Seismic Design of Liquid-Containing Concrete Structures (ACI 350.3-01) and Commentary (350.3R-01)

REPORTED BY ACI COMMITTEE 350

ACI Committee 350
Environmental Engineering Concrete Structures

Charles S. Hanskat
Chairman

Lawrence M. Tabat*
Secretary

Nicholas A. Legatos*
Subcommittee Chairman

Andrew R. Philip*
Subcommittee Secretary

James P. Archibald
Jon B. Ardahl*
Walter N. Bennett
Steven R. Close
Ashok K. Dhingra*
Anthony L. Felder
A. Ray Frankson
Anand B. Gogate*
William J. Hendrickson*
Jerry A. Holland
William J. Irwin
Dov Kaminetzky
M. Reza Kianoush*
David G. Kittridge
Larry G. Mrazek*
Jerry Parnes
David M. Rogowsky
Satish K. Sachdev
William C. Schnobrich*
Sudhaker P. Verma
Roger H. Wood

Voting Subcommittee Members

Osama Abdel-Aai*
John Baker
Patrick J. Creegan*
David A. Crocker
Ernst T. Cvikl
Robert E. Doyle
Clifford T. Early
Clifford Gordon
Paul Hedli
Keith W. Jacobson
Dennis C. Kohl
Bryant Mather
Jack Moll
Carl H. Moon
Javeed A. Munshi*
Terry Patzias
Narayan M. Prachand
John F. Seidensticker
William C. Sherman*
Lauren A. Sustic
Lawrence J. Valentine
Miroslav Vejvoda
Paul Zoltanetzky

*Members of ACI 350 Seismic Design Subcommittee who prepared this report.

Seismic Design of Liquid-Containing Concrete Structures (ACI 350.3-01) and Commentary (ACI 350.3R-01)

REPORTED BY ACI COMMITTEE 350

This standard prescribes procedures for the seismic analysis and design of liquid-containing concrete structures. These procedures address the "loading side" of seismic design and shall be used in accordance with ACI 350-01/ACI 350R-01, Chapter 21.

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

INTRODUCTION

The following outline highlights the development of this document and its evolution to the present format:

- From the time it embarked on the task of developing an "ACI 318-dependent" code, Committee 350 decided to expand on and supplement Chapter 21, "Special Provisions for Seismic Design," in order to provide a set of thorough and comprehensive procedures for the seismic analysis and design of all types of liquid-containing environmental concrete structures. 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: (a) To 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. This meant that these procedures should cover both aspects of seismic design: the "loading side" (namely the determination of the seismic loads based on the seismic zone of the site, the specified effective ground acceleration, and the geometry of the structure), and the "resistance side" (the detailed design of the structure in accordance with the provisions of the code, so as to safely resist those loads). (b) To establish the scope of the new procedures consistent with the overall scope of ACI 350. This required the inclusion of all types of tanks—rectangular, as well as circular; and reinforced concrete, as well as prestressed.

  [While there are currently at least two national standards that provide detailed procedures for the seismic analysis and design of liquid-containing structures (References 17 and 18), these are limited to circular, prestressed concrete tanks only].

As the "loading side" of seismic design is outside the scope of Chapter 21, 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 were retained with only enough revisions to adapt the chapter to environmental engineering structures. This approach offers at least two advantages: (a) It allows ACI 350 to maintain ACI 318's practice of limiting its seismic design provisions to the "resistance side" only; and (b) it makes it easier to update these seismic provisions so as to keep up with the frequent changes and improvements in the field of seismic hazard analysis and evaluation.

The seismic force levels and R_w-factors included herein provide results at allowable stress levels, such as are included for seismic design in the 1994 Uniform Building Code. When comparing these provisions with other documents defining

ACI 350.3-01/350.3R-01 became effective on December 11, 2001.

CHAPTER 4—EARTHQUAKE DESIGN LOADS

STANDARD

4.1—Earthquake pressures above base

The walls of liquid-containing structures shall be designed for the following dynamic forces in addition to the static pressures: (a) inertia forces P_w and P_r; (b) hydrodynamic impulsive pressure P_i from the contained liquid; (c) hydrodynamic convective pressure P_c from the contained liquid; (d) dynamic earth pressure from saturated and unsaturated soils against the buried portion of the wall; and (e) the effects of vertical acceleration.

4.1.1—Dynamic lateral forces

The dynamic lateral forces above the base shall be determined as follows:

$$P_w = ZSIC_i \times \frac{\varepsilon W_w}{R_{wi}} \quad (4\text{-}1)$$

$$P_w' = ZSIC_i \times \frac{\varepsilon W_w'}{R_{wi}} \quad (4\text{-}1a)$$

$$P_r = ZSIC_i \times \frac{W_r}{R_{wi}} \quad (4\text{-}2)$$

$$P_i = ZSIC_i \times \frac{W_i}{R_{wi}} \quad (4\text{-}3)$$

$$P_c = ZSIC_c \times \frac{W_c}{R_{wc}} \quad (4\text{-}4)$$

Where applicable, the lateral forces due to the dynamic earth and ground water pressures against the buried portion of the walls shall be computed in accordance with the provisions of Chapter 8.

4.1.2—Total base shear, general equation

The base shear due to seismic forces applied at the bottom of the tank wall shall be determined by the following equation:

$$V = \sqrt{(P_i + P_w + P_r)^2 + P_c^2} \quad (4\text{-}5)$$

COMMENTARY

R4.1—Earthquake pressures above base

The general equation for the total base shear normally encountered in the earthquake-design sections of governing building codes

$$\left[V = \frac{ZIC}{R_w} \times W\right]$$ is modified in Eq. (4-1) through (4-4) by

replacing the term W with the four effective masses: the effective mass of the tank wall, εW_w, and roof, W_r; the impulsive component of the liquid mass W_i; and the convective component W_c. Because the impulsive and convective components are not in phase with each other, normal practice is to combine them using the square root of the sum of the squares method (Eq. (4-5)).

The general equation for base shear is also modified in Eq. (4-1) through (4-4) by the soil profile coefficient S in accordance with Table 4(b).

The imposed ground motion is represented by an elastic response spectrum that is either derived from an actual earthquake record for the site, or is constructed by analogy to sites with known soil and seismic characteristics. The profile of the response spectrum is defined by the product ZC. Factor Z (Table 4(a)) represents the maximum effective peak ground acceleration for the site, while C is a period-dependent spectral-amplification factor. In Eq. (4-1) to (4-4) factor C is represented by C_i and C_c, corresponding to the responses of the impulsive and convective components, respectively.

Factor I provides a means for the engineer to increase the factor of safety for the categories of structures described in Table 4(c). (See also Reference 1, Section R21.2.1.7). The response modification factors R_{wc} and R_{wi} reduce the elastic response spectrum to account for the structure's ductility, energy-dissipating properties, and redundancy (Reference 1, Section R21.2.1). The resulting inelastic response spectrum is represented by $ZISC/R_w$.