IN-LB	Inch-Pound Units
SI	International System of Units

An ACI Standard

Code Requirements for Seismic Analysis and Design of Liquid-Containing Concrete Structures (ACI 350.3-20) and Commentary

Reported by ACI Committee 350

ACI 350.3-20

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First Printing
October 2021
ISBN: 978-1-64195-161-6

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ACI 350.3-20

Code Requirements for Seismic Analysis and Design of Liquid-Containing Concrete Structures (ACI 350.3-20) and Commentary

An ACI Standard

Reported by Joint ACI Committee 350

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This Code prescribes procedures for the seismic analysis and design of liquid-containing concrete structures. These procedures address the loading side of seismic design and are intended to complement Section 1.1.9 and Chapter 13 of ACI 350-20.

Keywords: circular tanks; concrete tanks; convective component; earthquake resistance; environmental concrete structures; impulsive component; liquid-containing structures; rectangular tanks; seismic resistance; sloshing; storage tanks.

ACI 350.3R-20 supersedes 350.3-06, became effective November 20, 2020, and was published October 2021.

PREFACE

From the time it embarked on the task of developing an ACI 318-dependent code, ACI Committee 350 decided to expand on and supplement the seismic provisions for "Special Provisions for Seismic Design" to provide a set of thorough and comprehensive procedures for the seismic analysis and design of commonly used types of liquid-containing structures of circular and rectangular configurations. The committee's decision was influenced by the recognition that liquid-containing structures are unique structures whose seismic design is not adequately covered by the leading national codes and standards. A seismic design subcommittee was appointed with the charge to implement the committee's decision.

The seismic subcommittee's work was guided by two main objectives:

(1) Produce a self-contained set of procedures that would enable a practicing engineer to perform a full seismic analysis and design of a liquid-containing structure. These procedures should cover both aspects of seismic design: the "loading side," which is the determination of the seismic loads based on the mapped risk-adjusted maximum considered earthquake spectral response accelerations at short periods (S_s) and 1 second (S_1) obtained from the Seismic Ground Motion maps (ASCE/SEI 7-16 Chapter 22) and the geometry of the structure; and the "resistance side," which is the detailed design of the structure in accordance with the provisions of ACI 350-20, to resist those loads safely.

(2) Establish the scope of the new procedures consistent with the overall scope of ACI 350-20. This required the inclusion of all types of tanks—rectangular as well as circular; and reinforced concrete as well as prestressed.

There are currently at least two national standards that provide detailed procedures for the seismic analysis and design of liquid-containing structures: ANSI/AWWA D110-13 (R18), which is limited to circular, prestressed concrete tanks; and ANSI/AWWA D115-17, which covers both rectangular and circular prestressed concrete tanks.

As the loading side of seismic design is outside the scope of ACI 318, it was decided to maintain this practice in ACI 350 as well. Accordingly, the basic scope, format, and mandatory language of Chapter 21 of ACI 318-11 were retained with only enough revisions to adapt the seismic provisions to environmental engineering structures. Provisions similar to Section 1.1.9 of ACI 318-11 are included in ACI 350. This approach offers at least two advantages:

(1) Allows ACI 350 to maintain the ACI 318 practice of limiting its seismic design provisions to the resistance side only.

(2) Makes it easier to update these seismic provisions to keep up with the frequent changes and improvements in the field of seismic hazard analysis and evaluation.

The forces due to earthquake determined in accordance with this Code are intended to be used in the determination of load effects due to earthquake, *E*, in accordance with Chapter 9 of ACI 350-20. The seismic force levels and *R*-factors included in this Code provide results at strength levels, such as those included for seismic design in the International Code Council (ICC) 2012 International Building Code (IBC 2012), particularly the applicable connection provisions of IBC 2012 as referenced in ASCE/SEI 7-16. When comparing these provisions with other documents defining seismic forces at allowable stress levels (for example, the 1997 Uniform Building Code [UBC-1997]), the seismic forces in this Code should be reduced by the applicable factors to derive comparable forces at allowable stress levels.

Users should note the following general design methods used in this Code, which represent the evolution of seismic design of liquid-containing structures over a number of years since ASCE (1984), as follows:

(a) Instead of assuming a rigid tank for which the acceleration is equal to the ground acceleration at all locations, this Code assumes amplification of response due to natural frequency of the tank.

(b) The response modification factor is included.

(c) Rather than combining impulsive and convective modes by algebraic sum, this Code combines these modes by square-root-sum-of-the-squares.

(d) The effects of vertical acceleration are included.

(e) An effective mass coefficient applicable to the mass of the walls is included.

For further information on seismic behavior of liquid-containing structures, refer to Housner (1957, 1963b). For fluids other than water, refer to Veletsos and Shivakumar (1997).

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CODE

CHAPTER 1—GENERAL REQUIREMENTS

1.1—Scope

This Code describes procedures for the design of liquid-containing concrete structures subjected to seismic loads. These procedures shall be used in accordance with Chapter 13 of ACI 350-20.

1.2—Notation

A_s = cross-sectional area of prestressed and nonprestressed steel reinforcement, in.^{2} (mm^2)

b = ratio of vertical to horizontal design acceleration

B = inside dimension (length or width) of a rectangular tank, perpendicular to the direction of the ground motion being investigated, ft (m)

C_c, C_i, and C_t = period-dependent seismic response coefficients (9.4, 9.5)

C_l, C_w = coefficients for determining the fundamental frequency of the tank-liquid system (Eq. (9.3.4b) and Fig. 9.3.4b)

C_s = period-dependent seismic coefficient

d_{max} = maximum vertical displacement of an oscillating wave measured from the liquid surface at rest, ft (m)

D = inside diameter of circular tank, ft (m)

EBP = excluding base pressure (datum line just above the base of the tank wall)

COMMENTARY

CHAPTER R1—GENERAL REQUIREMENTS

R1.1—Scope

This Code is a companion Code to Chapter 13 of the American Concrete Institute, "Code Requirements for Environmental Engineering Concrete Structures (ACI 350-20) and Commentary (ACI 350R-20)."

This Code provides requirements for the designer of liquid-containing concrete structures for computing seismic forces that are to be applied to the particular structure. The designer should also consider the effects of seismic forces on components outside the scope of this Code, such as piping, equipment (for example, clarifier mechanisms) and connecting walkways where vertical or horizontal movements between adjoining structures or surrounding backfill could adversely influence the ability of the structure to function properly (NSF 1981). Moreover, seismic forces applied at the interface of piping or walkways with the structure may also introduce appreciable flexural or shear stresses at these connections.

The hydrodynamic forces described in ACI 350.3 can be used in design of liquid-containing concrete structures other than environmental structures if the licensed design professional or another reference standard chooses to use or refer to it.

The operational conditions used to calculate the seismic forces determined by this Code need to be evaluated by the licensed design professional. Considerations such as normal operational liquid levels, and potential for a tank or cells within a tank to be empty during a seismic event should be included. It is common to consider several loading conditions when designing for seismic loading, such as with the liquid at normal operating levels and with the tank or individual tank cells empty.

R1.2—Notation

For C_s, refer to ASCE/SEI 7-16 Section 12.8.1.

EBP refers to the hydrodynamic design in which it is necessary to compute the overturning of the wall with respect to the top of the tank floor, excluding base pressure (that is, excluding the pressure on the floor itself). EBP

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E_c = modulus of elasticity of concrete, psi (MPa)
E_s = modulus of elasticity of cable, wire, strand, or conventional reinforcement, psi (MPa)
F_a = short-period site coefficient (at 0.2 second period) from ASCE/SEI 7-16 Table 11.4-1
F_v = long-period site coefficient (at 1.0 second period) from ASCE 7-16, Table 11.4-2
G_p = shear modulus of elastomeric bearing pad, psi (MPa)
G = acceleration due to gravity (32.17 ft/s^2 [9.807 m/s^2])
h_c = height above the base of the tank wall to the center of gravity of the convective lateral force for the case excluding base pressure (EBP), ft (m)
h_c' = height above the base of the tank wall to the center of gravity of the convective lateral force for the case including base pressure (IBP), ft (m)
h_{eg} = height above the base of the tank wall to the center of gravity of the lateral force due to the dynamic earth pressure, and from saturated and unsaturated soils, ft (m)
h_i = height above the base of the tank wall to the center of gravity of the impulsive lateral force for the case excluding base pressure (EBP), ft (m)
h_i' = height above the base of the tank wall to the center of gravity of the impulsive lateral force for the case including base pressure (IBP), ft (m)
h_r = height from the base of the tank wall to the center of gravity of the tank roof, ft (m)
h_w = height from the base of the tank wall to the center of gravity of the tank shell, ft (m)
H_L = design depth of stored liquid, ft (m)
H_w = wall height above top of floor (inside dimension), ft (m)
I = importance factor, from Table 4.1.1a
I_b = moment of inertia at the base of the tank
IBP = including base pressure (datum line at the base of the tank wall including the effects on the tank bottom including dynamic fluid pressure on the tank bottom)

COMMENTARY

hydrodynamic design is used to determine the need for hold-downs in non-fixed base tanks. EBP is also used in determining the design pressure acting on walls. (For explanation, refer to Housner [1963a].)

H = as defined in Section R9.2.4, ft (m)

IBP refers to the hydrodynamic design in which it is necessary to investigate the overturning of the entire structure with respect to the tank support foundation. IBP hydrodynamic design is used to determine the design pressure acting on the tank floor and the underlying foundation. This pressure is transferred directly either to the subgrade or to other supporting structural elements. IBP accounts for moment effects due to dynamic fluid pressures on the bottom of the tank by increasing the effective vertical moment arm to the applied lateral forces. (For explanation, refer to Housner [1963a].)

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k_a = spring constant of the tank wall system, lb/ft per foot of wall width (N/m per meter of wall width)

K = flexural stiffness of a unit width of a rectilinear tank wall, lb/ft per foot of wall width (N/m per meter of wall width)

K_a = active coefficient of lateral earth pressure

K_o = coefficient of lateral earth pressure at rest

L = inside dimension of a rectangular tank, parallel to the direction of the ground motion being investigated, ft (m)

L_c = effective length of restraint cable taken as the sleeve length plus 35 times the cable diameter, in. (mm)

L_p = length of individual elastomeric bearing pads, in. (mm)

m_i = impulsive mass of contained liquid per unit width of a rectangular tank wall, lb-s^2/ft per foot of wall width (kg per meter of wall width)

m_w = mass per unit width of a rectangular tank wall, lb-s^2/ft per foot of wall width (kg per meter of wall width)

M = total mass per unit width of a rectangular wall = $m_i + m_w$, lb-s^2/ft per foot of wall width (kg per meter of wall width)

M_b = bending moment on the entire tank cross section just above the base of the tank wall, ft-lb (kN-m)

M_c = bending moment of the entire tank cross section just above the base of the tank wall (EBP) due to the convective force P_c, ft-lb (kN-m)

M_c' = overturning moment at the base of the tank wall, including dynamic fluid pressure on the tank bottom (IBP), due to the convective force P_c, ft-lb (kN-m)

M_{eg} = bending moment of the entire tank cross section just above the base of the tank wall due to dynamic earth pressure and from saturated and unsaturated soils, ft-lb (kN-m)

M_i = bending moment of the entire tank cross section just above the base of the tank wall (EBP) due to the impulsive force P_i, ft-lb (kN-m)

M_i' = overturning moment at the base of the tank wall, including dynamic fluid pressure on the tank bottom (IBP), due to the impulsive force P_i, ft-lb (kN-m)

M_o = overturning moment at the base of the tank wall, including dynamic fluid pressure on the tank bottom (IBP), ft-lb (kN-m)

M_r = bending moment of the entire tank cross section just above the base of the tank wall

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k_{hw} = ratio of the saturated unit weight of the backfill to the buoyant unit weight of the backfill ($k_{hw} = \gamma_s/\gamma_b$], lb/ft^3