The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 38, Pages 276-282

IConTES 2025: International Conference on Technology, Engineering and Science

Deterministic Assessment of the Seismic Behavior of Cylindrical Steel Storage Tanks: A Methodological Framework Based on the New Algerian Seismic Code

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Abstract: The Steel storage tanks are critical structures, frequently used in the industrial sector for the storage of various types of products, primarily toxic or flammable. This type of structure is complex in terms of design, engineering, and safety management. During severe earthquakes, the loss of tank performance can be devastating, leading to uncontrollable chain reactions that can cause more damage than the earthquake itself. In Algeria, despite the economic importance of these structures and their growing number across the country, the various updates to the seismic code (1981, 1999, 2003, 2024) have not included storage structures (concrete and steel) in their designs. This forces civil engineers, in their studies, to rely on foreign standards such as API 650, BS 2654, etc.This study, focused on cylindrical steel tanks, proposes a practical deterministic methodology for establishing seismic design criteria tailored to the Algerian context. The approach primarily relies on two key considerations: hydrodynamic effects, represented by the housner's model, and the seismic load defined by the response spectrum of the Algerian Seismic Code (RPA-2024). The study concludes with practically relevant insights derived from the results obtained.

Keywords: Steel storage tanks, Deterministic approach, Seismic design, RPA 2024, Hydrodynamic model

Introduction

In the heavy industry sector, large storage tanks serve critical economic needs. In regions with high seismic activity, such as Algeria, the nature of the stored products, which are often toxic or flammable, makes these structures particularly sensitive in terms of safety against earthquakes. The failure of a tank can trigger socio-economic and environmental consequences that may cause more damage than the earthquake itself. Therefore, their design must ensure they remain functional during and after a seismic event. This challenge becomes more complex when, under seismic stress, part of the stored liquid shifts, creating a phenomenon known as the hydrodynamic effect. Indeed, research has shown the detrimental impact of fluid-structure interaction on the overall behaviour of these structures. From a regulatory standpoint, in Algeria, the only normative reference for seismic design is the RPA. Despite various updates (RPA 81, RPA 88, RPA 99, RPA 2003 and RPA 2024), the Algerian seismic code remains silent on the subject of hydraulic structures in general and storage tanks in particular. The only guideline provided concerns the consideration of the hydrodynamic effect for tanks with a capacity exceeding 1500 m³, located in zones of moderate and high seismicity.

In response to these shortcomings, we propose in this study, illustrated by a practical application, a new approach. This approach, based on coupling the Housner model with the RPA response spectrum, is used to assess the stability of a large industrial tank subjected to significant seismic forces. The analysis method is detailed in the following sections.

Description of the Mechanical Model

The model used to assess the effects of seismic loading on high-capacity storage tanks must accurately replicate the stiffness, mass, and geometric properties of the structure, while also considering the hydrodynamic response of the stored liquid. The entire tank is represented through its equivalent mechanical mass-spring model, as illustrated in Figure 1.

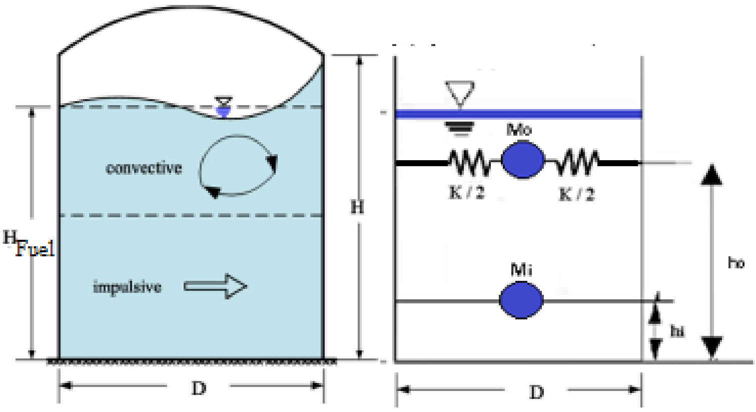

Figure 1. Description of mechanical model.

To analyze the stability of the reservoir and its hydrodynamic behavior (fluid-structure interaction), Housner (1963) breaks down the action of the liquid into two main actions, a passive action provoking impulse efforts, from that part of the fluid, denoted Mi, rigidly connected to the reservoir has an author hi, reacts by inertia to the translation of the walls of the reservoir. The second, called convective action, causing oscillation forces, from the fact that the other part of the mass, denoted active mass M0, rigidly connected via a stiffness spring K at a height h0, sets in oscillation motion under seismic action (Figure 1). These masses Mi and M0 are given by the following expressions of Housner (1963):

$$M_i = M_e \left[\frac{\boldsymbol{th}\left(\sqrt{3}\,\frac{R_i}{H_e}\right)}{\left(\sqrt{3}\,\frac{R_i}{H_e}\right)} \right] \tag{1}$$

$$M_0 = M_e 0.318 \frac{R_i}{H_e}\, \mathrm{th}\left(1.84 \frac{H_e}{R_i}\right) \tag{2}$$

Calculation of Impulse Actions

In our study, the reservoir is considered to be rigidly bound to the soil, thus undergoing the same value of the maximum acceleration Sa as the soil (Hammoum et al, 2010), (Aliche, 2016). The horizontal hydrodynamic resultant of the impulsive pressure, noted Pi, is given by the following relation (Housner 1963):

$$P_i = M_i . S_a \quad (3)$$

Given the soil-structure interaction, the seismic acceleration Sa imposed on the reservoir, is given by the Algerian RPA seismic regulation according to the seismic zone and other parameters.

Calculation of Oscillation Actions

The resultant of the horizontal hydrodynamic oscillation pressure, noted convective pressure Po, caused by the motion of the mass M0, under the effect of the seismic action, is given by the following relation:

$$P_o = 1.2 . M_0 . g . \varphi_0 \quad (4)$$

with:

$$\varphi_0 = 0.83 . \frac{S_a}{g} \quad (5)$$

Study of the Tank Stability

In the case of seismic loading at the ultimate limit state, the tank's overall stability against collapse must be ensured. The structure's stability may be influenced by slip or rollover under these conditions. To this end, the following inequality must be satisfied:

- $\dfrac{\text{stabilizer moment}}{\text{overturning moment}} \geq 1.5$
- Resultant of verticals strengths > Resultant of horizontal strengths

Another mode of failure that could lead to the decommissioning of a storage tank is the movement of fluid, caused by seismic action, in a partially filled tank. This can result in damage to the roof and overflow of the stored liquid. To prevent damage to the dome cover due to wave effects, a freeboard must be provided. According to Eurocode 8 (EC8 2003), the peak wave height, denoted as dmax, can be calculated as follows:

$$d_{\max} = 0.84 . \frac{S_a}{g} . R \quad (6)$$

Practical Application

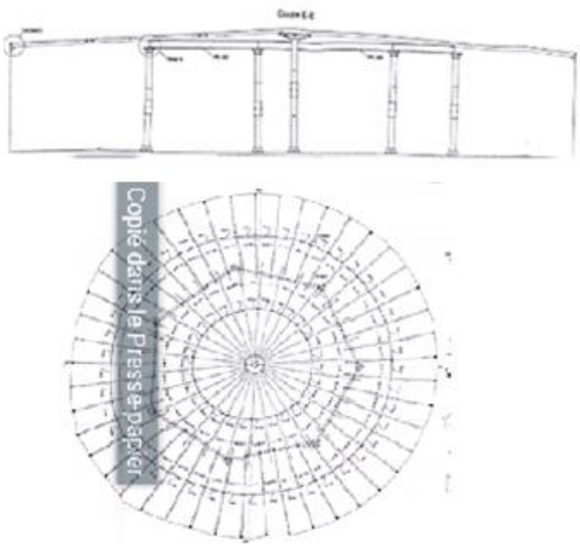

Figure 2. Planand elevation view of the structure

The structure that is the subject of our study is a steel storage tank with a capacity of 8000 m3, installed on a soil of category S3 in CAROUBIER (ALGIERS), classified Zone of strong seismicity (Zone VI) (Rpa 2024).

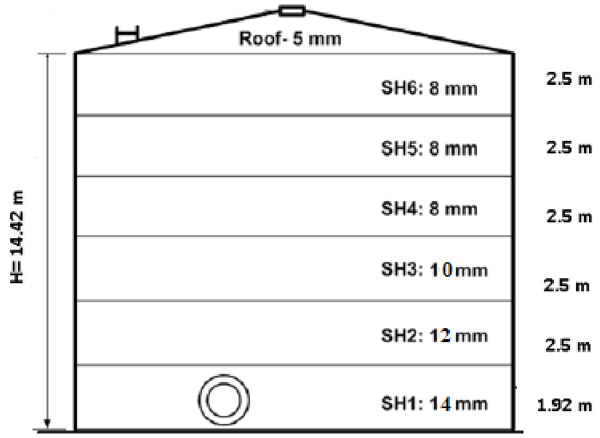

Figure 3. Geometry of mechanically tank

The geometric characteristics of the structure are mentioned in the table, which follows:

Table 1. Structure and mechanical properties of materials

	Values / designation
Stored product	Diesel fuel
Diameter of the tank	14 m
Tank height	14.42 m
Useful height of the fluid	13 m
Volume	8000 m^3
Roof style	Conical
Conditions of study	Temperature 50° C Density of the stored product 860 Kg/m^3

The thicknesses vary from top to bottom according to the position of the steel plates constituting each part of the cylinder, and are calculated according to paragraph 11.3.1 of Ec-3 as follows:

Table 2. Thickness of the ferrules constituting the cylinder.

N° ferrule	Ferrule height (m)	Fluid height (m)	t_{cal} (mm)	t_{min} (mm)	Over-thickness corrosion (mm)	t_{adp} (mm)
1	1.924	14.424	9.55	10	3.00	14
2	2.5	12.5	8.24	10	1.00	12
3	2.5	10	6.55	8	1.00	10
4	2.5	7.5	4.86	6	1.00	8
5	2.5	5	3.17	6	1.00	8
6	2.5	2.5	1.48	6	1.00	8

For the bottom of the tank, carbon steel was chosen, welded end to end. Hence the following results (Table 3):

Table 3. Roof and bottom thickness

	Calculated value	Adopted value	Unit
Roof thickness	7.06	8	mm
Bottom thickness	5.66	6	mm
Width of the annular plate	347.65	500	mm

Seismic Study

Calculation of the Fundamental Period T

The fundamental period of vibration is given by the following formula:

$$T = 1.79 H_t^2 \sqrt{\frac{P}{gEI}} \tag{7}$$

- the weight of the work P = 2132,794 KN
- Height of structure Ht = 14.424 m
- E: modulus of elasticity of the steel E = 2.1 * 10^5 MPa.
- moment of inertia of the wall with respect to the horizontal axis Ix:

$$I_x = \frac{\pi}{2}(14^4 - 13.986^4) = 241.2 \text{ m}^4 \tag{8}$$

So: *T = 0.415 s*

Calculation of the Acceleration Sa

Table 4. Parameters response spectra

Acceleration coefficient of the seismic zone	A = 0.3
Characteristic periods associated with the soil category of the site	S = 1.30 T1= 0.15 s T2= 0.6 s T3= 2.0 s
The quality factor of the structure	Q= 1
Damping correction factor	**η= 1**
Behaviour factor of the structure	R=2
Importance factor	I=1.2 (1B)

So for $T_1 \leq T \leq T_2$

$$\frac{S_a}{g}(T) = A.I.S\left(2.5\eta\right)\left(\frac{Q}{R}\right) \tag{9}$$

The acceleration of the ground $\boldsymbol{S_a = 5.85\ m/s^2}$ **/**(Sa=4.65 m/s² RPA2003**).**

Hydrodynamic Calculation

Table 5. Hydrodynamic calculation results.

Overturning moment M_r	197794.56	Kn.m
Stabilizer moment M_s	994018.5	Kn.m

The Stability of the Tank

The primary objective of analyzing the seismic behaviour of the structure, based on the response spectrum provided in the Algerian seismic code (RPA 2024), is to assess the stability of the structure under seismic loading. According to Eurocode, the stability of a reservoir under seismic action must be verified with respect to both the ultimate limit state (ULS) and the serviceability limit state (SLS) (Table 2). Limit state models focus on representing either the loss of functionality (serviceability limit states) or failure modes and loss of static equilibrium (ultimate limit states). This approach allows for the assessment of the structure's safety by determining stability criteria related to the limit states under actual operating conditions.

Serviceability Limit State

Under the effect of the seismic action at the ULS, the overall stability of the reservoir with respect to collapse must be satisfied. For this purpose, it is necessary to satisfy the following inequality:

$$\frac{M_s}{M_r} \geq 1.5 \quad \text{For our case} \quad \frac{M_s}{M_r} = \frac{994018.5}{197794.56} = 5.02 \geq 1.5$$

At Serviceability limit state**,** the overall stability of the tank with respect to collapse under the effect of the reversal is satisfied. This is the peculiarity of tanks placed on the ground.

Sloshing Effect

Under the effect of the seismic action, the tank may suffer damage or level of the roof. For this purpose, a freeboard must be provided to prevent roof damage due to the wave effect. According to Eurocode 8 (CEN, 1998), the predominant contribution to the height of the sloshing wave is provided by the first fundamental mode, and the expression of the peak of the edge is given by the following relation (9):

$$d_{max} = 0.84.\frac{S_a}{g}.R \quad \text{So in our case study:} \quad d_{max} = 5.03\ m$$

This value is greater than 1.492 m, expected as a free-board, so the waves will reach the roof of the tank this risk of damaging it.

Conclusions

The rules and standards specific to each country are influenced by various factors; the application of a code must consider these to meet the primary safety and economic requirements. In the field of storage tanks, the design process is a critical step that requires specialized expertise to comply with the relevant standards and regulations. In this sector, where the stored product holds significant socio-economic value, managing safety is crucial. This paper demonstrates that overlooking or neglecting the hydrodynamic phenomenon significantly underestimates the impact of waves on the tank roof. Such neglect can lead to overflow of the stored product, resulting in damage that may exceed the effects of the earthquake itself, depending on the nature of the product.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Technology, Engineering and Science (www.icontes.net) held in Antalya/Türkiye on November 12-15, 2025.

* The authors would like to thank the conference committee and the reviewers who reviewed the article for their valuable feedback

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To cite this article:

Aliche, A, Ider, O., Guemmoun, M., Hammoum, H., Bouzelha, K., & Atlaoui, D. (2025). Deterministic assessment of the seismic behaviour of cylindrical steel storage tanks: A methodological framework based on the new Algerian seismic code. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 38,* 276-282.