Technical Paper

Sloshing Effects in Large Liquid Storage Tanks

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1.0 Introduction

Sloshing effects in large liquid storage tanks during earthquakes are a critical design consideration, because excessive sloshing can lead to overtopping, roof damage, uplift of the tank shell, hydrodynamic pressure amplification, and even tank failure. Modern practice manages sloshing through a combination of theoretical modeling, structural detailing, and seismic design provisions.

When an earthquake occurs, the liquid in a large storage tank doesn't move as a single solid block. Instead, it splits into two distinct components: the impulsive mass (the bottom portion that moves rigidly with the tank walls) and the convective mass (the top portion that sloshes back and forth). This separation allows designers to:

- Estimate sloshing wave height
- Compute hydrodynamic pressures
- Evaluate base shear and overturning moments

Most design codes (ACI 350.3, API 650, Eurocode 8, IS 1893-Part 2) are based on this framework.

Managing these sloshing (convective) effects is critical to prevent "elephant foot" buckling, roof damage, or hazardous spills. Engineers use a combination of structural design, internal dampening, and isolation technologies.

2.0 Managing Sloshing Effects

In tanks where sloshing is excessive,

- Baffles or ring plates may be introduced to disrupt wave formation.
- Energy-dissipating devices (less common) reduce convective response.
- Internal columns or partitions (for special tanks) reduce sloshing length.

These are typically used in very large or critical tanks (e.g., LNG tanks).

2.1 Internal Damping: Baffles

Baffles are the most common mechanical way to break up waves and dissipate the energy of the sloshing liquid.

- Horizontal (Annular) Ring Baffles: These are rings attached to the inner wall of the tank near the liquid's surface. As the liquid rises, it must flow over and around these rings, creating turbulence that "drains" energy from the wave.
- Vertical Baffles: Used primarily in rectangular or long horizontal tanks to prevent the buildup of large, longitudinal waves.
- Perforated Baffles: These have holes that allow some liquid to pass through, which is often more effective at damping than solid plates because the resulting "jetting" through the holes creates significant energy-absorbing turbulence.

> **“Seismic safety is achieved through precise impulsive - convective mass modeling”**

2.2 Geometric Management: Freeboard

Large tanks are rarely filled to the very top. Engineers calculate a required Freeboard—the empty space between the liquid surface and the tank roof.

- Wave Height Prediction: Standards like API 650 or Eurocode 8 provide formulas to predict the maximum sloshing wave height based on the site's seismic risk.
- Impact Prevention: If the freeboard is insufficient, the sloshing liquid can hit the roof with enough force to tear it off or buckle the top of the tank wall.

2.3 Structural Decoupling: Floating Roofs

In many oil and chemical tanks, a floating roof sits directly on the liquid surface.

- Suppression: Because the roof rests on the liquid, it acts as a giant weight that physically restricts the free-surface motion.
- Sealing: Flexible seals around the edge of the floating roof prevent the liquid from splashing over the top while allowing the roof to move slightly with the fluid.

2.4 Structural Detailing of Tank Components

Tank Wall and Base

- Walls are designed for combined hydrostatic and hydrodynamic pressures.
- Base slabs and shell-to-base junctions are detailed to resist uplift and rotation.
- Anchorage is provided where uplift demands exceed self-weight.

Roof Systems

- Floating roofs are detailed to accommodate sloshing without binding.
- Fixed roofs are designed to resist sloshing impact or are isolated from the liquid surface

2.5 Foundation and Soil–Structure Interaction

- Flexible foundations can lengthen impulsive periods, reducing force demand.
- Soil–structure interaction is considered for tanks on soft soils.
- Sliding resistance is checked where unanchored tanks are used.

3.0 Advanced Mitigation: Seismic Isolation

Instead of trying to stop the sloshing inside, some modern tanks are built to move with the earthquake to reduce the forces transmitted to the liquid.

Base Isolators: The entire tank is placed on rubber bearings or "sliders" (Lead-Rubber Bearings). These act like shock absorbers, shifting the natural frequency of the tank away from the frequency of the earthquake.

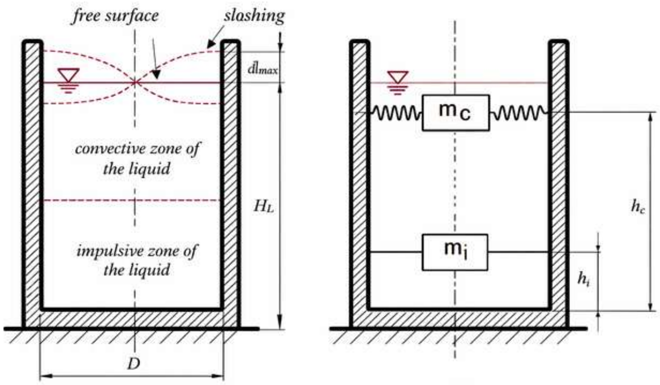
Benefit: This significantly reduces the impulsive force on the walls, though it can sometimes slightly increase the convective sloshing period, requiring a higher freeboard.

4.0 Code-based Seismic Design Provisions

Modern seismic codes manage sloshing by:

- Explicitly defining convective natural periods
- Providing equations for sloshing wave height
- Separately accounting for impulsive and convective forces
- Allowing performance-based checks for critical facilities

> **“Hydrodynamic pressures, uplift, and overturning—addressed through code-driven seismic detailing”**



(a) (b)

Fig. 1 Actual tank and equivalent simplified spring-mass mechanical model

To design these systems, engineers use the Housner Model (Spring-Mass Analogy). This simplifies the complex fluid dynamics into a mechanical system:

The total liquid mass in the mass is assumed to be divided into two masses and considered independently, as shown in Fig.1.

- Lower Impulsive Mass of liquid, which is not sloshing and remains rigidly attached to the walls.
- The upper Convective Mass of liquid, that is sloshing, is attached to the walls of the tank with a spring stiffness K_C.

API 650 Code

In API 650 Annex E (Seismic Design of Storage Tanks), the "freeboard" is managed by calculating the maximum sloshing wave height. This height determines the minimum clearance required between the liquid surface and the roof to prevent structural damage or overtopping. The calculation is a multi-step process involving the tank's geometry and the seismic characteristics of the site.

> “Designing for controlled sloshing—freeboard governed by quantified wave dynamics.”

1. Calculate the Convective (Sloshing) Period (Tc)

First, you must determine the natural period of the sloshing liquid.

$$T_c = K_s \sqrt{D} \quad (1)$$

Where:

- D: Nominal tank diameter (ft).
- K_s: The sloshing period coefficient, which depends on the ratio of the tank diameter (D) to the liquid height (H_L).

It is typically found using: $K_s = \dfrac{0.578}{\sqrt{tanh\left(\frac{3.68\,H_L}{D}\right)}}$,

or Fig. 2 given in API 650 code.(2)

2. Determine the Spectral Acceleration (A_f)

Next, find the acceleration coefficient specifically for the sloshing wave. This is based on the site's seismic response spectrum at the period T_C.

If $T_C \leq T_L$ (where T_L is the long-period transition period):

$$A_f = K\, S_{D1}\left(\frac{1}{T_c}\right) \quad (3)$$

K: Damping coefficient (usually 1.5 to adjust the 5% damped spectrum to the 0.5% damping typical of sloshing liquid), and SD1: Design spectral response acceleration parameter at a 1-second period.

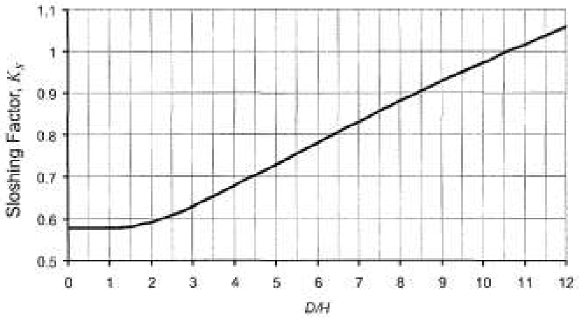


Fig. 2 Sloshing factor K_S

For site-specific analysis, the impulsive spectral acceleration is limited to 1.5g This is based on practical experience and observations of tank behavior

3. Calculate the Sloshing Wave Height (d_S)

The height of the wave above the product design level is calculated as: $d_s = 0.5\, DIA_f$ (4)

Where ‘I’ is the importance factor

4. Required Freeboard (Fb)

API 650 provides a table (Table E.7, which is reproduced below) for the minimum required freeboard based on the seismic design category and the calculated d_{CS}.

For example, if you have a tank with a 30m diameter and a calculated wave height d_S of 1.2m:

1. For a hazardous material tank (SUG III), one must provide at least 1.2m of freeboard.

Seismic Use Group (SUG)	Minimum Freeboard Required
SUG I (Standard)	Often a percentage of dS or as specified by the purchaser (frequently ~ 0.7 ds).
SUG III (Critical/Hazardous)	Full ds height (the roof must be higher than the maximum predicted wave).

2. For a standard water tank (SUG I) in a lower seismic zone, the code may allow a smaller freeboard (e.g., 0.7m), accepting that the wave might strike the roof in a maximum-intensity event, provided the roof is designed to handle that pressure.

The above calculations are important because:

- **Roof Damage**: If the wave hits a fixed roof, it creates upward pressure that can "pop" the roof-to-shell joint (designed to be frangible).
- **Spillage**: In open-top tanks, insufficient freeboard leads to the immediate loss of contents.
- **Floating Roofs:** For tanks with internal floating roofs, the freeboard calculation must also account for the height of the floating roof seal assembly to ensure it doesn't get crushed against the top angle.

5.0 Performance-Based and Advanced Analysis (Critical Facilities)

For nuclear, LNG, or lifeline tanks:

- Nonlinear time-history analysis with fluid–structure interaction is used.
- CFD-based sloshing simulations assess wave impact and roof interaction.
- Design targets include no loss of containment even under extreme shaking.

6.0 Seismic Sloshing Provisions in Different Codes

In the calculation of the seismic effects, simple equivalent mechanical models are used to investigate tank-liquid systems. The most widely used model adopted in various international codes is the one based on spring-mass modeling proposed for rigid tanks by G.W. Housner (See Fig. 1), which was later modified and extended for flexible tanks.

Some of the seismic sloshing provisions of different codes are compared in Table 1.

Table 1 Comparison of seismic sloshing provisions of different codes

Aspect	ACI 350.3 / ASCE 7	API 650 (App. E)	Eurocode 8 (EN 1998-4)	IS 1893 (Part 2)
Liquid model	Impulsive + convective	Impulsive + convective	Impulsive + convective	Impulsive + convective
Sloshing period	Closed-form (Housner-based)	Similar to ACI	Explicit modal expressions	Similar to ACI
Sloshing height	Explicit formula	Explicit	Explicit (often higher)	Explicit
Roof interaction	Checked explicitly	Checked	Explicitly addressed	Limited guidance
Anchorage	Required if uplift > weight	Strong emphasis	Explicit	Explicit
Damping (sloshing)	~0.5%	~0.5%	0.5–1%	~0.5%
Performance philosophy	Life safety / containment	Industry-based safety	Reliability-based	Prescriptive

From the above table, it is seen that all modern codes are mechanically consistent, but differ in:

- Conservatism of sloshing height
- Treatment of roof–liquid interaction
- Detailing and anchorage requirements

7.0 Example Calculation – Ground-Supported Circular Tank

Given

- Tank type: Ground-supported RC tank
- Inside Radius, R=15 m, Hence, Diameter D=30 m
- Liquid height, H_L =10 m
- Design peak ground acceleration, C_a =0.15g (Typical for Moderate Seismic Zones)
- Importance factor, I = 1.0
- Liquid density = 1000 kg/m3

Step 1: Determine the Convective Period (T_c)

The convective period depends on the ratio of the diameter to the liquid height.
Ratio D/H_L =30/10 =3.0

According to ACI 350.3, the formula for T_c in a circular tank is:

$$T_c = \frac{2\pi}{\sqrt{3.68 g \tanh\left(\frac{3.68 H_L}{D}\right)}} \sqrt{D} \tag{5}$$

Using the ACI frequency factor (Cc) for D/H_L = 3.0:
From ACI 350.3, Figure 9.3.4(b), for D/H_L = 3.0, the factor is 0.63 that gives approximately 0.63 x 1. 811 = 1.14 in metric units.
T_c= 1.14√30 = 6.24 sec.

Step 2: Determine Convective Spectral Acceleration (S_{ac})

For sloshing, ACI 350.3 typically uses 0.5% damping. S_{ac} is calculated based on the site response spectrum at period T_C.

If we assume a standard spectral shape where S_{ac} = 1.5 C_a/T_C for long periods:
S_{ac} = 1.5 x 0.15g / 6.24 = 0.036 g

Step 3: Calculate the Sloshing Height (ds)

The sloshing height is the maximum vertical displacement of the liquid surface at the tank wall. The ACI 350.3 formula is:

$$d_s = 0.5DIS_{ac}$$

Hence,
d_S=0.5×30×1.0×0.036=0.54 m

Design implication

- Minimum freeboard ≥ 0.54 m
- Add margin for uncertainty (often 20–30%), hence, adopt a minimum freeboard =1.3 x 0.54 = 0.70 m

Note that if Freeboard < 0.54m, the design of the roof slab should be designed to withstand the "slapping" or upward pressure of the liquid during an earthquake, and the impulsive forces must be increased to account for the restricted sloshing.

Impulsive Base Shear

Total liquid mass:

$$m = \rho \pi R^2 H = 1000 \times \pi \times 15^2 \times 10 = 7.068 \times 10^6 \text{ kg}$$

7.068 ×106×0.00981= 69337 kN

Determine the Convective Mass Ratio (W_C / W_L)

Using the ratio D/H_L =30/10 =3.0, using the ACI 350.3 formula for circular tanks:

$$\frac{W_c}{W_L} = 0.23\left(\frac{D}{H_L}\right)\tanh\left(3.68\frac{H_L}{D}\right)$$

$$\frac{W_c}{W_L} = 0.23 \times 3 \times tanh\left(\frac{3.68}{3.0}\right) = 0.58$$

The above ratio will normally be about 0.55 to 0.65.
Convective Weight, W_C = 0.58 x 69337 = 40264 kN

Calculate Convective Base Shear (V_C)

The base shear for the convective component is defined by the formula:

$$V_c = S_{ac} I W_c$$

From our previous step, we calculated the convective spectral acceleration, S_{ac} = 0.036g

Convective base shear:

$$V_c = 40264 \times 1 \times 0.036 \text{ g} = 1409.5 \text{ kN}$$

(This governs shell stresses and anchorage.)
Determine the Impulsive Mass Ratio (W_i / W_L)
Using the ACI 350.3 formula,

$$\frac{W_i}{W_L} = \frac{\tanh\left(0.866\frac{D}{H_L}\right)}{0.866\frac{D}{H_L}} = \frac{\tanh(0.866 \times 3)}{0.866 \times 3} = 0.381$$

Calculate Impulsive Weight (W_i)

Using the total liquid weight calculated previously (W_L = 69,337kN):
W_i =0.381 x 69337 =26,417 kN

Verification (Mass Balance Check)

In a simplified seismic model, the sum of the impulsive and convective masses should approximately equal the total mass of the liquid.
W_i = 26,417kN
W_C = 40,264 kN
Total (W_i + W_C): 66,681kN

Note: The sum is slightly less than W_L of 69,337 kN (approx. 96%) because ACI 350.3 accounts for higher-order sloshing modes that represent a very small fraction of the remaining mass.

Impulsive Base Shear (V_i)

To calculate the Impulsive Base Shear (V_i) and the Total Design Base Shear (V), we apply the response modification factors (R) prescribed by ACI 350.3-20. These factors account for the ductility and energy-dissipation capacity of the reinforced concrete structure.
For a "rigid" or "short-period" tank, the impulsive component corresponds to the constant acceleration region of the seismic response spectrum.

Design Spectral Acceleration (S_{ai}): For a peak ground acceleration (C_a) of 0.15g, the spectral acceleration is typically amplified by a factor of 2.5 in the plateau region.

$$S_{ai} = 2.5C_a = 2.5 \times 0.15 = 0.375\,\mathrm{g}$$

Response Modification Factor (R_i): For a ground-supported, anchored reinforced concrete tank, ACI 350.3 Table 4.1.1(a) specifies R_i = 3.25.
Importance Factor (I): 1.0
Calculation of Impulsive Base Shear (V_i)
The formula for the impulsive base shear is:

$$V_i = \frac{S_{ai}\, I\, W_i}{R_i} = \frac{0.375 \times 1 \times 26417}{3.25} = 3048\ \mathrm{kN}$$

Total Design Base Shear (V)

The total base shear is not a simple sum of the impulsive and convective parts because their peaks occur at different times. ACI 350.3 requires the SRSS (Square Root of the Sum of the Squares) combination.
Impulsive Shear (V_i): 3,048. kN
Convective Shear (V_C): 1409 kN

$$V = \sqrt{V_i^2 + V_c^2} = \sqrt{3048^2 + 1409^2} = 3358\ \mathrm{kN}$$

This total shear force, 3358 kN, is the lateral force used to design the tank's wall-to-foundation connection and to check for sliding and overturning stability.

> **Anchorage and shell–base detailing is engineered for reliable impulsive and sloshing force transfer**

8. 0 Summary and Conclusions

During seismic excitation, liquid storage tanks respond through a combined impulsive–convective mechanism. The impulsive component moves in unison with the tank wall and governs hydrodynamic pressures, base shear, and overturning moment, whereas the convective component represents sloshing of the free surface and controls wave height and roof interaction. Modern design codes such as ACI 350.3, API 650, Eurocode 8, and IS 1893 (Part 2) explicitly account for these mechanisms by assigning distinct natural periods, damping ratios, and force contributions. Adequate freeboard, proper anchorage, and detailing at the shell–base junction are essential to ensure containment integrity under earthquake loading.

Thus, the sloshing effects in large liquid storage tanks are managed by:

- Separating impulsive and convective liquid behavior
- Providing adequate freeboard and roof clearances
- Designing tank walls, base, and anchorage for hydrodynamic effects
- Using baffles or damping measures when necessary
- Following code-specified seismic liquid–structure interaction models

This integrated approach ensures containment integrity, operational safety, and seismic resilience of liquid storage tanks.

References

1. Housner, G.W. (1957)."Dynamic pressures on accelerated fluid containers", Bulletin of the Seismological Society of America, Vol. 47, No. 1, pp. 15–35. https://doi.org/10.1785/BSSA0470010015
2. A. S. Veletsos (1984). Seismic Response and Design of Liquid Storage Tanks, Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, Technical Council on Lifeline Earthquake Engineering ASCE, 1984.
3. EN 1998-4(2006), Eurocode 8 – Design of Structures for Earthquakes Resistance, Part 4 –Silos, Tanks and Pipelines.
4. IS 1893 (Part 2): 2014 Criteria for Earthquake Resistant Design of Structures, Part 2: Liquid Retaining Tanks, Fifth Revision (Reaffirmed 2019), Bureau of Indian Standards (BIS), New Delhi.
5. API Standard 650 (January 2021) Welded Tanks for Oil Storage, Annex E: Seismic Design of Storage Tanks, 13th Edition, American Petroleum Institute (API)
6. ACI CODE-350.3(2020) Code Requirements for Seismic Analysis and Design of Liquid-Containing Concrete Structures and Commentary, American Concrete Institute (ACI)
7. ASCE/SEI 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures, American Society of Civil Engineers (ASCE).Chapter 15.
8. Shah, H.J. Reinforced Concrete, Vol. II, 8th Revised and Enlarged Edition, Charotar Publishing House Pvt. Ltd., Anand, Gujarat, 2023, 776 pp.

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