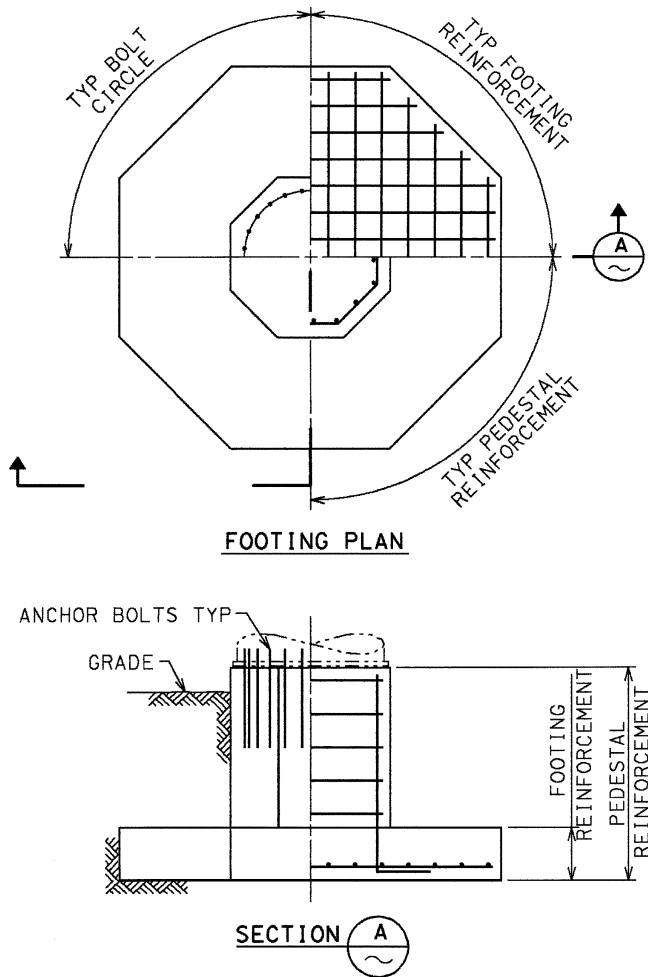


Fig. 3.1—Annular-ring type octagonal pedestal and footing for vertical vessel.

Circular pedestals may create construction difficulties in forming unless standard prefabricated forms are available. Square pedestals facilitate ease in forming, but may contain much more material than is required by analysis. Octagonal pedestals are a compromise between square and circular; hence, this type of pedestal is widely used for supporting vertical vessels and stacks with circular bases (Fig. 3.1). It is common to use square bases for 5.0 ft (1.5 m) diameter and smaller vessels and octagonal bases for large-diameter vessels.

3.2.2 Horizontal vessel and heat exchanger foundations—Horizontal equipment is typically supported on two separate saddles incorporated into the equipment. Each saddle is then supported by a concrete pedestal that rests on spread footings, strap footings, pile caps, or drilled piers. Elevation requirements of piping often dictate that these vessels are located several feet above grade. Consequently, pedestals are the logical means of support (Fig 3.2).

Horizontal equipment often operates at temperatures different than ambient temperature. The change in temperature causes the equipment to expand or contract, depending on whether the operating temperature is higher or lower than ambient temperature. The change in length will push the support pedestals laterally in equal and opposite directions.

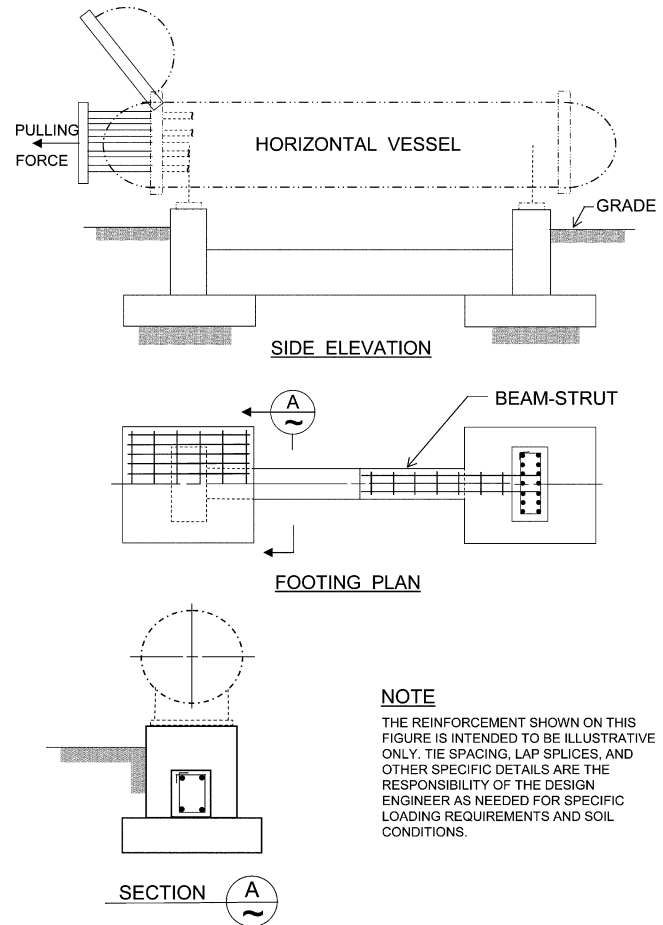


Fig. 3.2—Footing with beam-strut for horizontal vessels.

The loading associated with this temperature differential is covered in Chapter 4.

The configuration of pedestals varies with the type of saddles on the vessels, and with the magnitude and direction of forces to be resisted. The most common pedestal shape used for supporting the saddle is rectangular, when looking down in plan view. Pedestals or foundations may be tied together with beam-struts to reduce the effect of horizontal loading to the foundations (Fig. 3.2). T-shaped pedestals (looking in plan view) are sometimes used where additional horizontal stiffness to resist lateral loads is required (Fig. 3.3).

3.2.3 Spherical vessel foundations—Smaller spherical vessels are sometimes constructed with a skirt and base ring, but more often, spherical vessels have leg supports. For leg-supported spherical vessels, foundations typically consist of pedestals under each leg resting on individual spread footings, a continuous mat, or an octagonal, hexagonal, or circular annular ring. Concerns about differential settlement between legs and large lateral earthquake loads usually dictate a continuous foundation system. To economize on foundation materials, an annular ring-type foundation is often used (Fig. 3.4).

3.2.4 Machine tool foundations—Machine tool equipment is typically supported on mat foundations. Whether these are soil-bearing or pile-supported depends on the bearing capacity of the soil and the settlement limitations of the foundation. Where a machine tool produces impact-type loads, refer

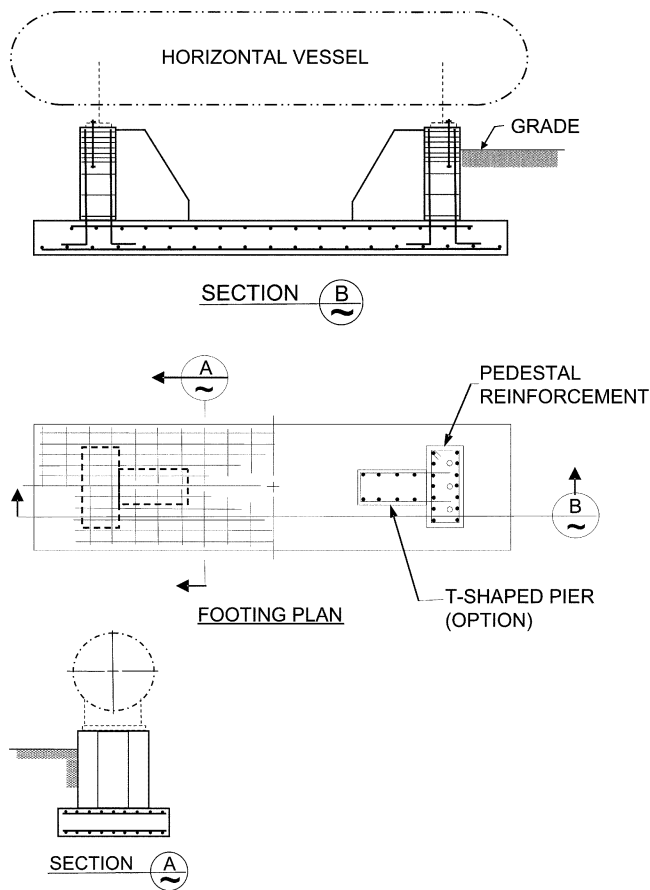


Fig. 3.3—Combined footing for horizontal vessel.

to ACI 351.3R for impact-type loading, design, and construction. If a machine tool foundation is sensitive to vibration, it is generally isolated from the neighboring dynamic equipment foundations to minimize transmission of vibration from other equipment.

3.2.5 Electrical equipment and support structure foundations—Electrical equipment typically consists of transformers, power circuit breakers, switchgear, and motor-control centers. Support structures consist of buses, line traps, switches, and lightning arrestors. Foundations for electrical equipment, such as transformers, power circuit breakers, and other massive energized equipment, are typically designed for: dead loads; wind loads; seismic loads; construction loads (that is, jacking); and operating loads. These foundations are typically slabs-on-ground or slabs-on-piles. Anchorage is provided by anchor bolts or by welding the equipment base to plates or structural shapes embedded in the top of the concrete foundation.

A typical electrical substation consists of structures supporting stiff electrical buses, switch stands, line traps, and lightning arrestors. Foundations for these types of equipment are designed to accommodate operating loads, wind loads, short circuit loads, and seismic loads. These loads are usually smaller than those of transmission line support structures. The supporting foundations commonly used are drilled piers or spread footings. Alternatively, pile-supported footings are used if soil-bearing conditions are unfavorable.

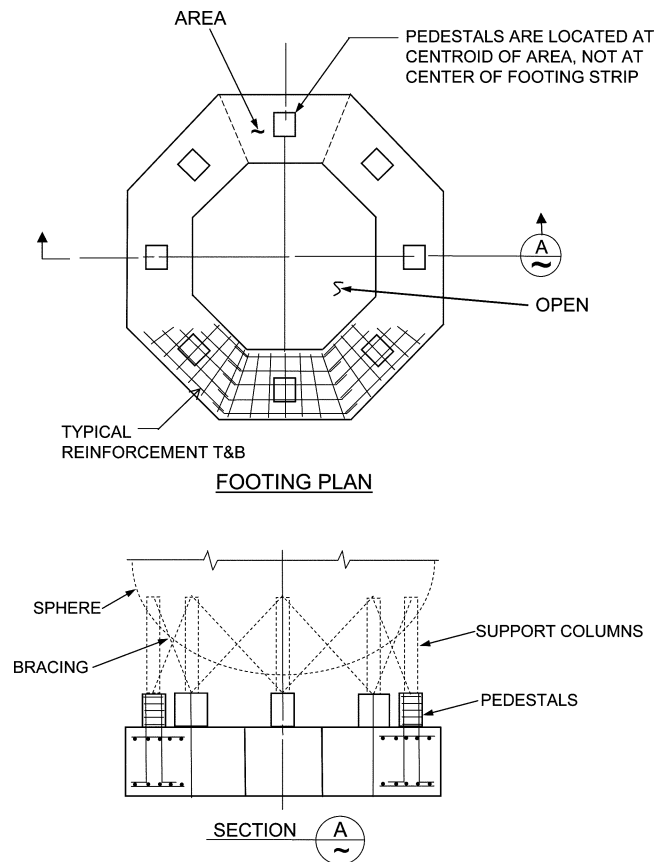


Fig. 3.4—Octagonal footing and pedestals for vertical sphere.

Another type of support structure consists of those for overhead electrical conductors, such as transmission towers, poles, dead-end structures, and flexible bus supports. These are designed for tensile loads from the conductors along with ice and wind loads. Drilled piers are commonly used to support such structures. Spread footings or pile-supported footings are also used when required by soil conditions.

CHAPTER 4—DESIGN CRITERIA

Criteria used for the design of static equipment foundations vary considerably among engineering practitioners. Most heavy equipment foundations are designed by or for large organizations, which may include utilities and government agencies. These organizations, with their in-house expertise, have developed their own engineering practices, including design criteria. Unfortunately, there is a limited amount of published information on the criteria used for the design of the types of static equipment foundations covered herein.

4.1—Foundation loading

Most practitioners first attempt to use the common loadings defined by local building codes or by ASCE/SEI 7. Many engineers, however, have difficulty classifying the numerous different loadings into the standard dead and live categories. There is, therefore, a need to define additional categories of loadings and load combinations with appropriate load factors.

4.1.1 Loads

4.1.1.1 Dead loads—Dead loads consist of the weight of the equipment, platforms, piping, fireproofing, cladding, duct work, and other permanent attachments. Some engineers also designate the operating contents (such as liquid or granular material) of the equipment as dead loads. Such a combination, however, is inconvenient when considering the possible combinations of loads that may act concurrently and when assigning load factors. Equipment may often be empty and still be subject to various other loads. Thus, a distinction between dead and operating loads is generally maintained.

4.1.1.2 Live loads—Live loads consist of the gravity load produced by personnel, movable equipment, tools, and other items that may be placed on the main piece of equipment, but are not permanently attached to it. Live loads also commonly include the lifted loads of small jib cranes, davits, or booms that are attached to the main piece of equipment or directly to the foundation.

Live loads will normally not occur during operation of the equipment. Typically, such loads will be present only during maintenance and shutdown periods.

4.1.1.3 Operating loads—Operating loads include the weight of the equipment contents during normal operating conditions. These are contents that are not permanently attached to the equipment. Such contents may include liquids, granular or suspended solids, catalyst material, or other temporarily supported products or materials being processed by the equipment. The operating load may include the effects of the contents movement or transfer, such as fluid surge loads in certain types of process equipment. These latter loads, however, are sometimes treated separately in project design criteria, and require different load factors (Section 4.1.3).

Operating loads also commonly include forces caused by thermal expansion (or contraction) of the equipment itself. An example would be a horizontal vessel or heat exchanger with two saddles, each supported on a separate foundation. Temperature change of the equipment can produce horizontal thrusts at the tops of the supporting piers. Allowing the equipment to slide on top of one of the pedestals can reduce the temperature-induced load. This is accomplished by adding a horizontal plate, commonly called a slide plate, between the top of one of the concrete support pedestals and the equipment saddle. The holes in the equipment saddle (used to attach to the anchor in the concrete pedestal) are slotted above the slide plate. This reduces the maximum lateral thermal load to a value commonly calculated by multiplying the vertical load at the sliding saddle times the coefficient of friction between the equipment saddle and the slide plate. This load is applied to both the fixed and sliding supports in equal and opposite directions. Alternatively, the maximum forces and moments in the pedestals may be calculated by assuming that the two pedestals deflect laterally by an amount equal to the thermal length change of the equipment. If the pedestals and footings are capable of resisting the forces and moments associated with the lateral thermal length change, the slide plate is sometimes omitted.

Operating loads also commonly include forces caused by thermal expansion (or contraction) of the piping connected to

the equipment. The temperature change of connecting piping can produce up to six component reactions at the connecting flanges (three forces and three moments). For large piping, such forces may significantly affect the foundation design.

4.1.1.4 Wind loads—Loads due to wind on the surface areas of the equipment and the support foundation are based on the design wind speed for the particular site, and are normally calculated in accordance with the governing local code or standard.

When designing equipment foundations and support structures, most practitioners use the wind load provisions of ASCE/SEI 7. The analytical procedure prescribed by ASCE/SEI 7 provides wind pressures and forces for use in the design of the wind-force-resisting systems and anchorage of equipment components.

Most structural systems involving equipment foundations are relatively stiff (natural frequency in the lateral direction greater than 1 Hz). Consequently, the systems can be treated as rigid with respect to the wind gust effect factor, and a factor of 0.85 as defined in ASCE/SEI 7 can be used. If the equipment is supported on flexible isolators and is exposed to the wind, the rigid assumption may not be reasonable, and more elaborate treatment of the gust effects is necessary as described in ASCE/SEI 7 for flexible structural systems.

Tall, flexible process towers, stacks, and chimneys are susceptible to wind-excited oscillations. The discussion in ACI 307 and ASME STS-1 addresses this issue. Another reference (ASCE 2011) offers recommendations for the types of equipment commonly found in petrochemical plants.

Appropriate consideration of the exposure conditions and topographic, directionality, and importance factors is also required to be consistent with the facility's requirements.

4.1.1.5 Seismic loads—While building codes have traditionally focused on the earthquake loading and seismic design requirements for buildings, the requirements for equipment foundations can be significantly different. This is because of differences in life-safety concerns, function and dynamic responses of the foundation, equipment system interaction with piping, and flammable, explosive, or hazardous substances associated with equipment, manufacturing processes, or both.

The FEMA 450 report is a guidance document that defines earthquake loading and seismic design criteria. It contains a section that specifically addresses seismic design and earthquake loading for non-building structures. These provisions have been incorporated in ASCE/SEI 7, in a section for non-building structures, and the "International Building Code" (ICC 2018) incorporated these non-building provisions by reference to ASCE/SEI 7.

Some of the non-building items from ASCE/SEI 7 that are applicable to equipment foundation design include:

1. A list of consensus standards for use when considering seismic design of non-building structures;
2. A list of accepted standards for use when considering seismic design of non-building structures;
3. Guidance on when to consider equipment as a structural, mechanical, or electrical component of a system;

4. Seismic coefficients and height limitations for numerous types of non-building structures; and

5. Earthquake loading and seismic design provisions for numerous types of non-building structures.

The foundation designer should use ASCE/SEI 7 and its referenced standards for applicable seismic design requirements for the equipment foundation.

4.1.1.6 Test loads—Most process equipment, such as pressure vessels, is hydro-tested when in place on its foundation. There is also a good possibility that sometime during the life of a vessel it will be altered or repaired; a hydrotest may then be required to meet the requirements of Section VIII of the American Society of Mechanical Engineers (ASME) “Boiler Pressure Vessel Code” (BPVC). Therefore, it is often considered necessary that all vessels, their skirts or other supports, and their foundations be designed to withstand the hydrotest loads. Testing requirements are specified by the owner, vendor, and/or governing codes for the equipment.

4.1.1.7 Maintenance and repair loads—For most heat exchangers, maintenance procedures require that an exchanger’s tube bundles be periodically unbolted, pulled from the exchanger shell, and cleaned (Fig. 3.2). The magnitude of the required pulling force that is transmitted to the exchanger foundation can vary over a wide range, depending on several factors. These factors include: 1) the service of the exchanger, including the type of product, the temperatures, and the corrosiveness of the participating fluids; 2) the frequency of the maintenance procedure; and 3) the pulling or jacking procedure actually used. The value used will depend on the engineers’ judgment and industry/client/designer practice.

Because the forces transmitted to a foundation from pulling an exchanger bundle vary, the design forces used are often based on past experience. Common criteria are to design for a longitudinal force ranging from 0.5 to 1.5 times the bundle weight. This force is assumed to act at the centerline of an exchanger and is taken in combination only with the exchanger dead (empty) load. For stacked or piggyback exchangers, the bundle pull is assumed to act on only one exchanger at a time.

4.1.1.8 Fluid surge loads—Many types of process vessels (such as reactors and catalyst regenerators) are subject to surge forces. Although the analogy may be less than perfect, it is often convenient to describe fluid surge as a coffee-pot effect. The essential mechanism may be similar to the boiling of a contained fluid, with the violent formation and sudden collapse of unstable gas bubbles, currents of merging fluids with fluctuating density, and sloshing of a liquid surface also contributing to the surge forces. These violent forces act erratically, being randomly distributed in both time and space within the liquid phase. Obviously, fluid surge is a dynamic load. Because of the difficulty in defining either the magnitude or the dynamic characteristics of these forces, however, they are almost always treated statically for foundation design.

Surge forces are usually represented as horizontal static forces located at the centroid of the contained liquid. The magnitude of this design force is taken as a fraction of the

weight of liquid below a normal operating liquid level. The fraction of liquid weight that is used will vary from 0.1 to 0.5, depending on the type of vessel, on the violence of its contained chemical process, and on the degree of conservatism desired by the owner-operator in resisting such loads. The value used will depend on the engineers’ judgment and client/industry/designer practice. For most vessels supported directly on foundations at-grade, surge forces are small, and may be neglected.

4.1.1.9 Construction loads—Construction procedures and the erection and setting of equipment frequently cause load conditions on a foundation that will act at no other time during the life of the equipment. For example, before a piece of equipment is grouted into position on its foundation, local bearing stresses under stacks of shims or erection wedges should be checked. Another more specific example is the case of a vertical vessel or stack that may be erected on its foundation before the installation of heavy internals or refractory lining. Once installed, these internals are categorized as part of a vessel’s permanent dead load. Many practitioners, however, believe it is necessary to examine the situation that could exist for the interim weeks, or sometimes months, before installation of this considerable internal weight. The design of a tall, vertical vessel foundation may well be governed by overall stability against overturning if it is required that the temporarily light structure be capable of withstanding full design wind (Ratay 2002). Coordination is required between the designer and the constructor to ensure that foundation will withstand the construction loads.

4.1.1.10 Buoyancy loads—The buoyant effect of a high groundwater table (water table above the bottom of the foundation) is sometimes considered as a separate load; that is, some engineers treat it as an upward-acting force that may (or may not) act concurrently with other loads under all load conditions. Perhaps, just as frequently, the buoyant effects are treated by considering them as a different condition in which the gravity weight of submerged concrete and soil are changed to reflect their submerged or buoyant densities.

Without addressing the philosophical difference between these two perceptions, the effect is the same. The buoyant effect of a high water table may govern not only the stability (as outlined in Section 4.4), but may also contribute to the critical design forces (moments and shears) used in the design of the foundation.

When it is probable that the elevation of the water table will fluctuate, both dry (neglecting water table) and wet (including the buoyancy effects of a high water table) conditions should be considered when designing foundations.

4.1.1.11 Miscellaneous loads—Other types of loads are sometimes defined as separate loadings and are sometimes grouped under one of the categories described previously. Some types of loads are fairly specialized, in that they are normally applied only to certain types of structures or equipment. They include the following:

- **Thermal loads**—Thermal loads are sometimes considered as a separate load category, but are not included in 4.1.2.3 as operating loads.

- *Impact loads*—Impact loads, such as those due to cranes, hoists, and davits, are sometimes classified separately. Just as often, they are classified as live loads or, depending on the type of equipment, as operating loads;
- *Blast loads*—Explosions and the resulting blast pressure wave represent extreme upset or accident conditions. Normally, blast pressures are only applied to the design of control buildings. Seldom is such a load considered in the design of equipment or foundations, except possibly to set locations so that there is adequate distance between critical equipment and a potential source of such an explosion;
- *Snow or ice loads*—Snow or ice loads may affect the design of access or operating platforms attached to equipment, including their support members. Seldom do they affect the design of equipment foundations, except for electric power distribution structures. Often, snow load is considered as a live load; and
- *Electrical loads*—Impact loads caused by the sudden movements within circuit breakers and load break disconnects may be greater than the dead weight of the equipment. Furthermore, the direction of the load will vary, depending upon whether the breaker is opening or closing. In alternating current devices, short-circuit loads are usually internal to the equipment and have little or no effect on the foundations. In the case of direct current transmission lines in which the earth acts as the reference, however, a short circuit between the aerial conductors and the earth may result in significant loads being applied to the supporting structures.

4.1.2 Loading conditions—Different steps in the construction of equipment, or different phases of its operation/maintenance cycle, represent distinct environments, or different “conditions,” for such equipment. During each of these conditions, there can be one or several combinations of loads that can, with reasonable probability, act concurrently on the equipment and its foundation. The following loading conditions are often considered during the life of equipment and its foundations.

4.1.2.1 Construction condition—The construction condition exists while the equipment or its foundation is still being constructed, and the equipment is being set, aligned, anchored, or grouted into position. In the construction condition, the equipment may be subject to gravity, construction, and reduced environment loads such as wind and earthquake.

4.1.2.2 Empty condition—The empty condition will exist after erection is complete, but before charging the equipment with contents or placing it into service. Also, the empty condition will exist at any subsequent time when operating fluid or other contents are removed, the equipment is removed from service, or both. This condition does not usually include the direct effect of maintenance operations. In the empty condition, the equipment may be subject to gravity, and environmental loads such as wind and earthquake.

4.1.2.3 Operating condition—The operating condition exists at any time when the equipment is in service, is charged with operating fluid or contents and is about to be placed into service, or is just in the process of being turned off and

removed from service. In the operating condition, the equipment may be subject to gravity, thermal, surge, and impact loads, and environmental forces such as wind and earthquake.

4.1.2.4 Test condition—This condition exists when equipment is being tested, either to verify its structural integrity, or to verify that it will perform adequately in service. Although the time period actually required for an equipment test is a few days, the test condition may last for several weeks. Thus, it is often assumed that during the test condition, an equipment foundation will be subjected not only to gravity loads (that is, dead load plus the weight of test fluids), but also wind or earthquake. Usually, these loads are taken at reduced intensity. Typical intensities vary from one-quarter to one-half of the wind or earthquake load. Refer to Ratay (2002) for further discussion on this subject.

4.1.2.5 Maintenance condition—The maintenance condition exists at any time that the equipment is being drained, cleaned, recharged, repaired, realigned, or the components are being removed or replaced. Loads may result from maintenance equipment, davits or hoists, jacking (such as when exchanger bundles are pulled), impact (such as from the recharging or replacing of catalyst or filter beds), and gravity. The gravity load is assumed to be dead load.

The duration of a maintenance condition is usually short, such as a few days. The probability of maximum wind or seismic loads occurring with maintenance loads is low. Also maintenance typically will not be scheduled or can be suspended during a major event, such as hurricane force winds. Therefore, environmental loads, such as wind and earthquake, are rarely assumed to act during the maintenance condition. Refer to Ratay (2002) for further discussion on short-term events and load probabilities.

4.1.2.6 Upset condition—An upset load condition exists at any time that an accident, malfunction, operator error, rupture, or breakage causes equipment or its foundation to be subjected to abnormal or extreme loads. It is often assumed that equipment subjected to severe upset loads may have to be shut down and repaired. Thus, it is not uncommon for the upset loads to be treated as ultimate (unfactored) loads rather than service level (factored) loads.

4.1.3 Load factors—Table 4.1 shows the general classification of loads used to determine the applicable load factors in strength design. In considering soil stresses, the normal approach is working stress design without load factors and with overall factors of safety identified as appropriate by geotechnical engineers. Load factor criteria for petrochemical facilities can be found in PIP STC01015.

4.1.4 Load combinations—Codes usually specify the more common loadings and combinations that are considered for building design. Industrial equipment, because of the many possible variations in operating loads, can have a far greater number of possible load combinations. Several different load combinations are often possible within a given load condition. Judgment should be used to decide which loads and corresponding load factors can reasonably be expected to act concurrently. In general, ACI 318 load combination factors are used with the load classifications in Table 4.1. The variations among different practitioners, the following