FLUID SEISMIC MOTION SIMULATION FOR A SCALE MODEL STORAGE TANK

SIMULAREA MIȘCĂRII SEISMICE A FLUIDELOR PENTRU UN REZERVOR DE STOCARE LA SCARĂ

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Abstract: *This article targets a simple and affordable approach to ease the understanding the effect of seismic motion on the product stored in a tank. The proposed method is to build a seismic simulator using the most common system now available: a 3D printer customized to accurately replicate the earthquake motion. Besides the visualization of the sloshing wave of the fluid under the seismic motion, this can also be recorded. Since one of the goals of this article is to make this experiment available without expensive and sophisticated measurement systems, the fluid motion is recorded using the most common and also very accurate sensor available that everyone is carrying around: LIDAR system within the smartphone. To go even further, this article also touches the means of decreasing the seismic actions on storage tanks using a common equipment: the seismic isolation device that is scaled and used in the experiment. The seismic isolators are widely used in the industry and can also easily be observed in action using the scales seismic simulator.*

Keywords: seismic simulation, storage tank, seismic isolation, 3D printing, sloshing, lidar.

Rezumat: *Acest articol vizează o abordare simplă și accesibilă pentru a facilita înțelegerea efectului mișcării seismice asupra produsului depozitat într-un rezervor. Metoda propusă este de a construi un simulator seismic folosind cel mai comun sistem disponibil în prezent: o imprimantă 3D personalizată pentru a reproduce cu acuratețe mișcarea cutremurului. Pe lângă vizualizarea oscilației fluidului sub mișcarea seismică, aceasta poate fi și înregistrată. Întrucât unul dintre obiectivele acestui articol este de a face acest experiment disponibil fără sisteme de măsurare costisitoare și sofisticate, mișcarea fluidului este înregistrată folosind cel mai comun și, de asemenea, foarte precis senzor disponibil pe care toată lumea îl poartă cu ea: sistemul LIDAR din smartphone. De asemenea, acest articol abordează și mijloacele de reducere a acțiunilor seismice asupra rezervoarelor de stocare folosind un echipament* *comun: dispozitivul de izolare seismică care este scalat și utilizat în experiment. Izolatoarele seismice sunt utilizate pe scară largă în industrie și pot fi, de asemenea, observate cu ușurință în acțiune folosind simulatorul seismic la scară.*

Cuvinte cheie: simulare seismică, rezervor de stocare, izolare seismică, imprimare 3D, sloshing, lidar.

1. Introduction

Oil storage tanks are widely used equipment regardless the industry type, but the largest ones are storing crude oil and petroleum finite products. Due to their nature, storage tanks are considered thin membrane equipment, meaning that the shell thickness is very small compared to their diameter. Because of this characteristic, storage tanks are susceptible to deformations and even catastrophic failure during seismic events and the main cause is the sloshing effect. The sloshing is phenomenon that represents the complex flow of the liquid contained in a partial filled tank due to an external excitation that is usually an earthquake [1]. The sloshing wave can have two main destructive effects: on shell due to alternative inductive and convective pressures that can deform it and the second being the force acting on the roof-to-shell joint which can ultimately damage the roof structure if the tank is not properly dimensioned [2].

While the impulsive and convective pressures acting on the shell can be mitigated by proper dimensioning of the shell and, when mandatory, using seismic isolators [3], the roof structure is protected by calculating the maximum sloshing wave in the given area seismic loadings and considering a proper freeboard to ensure the roof-to-shell joint protection.

In recent years, significant research efforts have been directed toward understanding and mitigating the effects of seismic-induced sloshing in liquid storage tanks. Sloshing dynamics represent a critical aspect of fluid–structure interaction problems, particularly for partially filled tanks subjected to horizontal ground motion. Experimental investigations, such as the work of Liu et al. [1], demonstrated that resonance amplifies sloshing, especially at low fill levels, while higher levels introduce frequency shifts due to nonlinear effects. Different wave patterns, including 3D vortices, appear, and dominant responses align with excitation frequencies.

Numerical approaches have also been extensively employed to simulate sloshing behavior. Ozdemir et al. [4] applied a fully nonlinear finite element model incorporating fluid dynamics, contact behavior, and geometric and material nonlinearities was developed to simulate both anchored and unanchored tanks. The numerical results were validated against experimental data, showing good agreement in predicting key response parameters such as sloshing height, pressure distribution, and shell stresses. The analysis also highlighted the important influence of base uplift in unanchored tanks. However, comparisons with existing seismic design codes revealed notable discrepancies, particularly in estimating uplift displacement and sloshing wave height, indicating limitations in current code provisions. Similarly, Ono et al. [2] used Smoothed Particle Hydrodynamics (SPH) simulation to evaluate sloshing loads on a fixed roof, showing good agreement with other methods. The results indicate that roof loads increase with tank width, even at constant roof–liquid clearance, highlighting the influence of tank geometry.

From an experimental standpoint, shake table testing remains one of the most reliable methods for assessing seismic performance. Cao et al. [5] developed a building-specific seismic assessment procedure to evaluate nonstructural elements using realistic loading conditions. Time history analyses highlighted the importance of considering building dynamics, leading to a tailored loading protocol implemented on a shake table (Nonstructural Element Simulator on Shake Table (NEST) system). Experimental validation showed good accuracy (errors below 30%) and confirmed the method’s effectiveness in identifying damage levels and sensitive frequency components.

To address mitigation strategies, seismic isolation has emerged as a widely adopted solution. Malhotra [3] showed that seismic isolation significantly reduces hydrodynamic forces in storage tanks, including base shear, overturning moments, and wall stresses, while having limited influence on sloshing height. In slender tanks, isolation bearings may also experience tensile forces during strong shaking

In addition, recent studies have explored fluid behavior during operational conditions beyond seismic events. Li et al. [6] analyzed the flow field and impact behavior of the liquid on the floating roof under varying inlet velocities, initial liquid levels, fluid densities, and tank diameters. The results indicate that higher inlet velocity and fluid density increase both peak pressure and impact forces. Additionally, increased inlet velocity intensifies turbulence on the side opposite the inlet, leading to higher pressures along the upper edge of the floating roof.

Despite these advances, there remains a gap in the availability of low-cost, accessible experimental platforms that can replicate seismic motion while enabling quantitative analysis of fluid behavior. Most existing studies rely either on complex numerical simulations or expensive laboratory equipment, limiting their applicability in educational and preliminary research contexts. Therefore, the present study proposes a simplified and affordable approach by adapting a 3D printer into a seismic simulator, combined with smartphone-based LIDAR measurements, offering a novel methodology for visualizing and quantifying sloshing phenomena.

The goal of this article is to build a seismic simulation device and experiment with the most commonly available measuring system that everybody carry in their pocket: the LIDAR sensor of the smartphone paired with a proper measuring software and an analysis algorithm.

2. Seismic motion effect on storage tanks

While most of the tank's lifetime the main load is the hydrostatic pressure due to the stored product there might be seismic events that can affect the tank integrity and these should be taken into consideration. The earthquakes are unpredictable events, but their magnitude and characteristics can be anticipated by past similar recurrent events [7].

Usually, depending on the country, there are local standards that treat the seismic action and impose the characteristics of the seismic events, like in example Eurocode 8 [8] and in most of the times are applicable together with the tank design standards, like EN 14015 [9] and EN 1993-4-2 [10] or API650 [11]/API620 [12]], these in particular including its own seismic design prescriptions.

The seismic event induces certain loads into the tank resulting in a complex behavior due to the fact that the tank itself and the contained fluid have different dynamics. The fluid interacts with the tank components, mainly the shell inducing loads like impulsive and convective pressures and sloshing [4] (that are explicitly shown in the experimental part of this article).

3. Materials and Methods used for the seismic simulator

The seismic simulator or shake table [5] is a device that simulates the seismic movements that act on a scaled structure or equipment.

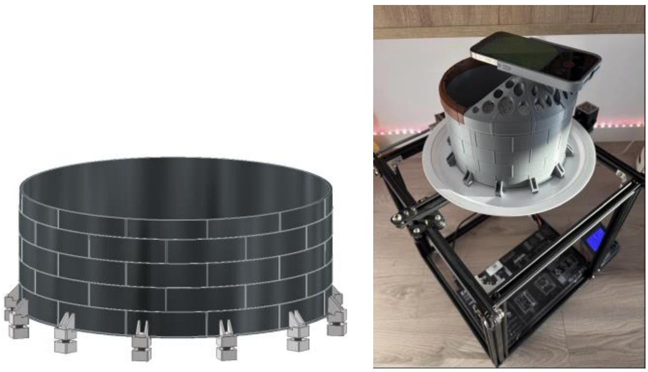
For a small case appliance, a 3D printer can be configured to act as a shake table. Usually, the vertical component of an earthquake can be neglected, so a printer the X and Y axes of a 3D printer can successfully replicate the quake motion with proper programming. For this purpose, a Creality Ender 5 Pro printer is used because its printer head can move on both X and Y axes (Figure 1). The motors are powerful, fast and accurate enough to replicate the movements. The printer extruder assembly was replaced with a fix table to support the storage tank scale model. Instead of extruding filament, the printer is used only as a motion platform.

The tank itself is a scale model of a 23-meter diameter tank, 3D printed in PLA. While the tank shell and bottom assembly is scaled, the anchor chairs are not at scale in order to fix them to the shake table. For the tank fixture, two cases are considered:

- ✓ First case the tank is anchored on foundation (shake table plate) by neodymium magnets to fix the assembly to directly transmit the seismic movements;
- ✓ Second case, the tank rests on ball bearing fixtures simulating the seismic isolators.

All these parts are printed in PLA.

Finally, in order to capture the fluid movement, a support to fix the iPhone is added instead of the tank roof. The support has multiple holes to decrease the weight and inertia, while the phone weight can be assimilated to the tank roof weight.



(a) (b)

Fig. 1. (a) The 3D model of the Tank; (b) Picture of the constructed assembly.

Usually, the shake tables run dedicated software to drive the motors in order to accurately simulate the seismic movements, but since this article is addressed to mechanical and structural engineers without specific programming experience, another approach was followed: to prepare a custom G-code that can run on the existing 3D printer firmware. This article outlines the procedure for generating such G-code, explains how the motion profile is mapped from earthquake phases, provides illustrative examples for historical events, and introduces a mathematical formulation of the displacement profiles.

3.1. G-code Fundamentals

G-code is the machine language for CNC and 3D printing. For this application, only a subset of commands is needed:

- G28 → Homing sequence;
- G90 / G91 → Absolute vs. relative motion modes;
- G1 → Linear move with feedrate (velocity);
- M104/M140 → Turn off heaters (safety);
- M84 → Disable motors after motion.

Key concept: Earthquake shaking is approximated by a series of small XY displacements at varying amplitudes and velocities. Each block of commands represents ~1 second of motion.

3.2. Mathematical Formulation

The simulated displacement along the X-axis can be expressed as a sinusoidal oscillation modulated by an amplitude envelope defined by Equation (1):

$$x(t) = A(t) \cdot \sin(2\pi\, f\, t + \varphi) \quad (1)$$

where:

- $A(t)$: time-varying amplitude envelope (mm), derived from earthquake profile;
- f: dominant shaking frequency (Hz);
- φ: initial phase (rad);
- $x(t)$: displacement in X direction (mm).

Similarly, the Y-axis displacement can be defined as Equation (2):

$$y(t) = A(t) \cdot \sin(2\pi\, f\, t + \varphi + \Delta\varphi) \quad (2)$$

where $\Delta\varphi$ is a phase shift between the two directions, simulating combined seismic wave effects.

3.3. Mapping Earthquake Phases to Printer Motion

Real seismic records contain three main stages:

1. P-wave onset (Primary waves)
- Small, high-frequency motions.
- Simulated with 1–2 mm displacements at higher feedrates.

2. Mainshock (S-wave dominated & surface waves)
- Large amplitude, lower-frequency, sustained shaking.
- Simulated with 5–10 mm displacements at moderate feedrates (0.5–2 Hz).
- Occasional bursts (pulses) for near-fault earthquakes.

3. Coda / Aftershocks

- Gradual decay, intermittent bursts.
- Simulated with decreasing amplitudes (2–3 mm) and mixed feedrates.

3.4. Procedure for Producing Earthquake Simulation G-code

Step 1 – Printer Preparation
Ensure no filament is loaded.
Raise the Z-axis 10–20 mm above the bed (G1 Z10).
Center the toolhead (G1 X110 Y110 for Ender 5).
Disable heaters (M104 S0, M140 S0).

Step 2 – Define Motion Parameters
Use relative motion (G91).
Define block length = ~1 second per seismic motion cluster.
Displacement amplitude = 0.5–10 mm depending on quake intensity.
Feedrate (F) controls velocity → mapped to target shaking frequency.
Example feedrate-frequency mapping:
1500–2000 mm/min → ~2 Hz feel
4000–7000 mm/min → ~0.5–1 Hz broad sways

Step 3 – Script Motion Blocks
Each block is four moves (±X, ±Y):

```
G1 X5.0 F4800
G1 X-5.0 F4800
```

```
G1 Y6.0 F5000
G1 Y-6.0 F5000
```

Larger displacements → stronger shaking.
Mixed feedrates → variable frequency feel.
60 blocks ≈ 1 minute.

Step 4 – Encode Earthquake Signature

For this step, four significant earthquakes were considered and the seismic data was retrieved from public reports, as follows:

Vrancea 1977 (Romania): Strong mid-shock amplitude, tapering decay [13].

Tohoku 2011 (Japan): Extended plateau with very strong shaking [14].

Kobe 1995 (Japan): Near-fault pulse (large one-directional push) [15].

Maule 2010 (Chile): Long, lower-frequency, rolling motion [16].

By scripting G-code to approximate earthquake phases, a desktop 3D printer can become a compact and low-cost educational earthquake simulator. Different historical events can be represented by adjusting amplitude, frequency, and duration parameters. The mathematical formulation provides a generalized approach to defining motion envelopes, making it easier to scale or adapt to various seismic scenarios.

3.5. Example Graphs of Mathematical Formulation

The following figures illustrate sample displacement curves generated using the mathematical formulation. The amplitude envelope A(t) modulates the sinusoidal oscillations in both X and Y directions as in Figures 2 and 3.

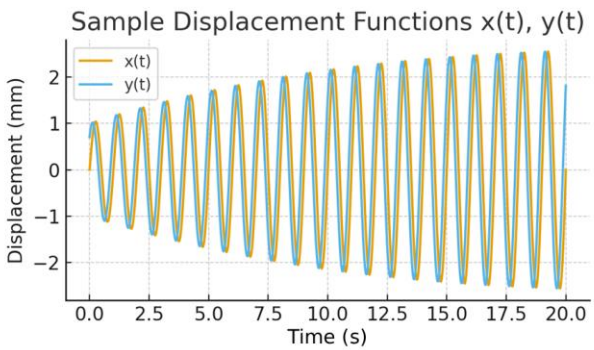


Fig. 2. Simulated displacements x(t) and y(t) using sinusoidal functions with an amplitude envelope.

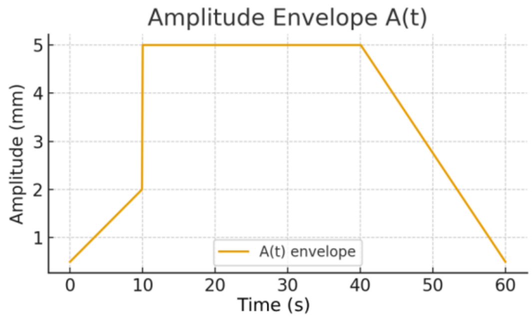


Fig. 3. Example amplitude envelope A(t) for a 60-second simulated earthquake.

Earthquake-Specific Amplitude Profiles

Figure 4, 5, 6 and 7 illustrate approximate amplitude envelopes A(t) for selected historical earthquakes. These simplified profiles were used to design the G-code motion sequences.

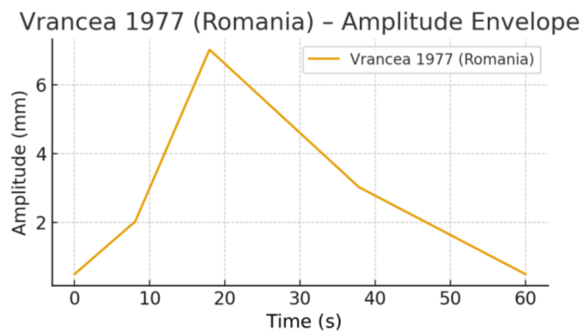


Fig. 4. Simplified displacement envelope for Vrancea 1977 (Romania).

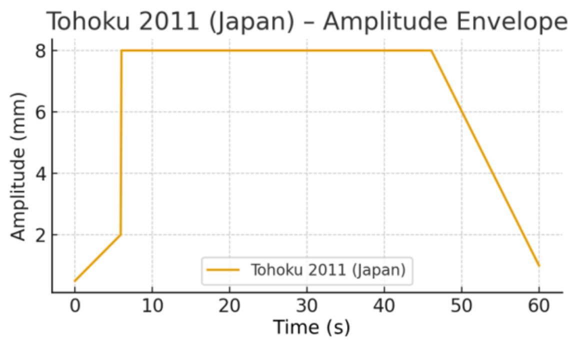


Fig. 5. Simplified displacement envelope for Tohoku 2011 (Japan).

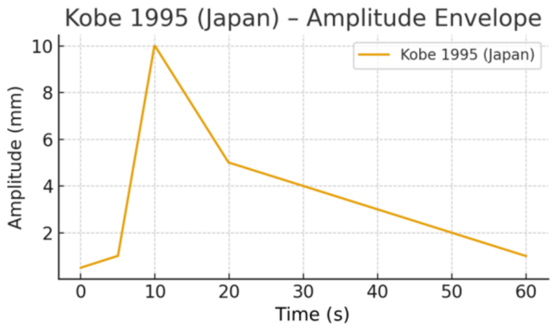


Fig. 6. Simplified displacement envelope for Kobe 1995 (Japan).

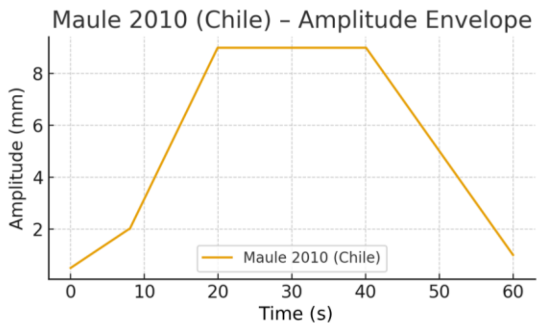


Fig. 7. Simplified displacement envelope for Maule 2010 (Chile).

For comparison with the simplified envelopes used in this article, the public sources [8], [9], [10], [11] provide original strong-motion records and accelerograms of the discussed earthquakes.

Seismic isolation and simulation of an isolator on the shake table

In the experiment the 3D printed scale tank was resting directly on the shake table, for the seismic motion to act directly on the tank and its contained liquid.

In order to visualize the seismic isolation effect, scale seismic isolators were installed. These isolators were manufactured from 3D printed base plates and custom bearing spherical parts. The isolators can be easily installed using neodymium magnets that were attached both the tank and shake table.

The Sliding Isolation Pendulum (SIP-S Type) is consisting of a single concave lower sliding plate with a stainless-steel sheet on the surface [17] (Figure 8).

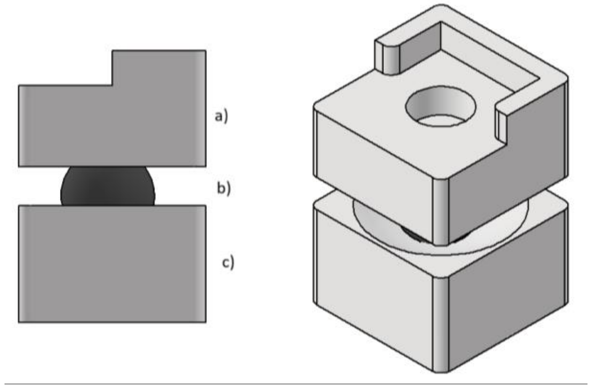


Fig. 8. 3D printed seismic isolator:
a) upper part, fixed on the tank; b) spherical part; c) lower part, fixed on the base plate.

4. Measurements and visualization of the liquid motion

The purpose of using a shake table is to visualize and make approximate measurements of the tank liquid motion under the seismic movements. In order to capture the motion, the most accessible method is the LIDAR scanner on an iPhone (other phone having this feature can be used as well) and an application that can record the movement.

Record3D app is used to record the fluid movement, the output being a video file that measures and record in real time the distance of the surface shape of the liquid from the LIDAR sensor and normal video side-by-side. Polystyrene particles are used to cover the liquid surface in order to facilitate an accurate scan, as the liquid surface reflects the laser.

The image is processed and colored, red being the closest and blue being the far from the sensor.

An example of a frame taken from the moving fluid surface in presented in Figure 9.

For the purpose of comparing the two recordings of the liquid motion with and without seismic isolators a Python algorithm is used and run in Google Copilot.

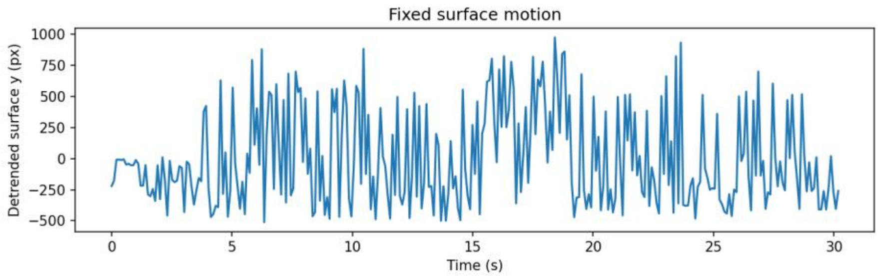
Fig. 9. Frame from the 3D recording app.

5. Results

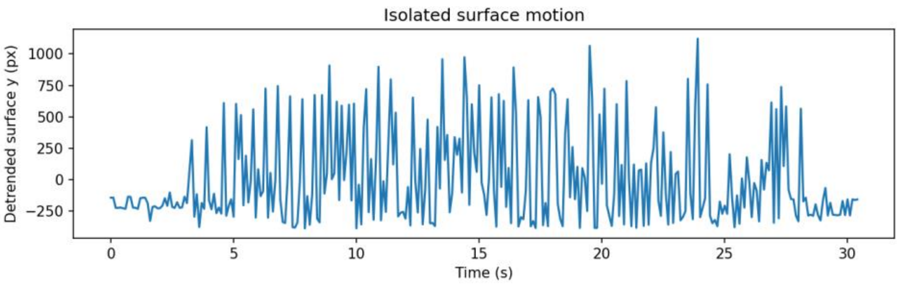
The experiment result was the series of recorded liquid motion simulated by different seismic events with and without seismic isolators. The comparation of the two recorded video feeds of the fluid motion, was made using Google Copilot due to high processing capacity and adaptive algorithms. During the fluid motion the higher peaks were recorded as in Figure 10. After video analysis, it was concluded that the motion using the seismic isolators was decreased by a certain percent as per Table 1 and Figures 10, 11, 12, and 13.

Table 1. Influence of seismic isolators in percent of fluid movement amplitude compared with the fixed tank.

Earthquake name	Year	Percent of fluid movement amplitude decrease by seismic isolators (%)
Maule	2010	6.163
Vrancea	1977	18.499
Fukushima	2011	15.296
Kobe	1995	8.050

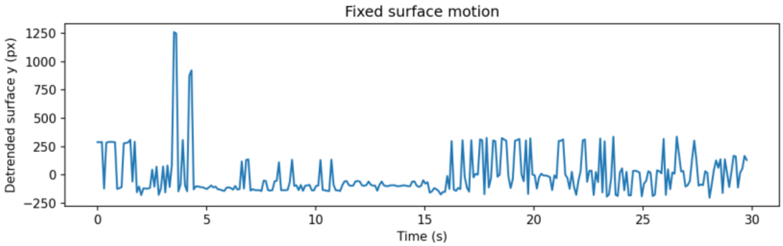


(a)

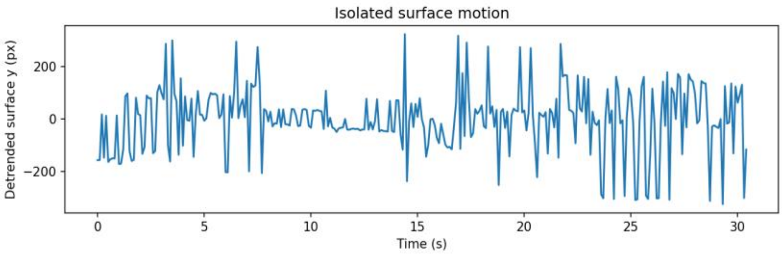


(b)

Fig. 10. Maule earthquake simulation graph plot: (a) Fixed tank; (b) Tank with seismic isolators

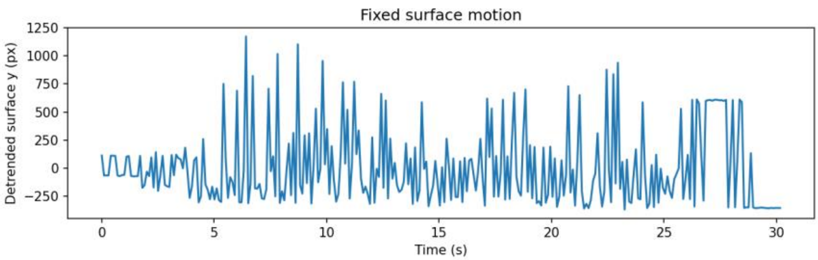


(a)

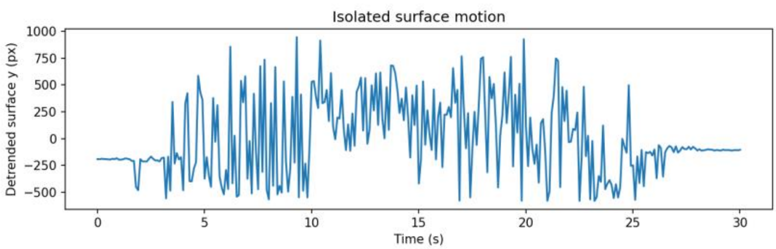


(b)

Fig. 11. Vrancea earthquake simulation graph plot: (a) Fixed tank; (b) Tank with seismic isolators.

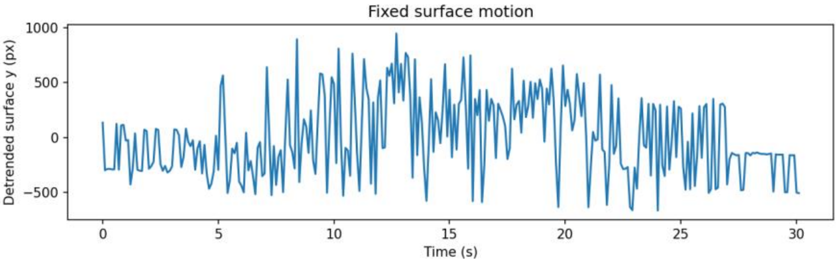


(a)

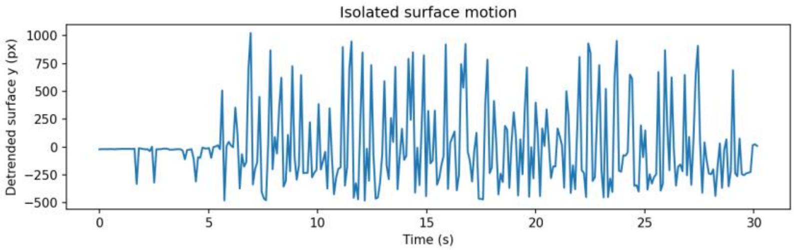


(b)

Fig. 12. Fukushima earthquake simulation graph plot:
(a) Fixed tank; (b) Tank with seismic isolators.



(a)



(b)

Fig. 13. Kobe earthquake simulation graph plot:
(a) Fixed tank; (b) Tank with seismic isolators.

6. Discussion

This simple model of shake table can have a high number of applications, due to its versatility and could be adapted for multiple scenarios, like fuel moving in a truck tanker, during an aggressive brake, or rail tanker passing a deformed rail section, even the vertical seismic component can be added, by simply adding an actuated third axis and rewrite the G-code.

This experiment can be upscaled for continuous fluid motion monitoring, not only due to seismic action, but especially during tank loading. The fluid surface analysis can add valuable information about the behavior during tank fill and discharge, especially when the tank is provided with an internal floating roof, that is known to be very sensitive to high fluid waves [6]. Also, this study can be upscaled and adapted to a full scale tank for measuring and monitoring the fluid movement, especially during filling and mixing (in cases where the tank has impeller mixers), this data could be valuable for vapor space corrosion assessment [18].

Using this shake table model that is easy to construct due to highly available components, like in this case by modifying 3D printers, other scaled and 3D printed components might be tested, for example structures to see the impact of the seismic movement. It can also be used as a practical demonstration of the seismic actions in student classes.

7. Conclusions

This study introduced a novel and cost-effective approach for simulating seismic-induced fluid motion in storage tanks by repurposing a commercially available 3D printer as a shake table. The proposed methodology successfully demonstrated that controlled seismic motion can be reproduced through customized G-code, enabling the visualization of sloshing phenomena under various earthquake scenarios.

The experimental results confirmed that the simplified sinusoidal-based motion model, combined with amplitude envelope modulation, is sufficient to approximate real seismic behavior for educational and preliminary research purposes. Furthermore, the use of smartphone-based LIDAR technology proved to be an accessible and reliable solution for capturing fluid surface dynamics, eliminating the need for specialized and expensive measurement systems.

A key outcome of the study is the validation of seismic isolation effectiveness at a reduced scale. The implementation of a sliding-type isolation system resulted in a measurable reduction in sloshing amplitude, with decreases ranging from approximately 6% to 18% depending on the simulated earthquake. These findings are consistent with established literature and confirm the ability of isolation systems to mitigate dynamic fluid effects.

Beyond its primary application, the developed setup demonstrates significant versatility. It can be extended to investigate other dynamic fluid scenarios, such as transport-induced sloshing or operational tank conditions during filling and discharge. Additionally, the platform provides a valuable tool for educational purposes, allowing intuitive visualization of complex fluid–structure interactions.

The proposed approach bridges the gap between high-cost experimental systems and purely numerical simulations, offering a practical and scalable solution for studying seismic effects on storage tanks. Future work may focus on integrating vertical motion components, improving measurement accuracy through advanced image processing, and extending the methodology to more complex geometries and multi-physics simulations.

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Authors' biographies

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