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# Investigation of the buckling behavior of cylindrical unanchored steel storage tank under near field 3-D seismic loading

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## Abstract

Maintaining the health of oil and other fluid storage tanks after an earthquake is one of the most important points for any earthquake-prone country. By examining the dynamic response of storage tanks in past earthquakes, it can be seen that steel storage tanks are more vulnerable than concrete tanks. Therefore, it is more important to investigate the seismic behavior of steel tanks. In this study, tank and the fluid inside it and interaction between fluid and structure in the ABAQUS software is simulated, to investigate the buckling behavior of an unanchored broad cylindrical steel storage tank built in Malayer. some near field earthquakes records are applied to storage tank. and all three components of these records, have been considered. the radial displacement of wall of the tank after the earthquake indicate the diamond-shaped buckling mode due to the significant effects of slashing. It should also be mentioned that the most deformations are observed at a height of 10.5 meters from the ground level on the wall of the tank, which due to the lower thickness of the sheet in the upper courses of the wall it can be strengthened in order to prevent the leaking of fluid inside the tank.

**Keywords:** Steel storage tanks; unanchored tanks; seismic behavior of storage tanks; buckling of storage tanks.

## 1. Introduction

One of the important issues in reducing losses caused by earthquakes and servicing after that is providing resistance and proper functioning of vital arteries during earthquakes. Among the most important vital arteries, we can mention the steel aboveground storage tanks for storing water and fuel and petroleum and petrochemical products. Also, in order to maintain the health of the storage tanks and their operation after the earthquake, it is necessary to ensure the proper functioning of the storage tanks. By examining the effects of horizontal and vertical displacements caused by earthquakes on these structures, it is possible to prevent the destructive effects of displacements that lead to leakage of the contents inside the tanks with more appropriate design and thinking of necessary arrangements.

Regarding the classification and introduction of the types of tanks, according to the type of structure, they can be divided into above ground, elevated and under pressure, based on a foundation or another structure. The tanks can be completely on the ground, semi-buried or completely buried. The elevated tank is placed on a support structure at a height above the ground level. A pressure tank, usually with a smaller volume, is installed on a foundation, its own special foundation or another structure. The tank can be made of metal, reinforced concrete, prestressed concrete, building materials or other suitable materials.

Metal underground tanks are divided into two categories: self-contained and mechanically contained. If the metal tank resting on the ground with the help of its own weight and the liquid inside it provides resistance to overturning, it is self-anchored and if it is restrained to the foundation by a harness rod, belt or other mechanical devices, it is called an anchored tank.

Basically, in the seismic design of reservoirs, the types of possible damage caused by an earthquake are meant, such as the following:

• Elephant foot buckling caused by compressive stress in the tank wall

• Destruction of the roof of the tank and the upper area of the wall due to the waves resulting from the sloshing movement of the fluid

• Rupture of the wall and concentration of stress around the tank restraints to the base or foundation

• Slippage of the ground reservoir caused by the dominance of the horizontal force of the earthquake over the frictional resistance

• Damage to non-flexible joints of pipes and other equipment connected to the tank, tearing of the weld between the floor and the wall, and the relative settlement of the foundation, due to the floor lifting from the ground in self-anchored tanks or with relative containment.

• Fires after earthquakes, often due to the failure of connections or the release of flammable fluid from the roof, especially in tanks with a floating roof.

Today, with the help of the experience of the performance of structures in the past and the progress of computing tools, the effort is to make the most accurate analysis of the seismic behavior of the structure with the lowest cost in the fastest possible time, taking into account all the effective parameters, and following this analysis, the optimal design is done.

## 2. Methodology

In this study, the finite element software ABAQUS was employed to simulate the tank–fluid system. The following modeling considerations and element types were utilized:

Tank structure modeling: The tank was modeled using shell elements, representing both the cylindrical wall and the bottom plate. The selected shell element is a four-node quadrilateral element designed specifically for thin-walled and shell-type structures. Each node in this element possesses six degrees of freedom: three translational and three rotational components.

Fluid modeling: The internal liquid was modeled using hexahedral acoustic elements. These are eight-node brick elements, where each node has a single degree of freedom corresponding to acoustic pressure. Unlike conventional mechanical elements, acoustic elements simulate pressure wave propagation in compressible media, with pressure being the primary state variable.

Rigid foundation modeling: The rigid base was modeled using eight-node solid (brick) elements with reduced integration. This element belongs to the family of continuum elements and is suitable for representing solid supports with high stiffness.

Fluid–structure interaction (FSI): The interaction between the fluid and the tank wall was implemented using a surface-based contact formulation with tie constraints, allowing pressure transfer while preventing relative motion.

Tank–foundation interaction: The contact between the tank bottom and the rigid base was defined using a general contact algorithm, specifically a surface-to-surface contact interaction.

Loading procedure: Initially, the self-weight of the structure and hydrostatic pressure of the fluid were applied. In the subsequent analysis step, seismic loading was introduced by applying earthquake-induced acceleration time histories in three orthogonal directions through boundary conditions.

## 3. Validation of the Numerical Model

To ensure the accuracy and reliability of the adopted modeling approach in this study, validation was conducted in multiple aspects, focusing on the seismic response of the tank. The numerical results were compared with those reported by Nam Phan [33] in the following areas:

- **Sloshing frequency of the tank**, to assess the dynamic characteristics of the fluid–structure system;
- **Hydrostatic pressure on the tank wall** at a specific location, measured after the application of seismic loading;
- **Sloshing height of the internal fluid** following the earthquake excitation, to verify fluid motion and free surface behavior

## 4. Seismic Input and Dynamic Response Evaluation

In this study, seven near-feild ground motion records were selected to investigate the dynamic behavior of the target tank. For each earthquake record, two horizontal components and one vertical component were considered. To scale the records uniformly, the peak acceleration was identified across all three components, and the acceleration time histories were normalized by dividing each component by its corresponding peak value.

These normalized acceleration records were applied incrementally to the tank model via the *acceleration boundary condition* in ABAQUS. The excitation was applied independently for each record at five increasing peak ground acceleration (PGA) levels, ranging from 1.0g to 1.5g with an increment of 0.1g per step.

To study the tank's dynamic behavior, particular attention was paid to the most dominant buckling mode, characterized by radial deformation of the tank wall. The combined effect of hydrodynamic pressure due to seismic loading and the pre-existing hydrostatic pressure induces significant deformation in the tank wall.

For this purpose, the maximum radial deformation along a specified vertical path on the tank wall was recorded throughout the earthquake time history. Radial deformation profiles were plotted versus height for all seven records at each of the six PGA levels (from 1.0g to 1.5g).

Analysis of the data reveals that, for most ground motions, radial deformation tends to increase with higher PGA values, which is consistent with the expected increase in energy transmitted to the structure. However, in some records, this trend deviates significantly. For instance, in the Tabas earthquake, due to characteristics such as high energy content in low-frequency ranges and a longer duration, the increase in radial deformation with PGA is more pronounced. Conversely, in the Loma Prieta earthquake, possibly due to higher frequency content or shorter duration, this trend is not strictly followed, and a different buckling pattern is observed.

These results suggest that, in addition to PGA, specific features of the ground motion—such as frequency content and duration—play a critical role in the initiation and development of radial deformations and the associated buckling modes.

## 5. Conclusions

The seismic response of unanchored cylindrical tanks subjected to three-component ground motions results in the emergence of two distinct buckling modes: the elephant-foot and diamond-shaped modes. The findings indicate that the maximum radial deformation in the diamond-shaped buckling pattern occurs at an elevation of 10.5 meters above ground level. This observation emphasizes the importance of vertical stress distribution and highlights the critical role of buckling modes in the overall stability of such storage structures.

A detailed examination of the plotted data reveals the high sensitivity of the tanks to increases in peak ground acceleration (PGA). Notably, when PGA rises from 0.4g to 0.5g, the radial wall deformation exhibits a substantial increase—specifically, a 35.7% rise in the mean radial deformation and a 50% rise in the mean plus standard deviation curve. These abrupt changes mark critical thresholds in the tanks' dynamic behavior and suggest a transition into nonlinear under intensified seismic loading.

Moreover, the initiation of deformation is observed from a height of approximately 7.5 meters, extending upward along the tank wall. This vertical distribution indicates a cumulative deformation pattern at higher elevations, which may elevate the risk of structural failure or compromise the tank's serviceability. In contrast, in the lower regions of the wall, evidence suggests the development of the elephant-foot buckling mode during the initial loading cycle, particularly around 1 meter above the base. This localized deformation reflects a concentration of compressive stresses, identifying this zone as a potential critical region requiring structural enhancement or design modification in future tank configurations.

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