vibration

MDPI

*Article*

# Experimental and Theoretical Reproducibility Research on the Earthquake Resistance of Cylindrical Steel Tanks

**Nurlan Zhangabay [1,*], Marco Bonopera [2,*], Akmaral Utelbayeva [3], Timur Tursunkululy [1] and Murat Rakhimov [4]**

1 Department of Architecture and Urban Planning, Mukhtar Auezov South Kazakhstan University, Shymkent 160012, Kazakhstan; info@spc.com.kz
2 Mechanics, Sound, & Vibration Laboratory, Department of Civil Engineering, College of Engineering, National Taiwan University, Taipei 10617, Taiwan
3 Department of Chemistry, Mukhtar Auezov South Kazakhstan University, Shymkent 160012, Kazakhstan; akmaral.utelbaeva@auezov.edu.kz
4 Department of Construction Materials and Technologies, Abylkas Saginov Karaganda Technical University, Karaganda 100005, Kazakhstan; m.rakhimov@kstu.kz
* Correspondence: nurlan.zhanabai@auezov.edu.kz (N.Z.); marco.bonopera@unife.it (M.B.)

**Abstract:** This article analyzes the convergence of the obtained values as a result of the authors' earlier experimental and theoretical studies. On the basis of the correlations, it was found that the analyses of a traditional cylindrical steel tank without a steel wire strand wrapping and with a filling level of zero by a liquid showed a difference in natural vibration frequencies of 8.4%, while with half and maximal filling by a liquid showed differences equal to 3.2% and 6.2%, respectively. Vice versa, analyses of a cylindrical steel tank with a steel wire strand winding pitch of a = 3d and with a filling level of zero by a liquid showed a difference in natural vibration frequencies of 8.1%, while with half and maximum filling by a liquid and with the same steel wire strand winding pitch showed differences of 10.1% and 5.9%, respectively. Conversely, analyses of a cylindrical steel tank with a steel wire strand winding pitch of a = d and in absence of filling level amounted to a difference of 5.5%, while with half and maximum filling and with the same steel wire strand winding pitch of a = d, differences of 1.6% and 1.4% were, respectively, achieved. Based on the aforementioned results, the general difference between experimental and theoretical vibration frequencies showed up to 10%, which is a satisfactory result of convergence. The obtained findings of this research can be used by engineers and technical workers in the industries of various fields, research institutes and professional companies in designing new earthquake-resistant steel tanks and strengthening existing ones. Conclusions were then mentioned at the end of the article.

**Keywords:** dynamic earthquake effect; dynamic oscillation; earthquake resistance; liquid; natural vibration frequency; cylindrical steel tank; wire strand

**Citation:** Zhangabay, N.; Bonopera, M.; Utelbayeva, A.; Tursunkululy, T.; Rakhimov, M. Experimental and Theoretical Reproducibility Research on the Earthquake Resistance of Cylindrical Steel Tanks. *Vibration* **2023**, *6*, 960–973. https://doi.org/10.3390/vibration6040057

Academic Editor: Aleksandar Pavic

Received: 10 October 2023
Revised: 25 October 2023
Accepted: 31 October 2023
Published: 4 November 2023



## 1. Introduction

Today, oil and petroleum products are one of the main fuels in the world and the main profitable raw materials in the formation of the economy of the Republic of Kazakhstan. It is obvious that intensive construction of cylindrical steel tanks will continue, and great attention will be paid to maintaining them in suitable operational and technical conditions. Therefore, significant funds will be allocated to restore the carrying power of existing cylindrical steel tanks. The construction and the operation of steel tanks is associated with high material costs, fire and explosion hazards, risk of environmental pollution, and danger to human life [1,2]. Consequently, they are specifically classified as critical structures, the design and construction of which must be based on strictly scientific principles, new fundamental design concepts [3–6] as well as on optimal and cost-effective design solutions. The problem is particularly given importance by the fact that, in the

Republic of Kazakhstan, areas with increased seismic activity, where steel storage tanks for oil and petroleum products are located, are being built, or are planned to be built, occupying approximately 30% of the territory [7]. Since the history on the operational conditions of steel tanks includes many accidents associated with dynamic effects, research in this area is a very urgent task, as illustrated in the following Table 1.

**Table 1.** Analyses of the failures of and damage to steel tanks associated with dynamic earthquake effects.

| № | Source | Year and Location of the Earthquakes | Caused Damages |
|---|---|---|---|
| 1 | [8] | 1933 Earthquake in Long Beach, California. Earthquake magnitude: 6.4 | One steel water storage tank was destroyed; 16 steel oil and water storage tanks experienced product overflow and various types of damage |
| 2 | [9] | 1952 Earthquake in Kern County, California. Earthquake magnitude: 7.3 | Of 12 steel tanks, only two withstood seismic loads. Massive destruction of the roofs of the tanks was revealed |
| 3 | [10] | 1960 Great Chilean Earthquake, Chile. Earthquake magnitude: 9.4–9.6 | In the city of Conchon, most of the 95 steel tanks collapsed |
| 4 | [11] | 1964 Earthquake in Niigata, Japan. Earthquake magnitude: 7.5 | The earthquake caused the destruction of many steel oil storage tanks, a fire in two steel tanks, as well as an oil and liquefied gas spill. The main damage to the tanks were: bending of roofs; loss of wall stability; destruction of floating roofs; displacement and local precipitation |
| 5 | [12] | 1964 Great Alaska Earthquake. Earthquake magnitude: 9.2 | In the city of Anchorage, of 21 steel tanks, only one withstood the shocks. In the city of Ritter, all the 13 existing steel tanks collapsed. In the city of Valdesse, all the 30 steel tanks collapsed, five of which overturned, while the other part was rendered unusable as a result of a fire. In the city of Seward, not a single one of the 30 steel tanks remained undamaged; the damage was aggravated by the fact that some of the oil spilled into the sea |
| 6 | [13] | 1971 Earthquake in San Fernando, California. Earthquake magnitude: 6.6 | Six steel tanks were damaged along their walls, roofs and anchors. One steel tank was destroyed, while eight floating roof tanks experienced product overflow and damage to floating roofs |
| 7 | [14] | 1972 Earthquake in Managua, Nicaragua. Earthquake magnitude: 6.2 | The nature of damage to the steel tanks was the formation of "dents" in the lower part of their wall structure |
| 8 | [14] | 1974 Earthquake in Peru. Earthquake magnitude: 7.8 | Swinging of liquid from the steel tanks and formation of "dents" along the wall structure |
| 9 | [9,10] | 1978 Earthquake in Miyagi, Japan. Earthquake magnitude: 7.4 | Cracks along three steel oil storage tanks and damage to the anchors of an additional steel water storage tank |
| 10 | [9,10] | 1979 Earthquake in the Imperial Valley on the Mexico-US border. Earthquake magnitude: 6.4 | A total of 16 steel tanks containing petroleum products were damaged. "Dents" and damage to wall and roof structures, as well as product leaks |
| 11 | [14] | 1980 Earthquake in Greenville, California. Earthquake magnitude: 5.5 | About 100 steel tanks were damaged. The main type of damage was the loss of stability of their wall structure |

| | | | |
|---|---|---|---|
| 12 | [15] | 1983 Coalinga Earthquake, California. Earthquake magnitude: 6.2 | A total of 17 steel tanks (9 static roof tanks and 8 floating roof ones) suffered by wall and roof structure damage, and product overflow |
| 13 | [8,9] | 1983 Earthquake in the Sea of Japan. Earthquake magnitude: 7.8 | Numerous steel oil storage steel floating roof tanks were damaged |
| 14 | [16] | 1989 Earthquake in Loma Prieta (near San Francisco), California. Earthquake magnitude: 7.1 | Cracks along wall structures, and destruction of auxiliary equipment were noted. Two steel tanks had wall damages, while additional two for petroleum products storage experienced dislocations |
| 15 | [17] | 1994 Earthquake in Los Angeles, known as Northridge earthquake. Earthquake magnitude: 6.7 | One steel tank was completely destroyed; damage to the lower wall chords were observed in several tanks |
| 16 | [18] | 1999 Earthquake in Turkish province Kocaeli. Earthquake magnitude: 7.6 | The disaster damaged more than 100 steel oil storage tanks; a fire on steel floating roof tanks and an oil spill |
| 17 | [8,9] | 1999 Earthquake in Jiji, Taiwan. Earthquake magnitude: 7.7 | Structures and connections between walls and bottoms of several steel oil storage tanks were damaged |
| 18 | [8,9] | 2003 Earthquake in Hokkaido, Japan. Earthquake magnitude: 8.3 | Seven steel oil storage tanks with floating roofs had flooded roofs, while additional two tanks caught fire |
| 19 | [19] | 2011 Tohoku Earthquake and Tsunami, Japan. Earthquake magnitude: 9.0–9.1 | More than 50 accidents were recorded at gas industry facilities (four fires/explosions; six leaks; 20 cases of pipeline damaged; 20 steel tanks damaged); 139 accidents at facilities in other industries (five fires/explosions; 23 leaks; 59 pieces of equipment damaged; 52 cases of damage to steel tanks) |
| 20 | [20] | 2012 Earthquake in the Northern Italy. Earthquake magnitude: 6.0 | Damage to the wall and anchor structures of numerous steel tanks were observed |

The aforementioned consequences of the failures of and damage to steel tanks were mainly the result of strong earthquake effects. We have highlighted several of the most significant findings from the point of view of this research object in the following Figure 1.

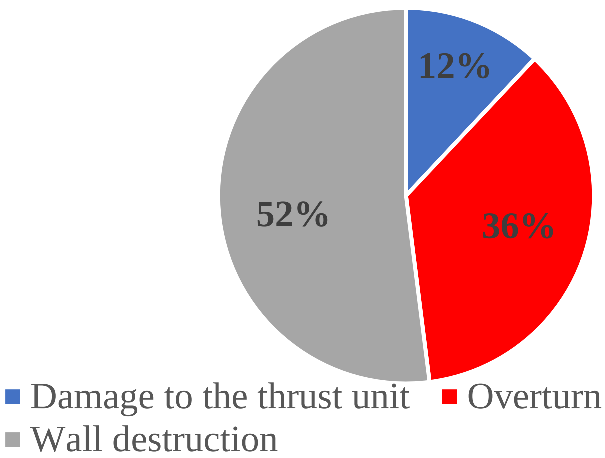


**Figure 1.** Analysis of the failures of and damage to steel tanks as a result of the dynamic earthquake effects.

Figure 1 shows that the cause of more than half of the failures of and damage to the steel tanks was due to the destruction of their wall structures. In this context, the study of this problem requires additional investigations since the destruction of the walls under dynamic seismic effects showed the complexity of the dynamic behavior of steel tanks based on simple numerical solutions. This issue is made more complex still by the hydrodynamic influence of the liquid stored within the tank structure and especially by the inertial component of its load [21–25].

The development of the research in the field of the earthquake resistance of steel tanks has widely been described in the literature [26–31]. Serious research regarding the dynamics and earthquake resistance of steel liquid storage tanks and vessels dates back to the 1930s. In 1934, the pressure ratio for rectangular vertical dams was obtained by Westergaard [26]. In the same year, pulse pressure was experimentally determined for similar rectangular structures in the form of cylindrical tanks [27]. In 1945, a German scientist established the fundamental expression for determining the natural vibration frequency of the splashing of liquid (water) [28]. In 1949, the value of the hydrodynamic pressure was found by solving problems for cylindrical steel tanks filled with a liquid [28]. In 1954, Housner [29] proposed a simplified mechanical model that, in turn, replaced the "structure–liquid" interaction with a system of point masses by simplifying the calculation of the hydrodynamic loads. However, in 1964, the earthquakes that happened in Niigata (Japan) and Alaska (USA) led to much damage to the existing steel tanks which were designed according to code provisions. Consequently, the approaches proposed by the codes have required significant improvements. Subsequently, a detailed calculation methodology was developed by Wozniak and Mitchell [30] which, in turn, formed the basis of the American Petroleum Institute (API) 650 regulatory document [31], the calculation which became the most common and largely used as a standard.

Following this trend, in Europe, an important number of studies were performed to study the issue of the earthquake resistance of steel tanks: a mechanical model was developed for steel tanks with rigid walls [32], while an analytical method was implemented for flexible steel ones [33]. The problem of the behavior of a steel tank when detached from the base was also studied by Peek et al. [34]. Serious additions to the problem of fixed and unfixed bases of steel tanks were considered by other works [35,36]. The corresponding results of these studies were then included in European and domestic standards [37,38]. It is also possible to note such information in works carried out during the 1960s [39–41]. Particularly, the findings of these investigations were mainly recommendations for the design of steel tanks and gas receivers under seismic impacts [39]. Subsequently, taking into account the results presented by Elenitsky E. Ya [42,43], a new standard was generated [44]. This developed regulatory document was of a general nature, and its application to the calculation of steel tanks had some significant limitations [45,46].

At the present stage of the ongoing research in the field of the earthquake resistance of plate and shell structures, a number of relevant studies can be found [47–61]. Particularly, in the work proposed by Śliwa et al. [47], in order to restore the carrying power of a structure, the problem of repairing the "dents" with carbon fibers was considered, but the issue of the dynamic effects was not investigated. In the work proposed by Ghazijahani and Showkati [48], a series of experimental results were instead highlighted. Moreover, the study proposed by Joniak et al. [49] considered the issue of elastic bending, where an analytical formula for critical stresses for open round cylindrical thin shells in a state of pure bending was proposed. Conversely, the work presented by Al-Yacouby et al. [50] focused on numerical modeling for the design of operational loads taking into account hydrodynamic pressure. In Hud [51] and Sierikova et al. [52], a Finite Element (FE) model of a full-scale steel tank was implemented and calculations were executed under operational loading. The values of the frequencies and periods of the natural dynamic oscillations of a steel tank under various operational modes were then gained. Specifically, the study performed by Jaramillo et al. [53] addressed the problem of lifting and swaying taking the flexibility of the soil into account. A comprehensive analysis of the effects of the interaction between soil, foundation and structure was presented. In Wang and Kusunoki [54], the buckling of cylindrical steel shells was investigated, in which the goal was to compare the results of numerical, analytical and experimental studies regarding the buckling of a traditional shell structure under extreme loading. Furthermore, in the work presented by Thongchom et al. [55], a number of variable calculations were performed based on the results achieved in some calculation modules. The dynamic behavior of the traditional design of a steel liquid storage tank was also analyzed. Particularly, the study executed by Wang et al. [56] considered the possibility of strengthening a cylindrical steel tank for storing petrochemical products with anti-explosion strips. Simulations were carried out for various parameters of amplification bands during an external explosion. The possibility of strengthening a steel tank structure by prestressing its entire structure was proposed. Specifically, the works performed by Bragov et al. [57] and Chernobryvko et al. [58] presented the results of a comparative analysis of the mechanical properties of some steel structures by considering the influence of the environmental temperature on the process of their elastic deformation [59–64]. Since, during dynamic impacts, the issue of considering the influence of loads from the liquid stored is crucial, Ye and Birk [65] examined the distribution of the hydrostatic pressure along the wall of a traditional steel tank where it was shown that the change in stress depends on the hydrodynamic pressure and geometries of the tank itself.

The above analyses showed that, despite the simplicity of the shape and design solutions of steel tanks, the thin-walled structure and the presence of a liquid inside causes significant problems. It is also necessary to assume operational conditions, an important one of which is the level of liquid filling within the structure. Under earthquake conditions, the above factors give a peculiarity to the dynamic operations of the steel tank structure under operational conditions. As a result, it can be concluded that there is a need to develop constructive solutions for cylindrical tanks and, for the completeness of the research, it is also necessary to conduct a comparative analysis of the experimental and theoretical studies present in the literature. In connection with this, the purpose of this article was to correlate the values of natural vibration frequencies of a cylindrical steel tank determined by the experimental and theoretical studies conducted by the authors earlier [66,67].

## 2. Theoretical-Numerical Model

The study of the operational conditions of structures under dynamic effects using numerical modeling has become widespread in various fields of modern technology and constitutes an important field in civil engineering. Particularly, the main difficulties in modeling cylindrical shells are related to the thin-walled factors, which significantly complicate the production and testing of the structural models. Therefore, when modeling thin-walled cylindrical shells for dynamic experiments, such models are usually utilized for which the scale of shell thicknesses is independently chosen from the scale of its overall dimensions. The main geometric and dynamic parameters, as well as the mechanical properties of the material of a typical cylindrical steel tank with a volume of 3,000 $m^3$, and a steel wire strand wrapping, are described in Tursunkululy et al. [66]. The corresponding parameters used in the experimental studies on reduced models are instead presented in Zhangabay et al. [67]. We establish the similarity criteria for dynamic testing of a model of a cylindrical steel tank based on the affine (multi-scale) correspondence between the model and the full-scale design of the tank itself [68]. Specifically, we use the method of dimensional analysis to determine the criteria for defining the similarity of a vessel under dynamic earthquake effects. In such a method, by selecting the main values for measuring the geometric parameters of the tank, the values which describe the dynamics of the tank itself are limited by the following series:

$$\sigma, u, \varepsilon, f, q, l, \delta, r, E, \rho \tag{1}$$

where $\sigma$—stress; $u$—displacement; $\varepsilon$—relative deformation; $f$—natural dynamic oscillation frequency; $q$—external load intensity; $l,\ \delta,\ r$—curvature radius, wall thickness and length of the tank; $\mu,\ \rho,\ E$—Poisson's ratio, material density and elastic modulus of the tank. We exclude the dimensionless parameters: $\varepsilon$—relative deformation and $\mu$—Poisson's ratio—from the series (1) and we consequently obtain:

$$\sigma, u, f, q, l, \delta, r, E, \rho \tag{2}$$

The matrix of the dimensions of the physical quantities of the series (2) relative to the international system of units for the main linear dimensions $L_l$ (m), $F$ (N), thickness $L_\delta$ (m) and time $T$ (s) take the following form [68]:

$$\begin{array}{c} \\ \\ F \\ L_l \\ L_\delta \\ T \end{array} \begin{array}{c} \begin{array}{ccccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \\ \sigma & u & f & q & l & \delta & r & E & \rho \end{array} \\ \left\| \begin{array}{ccccccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 2 & 0 & 0 & -2 & 1 & 0 & 2 & 2 & -2 \\ -4 & 1 & 0 & 0 & 0 & 1 & -1 & -4 & -2 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 2 \end{array} \right\| \end{array} \tag{3}$$

The matrix rank is $r = 4$, while the number of the main parameters is $n = 9$. According to the $\Pi$—theorem of dimensional analysis—the number of independent dimensionless complexes $\Pi_k$, composed of the basic parameters, is $k = n - r = 5$. Therefore, for the unknown dimensionless ratio, it is possible to write the following expression:

$$\Pi = \sigma^{x_1} u^{x_2} f^{x_3} q^{x_4} l^{x_5} \delta^{x_6} r^{x_7} E^{x_8} \rho^{x_9}. \tag{4}$$

Based on the exponents of the parameters (4) $x_i (i = 1 \ldots 9)$, we take the following system of algebraic equations:

$$\begin{gathered} x_1 + x_4 + x_8 + x_9 = 0 \\ 2x_1 - 2x_4 + x_5 + 2x_7 + 2x_8 - 2x_9 = 0 \\ -4x_1 + x_2 + x_6 - x_7 - 4x_8 - 2x_9 = 0 \\ x_3 + 2x_9 = 0 \end{gathered} \tag{5}$$

We then normalize the system of Equation (5) as a matrix of solutions for exponents $x_i$ [68]:

$$\begin{array}{c} \\ \\ \Pi_1 \\ \Pi_2 \\ \Pi_3 \\ \Pi_4 \\ \Pi_5 \end{array} \begin{array}{c} \begin{array}{ccccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \\ \sigma & u & f & q & l & \delta & r & E & \rho \end{array} \\ \left\| \begin{array}{ccccccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & 0 & 0 & 1 & 0 & -2 & 2 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & -\frac{1}{2} & -\frac{1}{2} & 0 & 0 \end{array} \right\| \end{array} \tag{6}$$

By using the matrix solution expressed in Equation (6), we can present the dimensionless relations by the following expressions:

$$\begin{gathered} \Pi_1 = \sigma E^{-1};\ \Pi_2 = u\delta^{-1};\ \Pi_3 = frE^{-1/2}\rho^{1/2}; \\ \Pi_4 = q\delta^{-2}r^2E^{-1};\ \Pi_5 = l\delta^{-1/2}r^{-1/2}. \end{gathered} \tag{7}$$

Consequently, we supplement the system of the dimensionless complexes (7) with the dimensionless quantities—$\mu$—Poisson's ratio and $\varepsilon$—relative deformation:

$$\Pi_6 = \mu, \Pi_7 = \varepsilon.$$

We can then write the invariance of the similarity criteria by using the form based on the following conditions:

$$\sigma E^{-1} = idem;\ u\delta^{-1} = idem;\ frE^{-1/2}\rho^{1/2} = idem;\ q\delta^{-2}rE^{-1} = idem;$$
$$l\delta^{-1/2}r^{1/2} = idem;\ \mu = idem;\ \varepsilon = idem, \tag{8}$$

where the symbol *idem* means that the corresponding dimensionless ratio for the model and for the full-scale structure must remain unchanged. The conditions in Equation (8), using the expanded solution, are then written as follows:

$$\sigma_m/E_m = \sigma_n/E_n;\ u_m/\delta_m = u_n/\delta_n;\ f_m r_m\sqrt{\rho_m}/\sqrt{E_m} = f_n r_n\sqrt{\rho_n}/\sqrt{E_n}$$
$$q_n r_n^2/\delta_n^2 E_n = q_m r_m^2/\delta_m^2 E_m;\ l_m/\sqrt{\delta_m r_m} = l_n/\sqrt{\delta_n r_n} \tag{9}$$
$$u_n = u_m;\ \varepsilon_n = \varepsilon_m$$

If we assume that the material of the model is the same as that of the full-scale structure then, for the elastic modulus $E$, Poisson's ratio $\mu$ and density of the material $\rho$ of the model and full-scale structure, we can consider:

$$E_n/E_m = 1;\ \mu_n/\mu_m = 1;\ \ \rho_n/\rho_m = 1. \tag{10}$$

Subsequently, taking into account the formulas in (10), the expressions in (9) can be represented as follows:

$$\sigma_n = \sigma_m;\ u_m/u_n = \delta_m/\delta_n;\ f_m/f_n = r_n/r_m;$$
$$q_n r_n^2/\delta_n^2 = q_m r_m^2/\delta_m^2;\ l_m^2/\delta_m r_m = l_n^2/\delta_n r_n \tag{11}$$

Considering the modeling scale for linear dimensions $m_l = l_n/l_m$, and the pipeline thickness $m_\delta = \delta_n/\delta_m$, expressions in (11) in their final form through linear scales $m_l$ and similarity coefficients take the following formulas:

- for stress $m_\sigma = \sigma_m/\sigma_n = 1$;
- for displacement $m_u = u_n/u_m = m_\delta$;
- for natural vibration frequency $m_f = f_n/f_m = r_n/r_m = m_\delta^2/m_l$;
- for surface load intensity $m_q = q_n/q_m = m_l^2 \cdot m_\delta^2$;
- for curvature radius $m_r = r_n/r_m = l_n^2\ \delta_n/l_m^2\ \delta_m = m_l^2/m_\delta$.

The damping decrement of the dynamic oscillations in the structures can quite accurately be determined by the area of the hysteresis loop. If we denote $\omega$ —energy absorbed per unit volume, and $k$ —maximum elastic energy, it is possible to obtain:

$$\omega_m = m_\sigma \cdot m_k \cdot \omega_n;\ k_m = m_\sigma \cdot m_k \cdot k_n. \tag{12}$$

Consequently, the relative energy absorption is equal to:

$$\psi = \frac{\omega_m}{k_m} = \frac{\omega_n}{k_n} \tag{13}$$

, i.e., the damping decrement of the free dynamic oscillations of the model and that of the full-scale structure are the same.

## 3. Results and Discussion

In their previous theoretical work, the authors based their study on FE modeling according to the standard calculation modules of the American company ANSYS software (Canonsburg, PA, USA), where a model of free oscillations of a liquid in a tank, and an additional one of free oscillations of a tank without any liquid, were investigated. A cylindrical steel tank with a storage capacity of 3,000 $m^3$ and various internal loading was assumed which, in turn, was characterized by a filling level where the distributed pressure acted on the outer surface of its wall structure by steel wire strand wrapping under prestressing. The preliminary stresses, caused by four variables of wire tension in the winding, were considered. Moreover, the cases for the coefficients of the tensile force along the steel wire relative to its tensile strength were investigated: at $k_1 = 0.2$; $k_2 = 0.4$; $k_3 = 0.6$; and $k_4 = 0.8$. Other investigations were performed both considering additional loads caused by the action of the hydrostatic pressure from the maximum and half-filled level with and without oil within the tank. As a result, the magnitude of the variations in oscillation frequencies of the wall structure from the application of the prestressing showed a positive value with a reading of 21–62%, depending on the degree of filling level of the tank [66]. Conversely, in the experimental work, the oscillations of the natural frequencies of the tank were additionally analyzed. For this purpose, scale models of traditional cylindrical steel tanks were generated, while a special vibration stand was assembled [67]. Taking into account the values obtained from these studies, there is a need to analyze the achieved findings. Based on the theoretical-numerical model described in Section 2 [68], to verify the adequacy of the calculated (theoretical) values [66], a comparison was made with the experimental results from models of the steel tank with and without steel wire strand wrapping [67] and, additionally, assuming the similarity criterion for the dynamic oscillations of the natural frequencies [68]. The corresponding results from the comparative analyses are thus illustrated in the following Tables 2–4.

**Table 2.** Comparison of the values of the natural vibration frequencies (NVF) of dynamic oscillations obtained when testing the traditional cylindrical steel tank without a steel wire strand wrapping and at different filling levels (considering the similarity criterion).

| № NVF | Average Calculated (Theoretical) Values of Natural Frequencies of Oscillations of the Steel Tank with a Volume of 3,000 m³ Modeled by ANSYS ($f_1$), Hz [66] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank ($f_e$), Hz [67] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank Taking into Account the Scale Effect ($f_E$), Hz [68] | Average Values of Natural Frequencies of the Steel Tank ($f_\Delta$), Hz | Absolute Percentage Differences between $f_1$ and $f_\Delta$, % |
|---|---|---|---|---|---|
| Tank without a liquid | | | | | |
| 1 | 14.01 | 11.24 | 14.06 | 15.19 | 8.4 |
| 2 | | 11.89 | 14.87 | | |
| 3 | | 12.18 | 15.23 | | |
| 4 | | 13.26 | 16.58 | | |
| Tank half-filled by a liquid | | | | | |
| 1 | 17.16 | 12.92 | 16.16 | 16.61 | 3.2 |
| 2 | | 14.14 | 17.68 | | |
| 3 | | 12.48 | 15.61 | | |
| 4 | | 13.58 | 16.98 | | |
| Tank maximally filled by a liquid | | | | | |
| 1 | 17.71 | 12.72 | 15.91 | 16.62 | 6.2 |
| 2 | | 13.81 | 17.26 | | |
| 3 | | 13.98 | 16.23 | | |
| 4 | | 13.66 | 17.08 | | |

**Table 3.** Comparison of the values of the natural vibration frequencies (NVF) of dynamic oscillations obtained when testing the prestressed composite cylindrical steel tank at different filling levels (considering the similarity criterion with a steel wire strand winding pitch equal to a = 3d).

| № NVF | Average Calculated (Theoretical) Values of Natural Frequencies of Oscillations of the Steel Tank with a Volume of 3,000 m³ Modeled by ANSYS ($f_1$), Hz [66] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank ($f_e$), Hz [67] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank Taking into Account the Scale Effect ($f_E$), Hz [68] | Average Values of Natural Frequencies of the Steel Tank ($f_\Delta$), Hz | Absolute Percentage Differences between $f_1$ and $f_\Delta$, % |
|---|---|---|---|---|---|
| Tank without a liquid | | | | | |
| 1 | 12.55 | 10.01 | 12.51 | 13.57 | 8.1 |
| 2 | | 10.34 | 12.93 | | |
| 3 | | 11.11 | 13.89 | | |
| 4 | | 11.96 | 14.95 | | |
| Tank half-filled by a liquid | | | | | |
| 1 | 16.21 | 10.88 | 13.61 | 14.58 | 10.1 |
| 2 | | 11.23 | 14.04 | | |
| 3 | | 11.64 | 14.55 | | |
| 4 | | 12.88 | 16.11 | | |
| Tank maximally filled by a liquid | | | | | |
| 1 | 16.75 | 12.05 | 15.07 | 15.76 | 5.9 |
| 2 | | 12.08 | 15.11 | | |
| 3 | | 13.10 | 16.37 | | |
| 4 | | 13.17 | 16.47 | | |

**Table 4.** Comparison of the values of the natural vibration frequencies (NVF) of dynamic oscillations obtained when testing the prestressed composite cylindrical steel tank at different filling levels (considering the similarity criterion with a steel wire strand winding pitch equal to a = d).

| № NVF | Average Calculated (Theoretical) Values of Natural Frequencies of Oscillations of the Steel Tank with a Volume of 3,000 m³ Modeled by ANSYS ($f_1$), Hz [66] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank ($f_e$), Hz [67] | Experimental Values of Natural Oscillation Frequencies of the Steel Tank Taking into Account the Scale Effect ($f_E$), Hz [68] | Average Values of Natural Frequencies of the Steel Tank ($f_\Delta$), Hz | Absolute Percentage Differences between $f_1$ and $f_\Delta$, % |
|---|---|---|---|---|---|
| Tank without a liquid | | | | | |
| 1 | 11.77 | 9.08 | 11.35 | 12.42 | 5.5 |
| 2 | | 9.46 | 11.83 | | |
| 3 | | 10.08 | 12.61 | | |
| 4 | | 11.10 | 13.88 | | |
| Tank half-filled by a liquid | | | | | |
| 1 | 15.03 | 11.38 | 14.23 | 15.27 | 1.6 |
| 2 | | 12.24 | 15.31 | | |
| 3 | | 11.28 | 14.11 | | |
| 4 | | 13.95 | 17.44 | | |
| Tank maximally filled by a liquid | | | | | |
| 1 | 16.86 | 12.85 | 16.07 | 17.09 | 1.4 |
| 2 | | 13.61 | 17.02 | | |
| 3 | | 12.20 | 15.25 | | |
| 4 | | 16.01 | 20.01 | | |

The results from the comparative analyses between calculated and experimental data of the traditional cylindrical steel tank without steel wire strand wrapping, and with a filling level of zero, showed a difference in natural vibration frequencies of 8.4% (Table 2). The comparisons regarding the traditional steel tank half-filled by a liquid instead showed a difference in natural vibration frequencies of 3.2% (Table 2). Conversely, the comparison of the traditional tank with maximal filling level by a liquid showed a difference in vibration frequencies of 6.2% (Table 2). Furthermore, the results from the comparative analyses between calculated and experimental data of the prestressed composite cylindrical steel tank with a steel wire strand winding pitch of a = 3d, and filling level of zero, showed a difference in natural vibration frequencies of 8.1% (Table 3). The comparisons considering the half-filled level and steel wire strand winding pitch of a = 3d instead showed a difference in natural vibration frequencies of 10.1% (Table 3). Taking the same comparison into account and, particularly, with the maximum filling level and steel wire strand winding pitch of a = 3d, a difference in vibration frequencies of 5.9% was conversely obtained (Table 3). Regarding the prestressed composite steel tank with a steel wire strand winding pitch of a = d, and in absence of filling level, a difference in natural vibration frequencies of 5.5% was showed, while differences in vibration frequencies of 1.6% and 1.4% were, respectively determined with a filling level of half and maximum filling (Table 4).

On the basis of the aforementioned results (Tables 2–4), we can conclude that the difference between the calculated and experimental natural vibration frequencies showed a satisfactory convergence of values, which generally varied between a percentage range equal to 1.4–10.1%. This fact proves the reliability of the calculation models by justifying the proposed calculation method of the dynamic oscillations of natural frequencies and modes of the composite cylindrical steel tank prestressed by wire strand wrapping proposed by Tursunkululy et al. [66] and Zhangabay et al. [67]. The practical significance of these works, consisting of experimental and theoretical approaches [66,67], as well as the aforementioned comparison analyses, lies in the development of a seismic-resistant design of prestressed composite cylindrical steel tanks for oil and petroleum products, thus ensuring the optimal stress distribution along the wall structure and improving its dynamic characteristics which, in turn, increases the reliability and safety of steel tanks under earthquake impacts. The developed solutions for cylindrical steel tanks and methods for engineering calculations and optimal design can be used by engineers and technical workers in various field industries, research institutes and professional companies in designing new earthquake-resistant steel tanks and the strengthening of existing ones [69,70].

## 4. Conclusions

According to the conducted literature review, and within the limitations of this study, the results from the comparison between the experimental and theoretical natural vibration frequencies of the traditional cylindrical steel tank and those of the prestressed composite cylindrical steel one have demonstrated that:

- The tank without steel wire strand wrapping, and with zero filling level, showed a difference in natural vibration frequencies of 8.4%. The results of the traditional tank half-filled by a liquid instead showed a difference in percentage of 3.2%. Conversely, the results of the traditional tank maximally filled by a liquid showed a difference of 6.2% (Table 2).
- The tank with steel wire strand winding pitch of a = 3d, and zero filling level, showed a difference in natural vibration frequencies of 8.1%. The results when the filling level by a liquid was half, and the steel wire strand winding pitch was of a = 3d, instead showed a percentage difference of 10.1%. When the tank was filled to its maximum level, and the steel wire strand winding pitch was of a = 3d, a difference in vibration frequencies of 5.9% was conversely obtained (Table 3).

- When the tank was with a steel wire strand winding pitch of a = d, and in absence of any liquid, the difference in natural vibration frequencies amounted to a percentage value of 5.5%. Conversely, with a half and a maximum filling level, and a steel wire strand winding pitch of a = d, differences in vibration frequencies were, respectively, equal to 1.6% and 1.4% (Table 4).

Based on these results, it can undoubtedly be concluded that the difference between the studies conducted by the authors showed a satisfactory convergence of their achieved findings, which did not exceed the absolute percentage difference in natural vibration frequencies of 10%. The prestressing method can be defined as an effective solution to increase the strength and seismic resistance characteristics of vertical cylindrical steel tanks. At the same time, the prestressing method can be suitable for newly designed tanks, as well as for those existing in situ. In conclusion, the prestressing method provides an opportunity to create the necessary strength conditions for the cylindrical steel tanks by selecting effective design parameters.

**Author Contributions:** Conceptualization, N.Z., M.B. and T.T.; methodology, N.Z. and T.T.; investigation, N.Z.; data curation, N.Z., M.B. and M.R.; writing—original draft preparation, N.Z.; writing—review and editing, N.Z., M.B. and M.R.; supervision, N.Z., A.U.; project administration, N.Z.; funding acquisition, N.Z., A.U. and T.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This article was funded by the Mukhtar Auezov South Kazakhstan University.

**Data Availability Statement:** Data sharing is not applicable to this article.

**Acknowledgments:** As a result of this research conducted on the use of prestressing in shell structures, a patent [69] of the Republic of Kazakhstan for the invention was published: method for increasing the seismic resistance of steel vertical cylindrical reservoirs by using a pre-tensioned winding, 2022, No. 35915. As a result of this research conducted on the use of prestressing in shell structures, a patent [70] of the Republic of Kazakhstan for a utility model was published: cylindrical shell for storage and transportation of liquid and hydrocarbon raw materials, 2021, No. 6208. M.B. would like to thank the National Science and Technology Council (NSTC) of Taiwan under the framework of the project "Recruitment of Visiting Science and Technology Personnel" (NSTC 112–2811–E–002–046–MY2) for their financial support.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Zhang, M.; Zheng, F.; Chen, F.; Pan, W.; Mo, S. Propagation probability of domino effect based on analysis of accident chain in storage tank area. *J. Loss Prev. Process Ind.* **2019**, *62*, 103962. https://doi.org/10.1016/j.jlp.2019.103962.
2. Krentowski, J.; Ziminski, K. Consequences of an incorrect assessment of a structure damaged by explosion. *Eng. Fail. Anal.* **2019**, *101*, 135–144. https://doi.org/10.1016/j.engfailanal.2019.03.009.
3. Zhangabay, N.; Suleimenov, U.; Utelbayeva, A.; Buganova, S. Experimental research of the stress-strain state of prestressed cylindrical shells taking into account temperature effects. *Case Stud. Constr. Mater.* **2022**, *18*, e01776. https://doi.org/10.1016/j.cscm.2022.e01776.
4. Tursunkululy, T.; Zhangabay, N.; Avramov, K.; Chernobryvko, M.; Suleimenov, U.; Utelbayeva, A.; Duissenbekov, B.; Aikozov, Y.; Dauitbek, B.; Abdimanat, Z. Strength analysis of prestressed vertical cylindrical steel oil tanks under operational and dynamic loads. *East.-Eur. J. Enterp. Technol.* **2022**, *2*, 14–21. https://doi.org/10.15587/1729-4061.2022.254218.
5. Tursunkululy, T.; Zhangabay, N.; Avramov, K.; Chernobryvko, M.; Suleimenov, U.; Utelbayeva, A. Influence of the parameters of the pre-stressed winding on the oscillations of vertical cylindrical steel oil tanks. *East.-Eur. J. Enterp. Technol.* **2022**, *5*, 6–13. https://doi.org/10.15587/1729-4061.2022.265107.
6. Tursunkululy, T.; Zhangabay, N.; Suleimenov, U.; Abshenov, K.; Chernobryvko, M.; Utelbayeva, A. Analysis of strength and eigenfrequencies of a steel vertical cylindrical tank without liquid, reinforced by a plain composite thread. *Case Stud. Constr. Mater.* **2023**, *18*, e02019. https://doi.org/10.1016/j.cscm.2023.e02019.
7. Code of Rules of the Republic of Kazakhstan 2.03-30-2017 Construction in Earthquake Zones. State Standards in the Field of Architecture, Urban Planning and Construction. Code of Rules of the Republic of Kazakhstan, Astana, 2018. Available online: https://online.zakon.kz/Document/?doc_id=36128461&pos=2;-106#pos=2;-106 (accessed on 7 September 2023).
8. Koketsu, K.; Miyake, H. A seismological overview of long-period ground motion. *J. Seismol.* **2008**, *12*, 133–143. https://doi.org/10.1007/S10950-007-9080-0.

9. Shigapov, R.R.; Kovalchuk, O.A. Review of typical accidents with vertical cylindrical storage tanks during earthquakes. *Earthquake engineering. Constructions safety* **2018**, *1*, 14–19. Available online: http://www.seismic-safety.ru/sites/default/files/ssbs-2018-01_shigapov.pdf (accessed on 7 September 2023).
10. Shimizu, N. Advances and Trends in Seismic Design of Cylindrical Liquid Storage Tanks. *JSME* **1990**, *2*, 111–124. Available online: https://www.academia.edu/56068593/Advances_and_trends_in_seismic_design_of_cylindrical_liquid_storage_tanks (accessed on 28 April 2023).
11. Akatsuka, H.; Kobayashi, H. Fire of Petroleum Tank, etc. by Niigata Earthquake. Failure Knowledge Database, Japan Science and Technology Agency 2008. Available online: http://www.shippai.org/fkd/en/hfen/HB1012035.pdf (accessed on 7 September 2023).
12. Hanson, R. *Behavior of Liquid Storage Tanks. The Great Alaska Earthquake of 1964*; Committee on the Alaska Earthquake, Division of the Earth Sciences, National Research Council, National Academy of Sciences: Washington, DC, USA, 1973; pp. 331–339. Available online: https://web.archive.org/web/20170202001102/https://books.google.co.nz/books?id=5EArAAAAYAAJ&dq (accessed on 7 September 2023).
13. Hamdan, F.H. Seismic behavior of cylindrical steel liquid storage tanks. *J. Constr. Steel Res.* **2000**, *3*, 307–333. https://doi.org/10.1016/S0143-974X(99)00039-5.
14. Niwa, A.; Clough, R.W. Buckling of cylindrical liquid-storage tanks under earthquake loading. *Earthq. Eng. Struct. Dyn.* **1982**, *10*, 107–122.
15. Manos, G.C.; Clough, R.W. Tank damage during the May 1983 Coalinga earthquake. *Earthq. Eng. Struct. Dyn.* **1985**, *13*, 449–466.
16. Haroun, M.A.; Mourad, S.A.; Izzeddine, W. Performance of liquid storage tanks during the 1989 Loma Prieta earthquake. *Proc. Lifeline Earthq. Eng.* **1991**, 1152–1160. Available online: https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0074227 (accessed on 26 April 2023).
17. Haroun, M.A.; Bhatia, H. Analysis of tank damage during the 1994 Northridge Earthquake. In Proceedings of the 4th US Conference on Lifeline Earthquake Engineering, ASCE, San Francisco, CA, USA, 10–12 August 1995; pp. 763–770. Available online: https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0095788 (accessed on 5 September 2023).
18. Yazici, G.; Cili, F. Evaluation of the Liquid Storage Tank Failures in the 1999 Kocaeli Earthquake. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008. Available online: https://www.researchgate.net/publication/228894607_EVALUATION_OF_THE_LIQUID_STORAGE_TANK_FAILURES_IN_THE_1999_KOCAELI_EARTHQUAKE (accessed on 5 September 2023).
19. Krausmann, E.; Cruz, A.M. Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry. *Nat. Hazards* **2013**, *67*, 811–828.
20. Brunesi, E.; Nascimbene, R.; Pagani, M.; Beilic, D. Seismic performance of storage steel tanks during the May 2012 Emilia, Italy, Earthquakes. *J. Perform. Constr. Facil.* **2012**, *6*, 1–9.
21. Kangarlou, K. Earthquake induced sloshing in vertical cylindrical steel tanks with insufficient freeboard. *Bull. MGSU* **2011**, *2*, 131–136.
22. Zharova, V.D. A method for calculating fluid flow and its influence on the strength properties of the components of a liter tank based on the influence of fluid during seismic events. *Bull. Sci. Creat.* **2018**, *1*, 47–51.
23. Kangarlou, K. Dynamic model of flushing liquid in steel vertical cylindrical tanks. *Bulletin of MGSU* **2011**, *1*, 111–115.
24. Kormanikova, E.; Kotrasova, K. Multiscale modeling of liquid storage laminated composite cylindrical tank under seismic load. *Compos. B Eng.* **2018**, *146*, 189–197.
25. Spritzer, J.M.; Guzey, S. Nonlinear numerical evaluation of large open-top aboveground steel welded liquid storage tanks excited by seismic loads. *Thin-Walled Struct.* **2017**, *119*, 662–676. https://doi.org/10.1016/j.tws.2017.07.017.
26. Westergaard, H.M. Water pressures on dams during earthquakes. *Trans. Am. Soc. Civ. Eng.* **1933**, *98*. https://doi.org/10.1061/TACEAT.0004496.
27. Hoskins, L.M.; Jacobsen, L.S. Water pressure in a tank caused by a simulated earthquake. *Bull. Seism. Soc. Am.* **1934**, *24*, 1–32.
28. Lamb, H. *Hydrodynamics*; Cambridge University Press: Cambridge, UK, 1994; p. 644. Available online: https://www.cambridge.org/ru/universitypress/subjects/mathematics/fluid-dynamics-and-solid-mechanics/hydrodynamics-6th-edition?format=PB&isbn=9780521458689 (accessed on 7 September 2023).
29. Housner, G.W. *Earthquake Pressures on Fluid Containers*; California Institute of Technology: Pasadena, CA, USA, 1954. Available online: https://www.amazon.co.uk/Earthquake-pressures-fluid-containers-Housner/dp/B0007H8OA4 (accessed on 7 September 2023).
30. Wozniak, R.S.; Mitchell, W.W. *Basis of Seismic Design Provisions for Welded Steel Oil Storage Tanks*; Sessions on Advances in Storage Tank Design; American Petroleum Institute: Washington, DC, USA, 1978; p. 35 https://freebooksplanet.com/basis-of-seismic-design-provisions-for-welded-stee/ (accessed on 7 September 2023).
31. American Petroleum Institute. *API Standard 650 Welded Steel Tanks for Oil Storage*, 10th ed.; American Petroleum Institute: Washington, DC, USA, 2012; p. 449. Available online: https://vzrk.ru/public/images/api.650.2007.pdf (accessed on 25 April 2023).
32. Veletsos, A.S.; Yang, J.Y. Earthquake response of liquid storage tanks. In Proceedings of the 2nd Engineering Mechanics Specialty Conference ASCE, Raleigh, NC, USA, 25 May 1977; pp. 1–24. Available online: https://www.semanticscholar.org/paper/Earthquake-Response-of-Liquid-Storage-Tanks-Veletsos-Auyang/e75bebdf3839f569a97d3a57092e745bf5c1625d (accessed on 8 September 2023).

33. Malhotra, P.K.; Wenk, T.; Wieland, M. Simple procedure for seismic analysis of liquid-storage tanks. *Struct. Eng. Int.* **2000**, *10*, 197–201. https://doi.org/10.2749/101686600780481509.
34. Peek, R. Analysis of unanchored liquid storage tanks under lateral loads. *Earthq. Eng. Struct. Dyn.* **1988**, *16*, 1087–1100. https://doi.org/10.1002/EQE.4290160710.
35. Fischer, D. Dynamic fluid effects in liquid-filled flexible cylindrical tanks. *Earthq. Eng. Struct. Dyn.* **1979**, *7*, 587–601. https://doi.org/10.1002/EQE.4290070608.
36. Rammerstorfer, F.G.; Fischer, F.D.; Scharf, K. A proposal for the earthquake resistant design of tanks—results from the Austria research project. In Proceedings of the Ninth World Conference on Earthquake Engineering, Tokyo–Kyoto, Japan, 2–9 August 1988. Available online: https://www.iitk.ac.in/nicee/wcee/article/9_vol6_715.pdf (accessed on 8 September 2023).
37. Eurocode 8: Design of Structures for Earthquake Resistance. Part 4: Silos, Tanks, and Pipelines. 2006. Available online: https://www.phd.eng.br/wp-content/uploads/2014/12/en.1998.4.2006.pdf (accessed on 25 April 2023).
38. *EN 1998-4:2006/2012*; Design of Earthquake-Resistant Structures. Part 4. Bunkers, Tanks and Pipelines. UNE Standars: Astana, Kazakhstan, 2012. Committee for Construction, Housing and Communal Services and Land Management of the Republic of Kazakhstan. Available online: https://online.zakon.kz/Document/?doc_id=37105813&doc_id2=37807474#activate_doc=2&pos=1;-0.0999908447265625&pos2=3;-100.09999084472656 (accessed on 25 August 2023).
39. Goldenblat, I.I.; Nikolaenko, N.A.; Shtol, A.T.; Tumasov, V.R. *Recommendations for the Design of Vessels and Gas Receivers for Earthquake Impacts*; Stroyizdat: Moscow, Russia. 1969; 49p. Available online: https://standartgost.ru/g/pkey-14293763172 (accessed on 25 August 2023).
40. Nikolaenko, N.A. *Dynamics and Earthquake Resistance of Load-Bearing Tank Structures*; Gosstroyizdat: Moscow, Russia. 1963; 156p. Available online: https://search.rsl.ru/ru/record/01006422089 (accessed on 25 August 2023).
41. Nikolaenko, N.A. *Probabilistic Methods for Dynamic Calculation of Mechanical Engineering Structures*; Mechanical Engineering: New York, NY, USA, 1967; 368p. Available online: https://search.rsl.ru/ru/record/01006422087 (accessed on 29 August 2023).
42. Elenitsky, E.Y. Bearing capacity of the body of vertical cylindrical steel tanks in conditions of seismic impact. *Earthq. Resist. Saf. Spec. Struct.* **2009**, *1*, 41–43. (In Russian). Available online: http://old.vestnikmgsu.ru/index.php/archive/articles/display/keyword/12463 (accessed on 29 August 2023).
43. Elenitsky, E.Y. Ensuring earthquake resistance of vertical cylindrical steel tanks. Earthquake-resistant construction. *Saf. Struct.* **2006**, *5*, 45–49. (In Russian). Available online: http://www.seismic-safety.ru/sites/default/files/ssbs-2018-02_shigapov.pdf (accessed on 30 August 2023).
44. *STO-SA-03-002-2009*; Rules for the Design, Manufacture and Installation of Vertical Cylindrical Steel Tanks for Oil and Petroleum Products. Scientific Practical Conference Isothermal, Moscow, Russia. 2009; 216p. Available online: https://meganorm.ru/Index2/1/4293828/4293828021.htm (accessed on 30 August 2023).
45. *SP 14.13330.2011*; Construction in Seismic Areas (Updated Edition of Construction Norms and Regulations II-7-81*). OJSC "TsPP": Moscow, Russia. 2011. Available online: https://meganorm.ru/Index2/1/4293811/4293811420.htm (accessed on 30 August 2023).
46. *SP 16.13330.2011*. Steel Structures (Updated Edition of Construction Norms and Regulations II-23-81*). OJSC "TsPP": Moscow, Russia. 2011. Available online: https://meganorm.ru/Index2/1/4293811/4293811639.htm (accessed on 30 August 2023).
47. Śliwa, A.; Kwaśny, W.; Nabiałek, M.; Dziwis, R. Numerical analysis of static tensile test of the sample made of polyethylene reinforced by halloysite nanoparticles. *Acta Phys. Pol.* **2019**, *136*, 996–1000. https://doi.org/10.12693/APhysPolA.136.996.
48. Ghazijahani, T.G.; Showkati, H. Experiments on cylindrical shells under pure bending and external pressure. *J. Constr. Steel Res.* **2013**, *88*, 109–122. https://doi.org/10.1016/j.jcsr.2013.04.009.
49. Joniak, S.; Magnucki, K.; Szyc, W. Buckling study of steel open circular cylindrical shells in pure bending. *Strain* **2011**, *47*, 209–214. https://doi.org/10.1111/j.1475-1305.2009.00669.x.
50. Al-Yacouby, A.M.; Hao, L.J.; Liew, M.S.; Chandima-Ratnayake, R.M.; Samindi-Samarakoon, M.K. Thin-walled cylindrical shell storage tank under blast impacts: Finite element analysis. *Materials* **2021**, *14*, 7100. https://doi.org/10.3390/ma14227100.
51. Hud, M. Simulation of the stress-strain state of a cylindrical tank under the action of forced oscillations. *Procedia Struct.* **2022**, *36*, 79–86. https://doi.org/10.1016/j.prostr.2022.01.006.
52. Sierikova, O.; Strelnikov, E.; Degtyarev, K. Strength Characteristics of Liquid Storage Tanks with Nanocomposites as Reservoir Materials. In Proceedings of the 2022 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek), Kharkiv, Ukraine, 3–7 October 2022; pp. 151–157. https://doi.org/10.1109/KhPIWeek53812. 2022.9916392.
53. Jaramillo, F.; Almazán, J.L.; Colombo, J.I. Effects of the anchor bolts and soil flexibility on the seismic response of cylindrical steel liquid storage tanks. *Eng. Struct.* **2022**, *263*, 114353. https://doi.org/10.1016/j.engstruct.2022.114353.
54. Wang, J.; Kusunoki, K. Study on the Flexural Strength of Interior Thick Wall-Thick Slab Joints Subjected to Lateral Force Using Finite-Element Analysis. *Buildings* **2022**, *12*, 535. https://doi.org/10.3390/buildings12050535.
55. Thongchom, C.; Jearsiripongkul, T.; Refahati, N.; Roudgar Saffari, P.; Roodgar Saffari, P.; Sirimontree, S.; Keawsawasvong, S. Sound Transmission Loss of a Honeycomb Sandwich Cylindrical Shell with Functionally Graded Porous Layers. *Buildings* **2022**, *12*, 151. https://doi.org/10.3390/buildings12020151.
56. Wang, Z.; Hu, K.; Zhao, Y. Doom-roof steel tanks under external explosion: Dynamic responses and anti-explosion measures. *J. Constr. Steel Res.* **2022**, *190*, 107118. https://doi.org/10.1016/j.jcsr.2021.107118.

57. Bragov, A.; Konstantinov, A.; Lomunov, A.; Kruszka, L. Comparative analysis of dynamic strength and impact toughness of pipe steels. *EPJ Web Conf.* **2021**, *250*, 04002. Available online: https://www.epj-conferences.org/articles/epjconf/pdf/2021/04/epjconf_dymat2021_04002.pdf (accessed on 30 August 2023).
58. Chernobryvko, M.; Kruszka, L.; Vorobiev, Y. Thermo-elastic-plastic constitutive model for numerical analysis of metallic structures under local impulsive loadings. *Appl. Mech. Mater.* **2014**, *566*, 493–498. https://doi.org/10.4028/www.scientific.net/AMM.566.493.
59. Bonopera, M.; Chang, K.-C.; Tullini, N. Vibration of prestressed beams: Experimental and finite-element analysis of post-tensioned thin-walled box-girders. *J. Constr. Steel Res.* **2023**, *205*, 107854. https://doi.org/10.1016/j.jcsr.2023.107854.
60. Bonopera, M.; Liao, W.-C.; Perceka, W. Experimental-theoretical investigation of the short-term vibration response of uncracked prestressed concrete members under long-age conditions. *Structures* **2022**, *35*, 260–273. https://doi.org/10.1016/j.istruc.2021.10.093.
61. Suleimenov, U.; Zhangabay, N.; Abshenov, K.; Utelbayeva, A.; Imanaliyev, K.; Mussayeva, S.; Moldagaliyev, A.; Yermakhanov, M.; Raikhanova, G. Estimating the stressed-strained state of the vertical mounting joint of the cylindrical tank wall taking into consideration imperfections. *East.-Eur. J. Enterp. Technol.* **2022**, *3*, 14–21. https://doi.org/10.15587/1729-4061.2022.258118.
62. Kudabayev, R.; Mizamov, N.; Zhangabay, N.; Suleimenov, U.; Kostikov, A.; Vorontsova, A.; Buganova, S.; Umbitaliyev, A.; Kalshabekova, E.; Aldiyarov, Z. Construction of a model for an enclosing structure with a heat-accumulating material with phase transition taking into account the process of solar energy accumulation. *East.-Eur. J. Enterp. Technol.* **2022**, *6*, 26–37. https://doi.org/10.15587/1729-4061.2022.268618.
63. Suleimenov, U.; Zhangabay, N.; Utelbayeva, A.; Azmi Murad, M.A.; Dosmakanbetova, A.; Abshenov, K.; Buganova, S.; Moldagaliyev, A.; Imanaliyev, K.; Duissenbekov, B. Estimation of the strength of vertical cylindrical liquid storage tanks with dents in the wall. *East.-Eur. J. Enterp. Technol.* **2022**, *1*, 6–20. https://doi.org/10.15587/1729-4061.2022.252599.
64. Suleimenov, U.; Zhangabay, N.; Utelbayeva, A.; Ibrahim, M.N.M.; Moldagaliyev, A.; Abshenov, K.; Buganova, S.; Daurbekova, S.; Ibragimova, Z.; Dosmakanbetova, A. Determining the features of oscillations in prestressed pipelines. *East.-Eur. J. Enterp. Technol.* **2021**, *6*, 85–92. https://doi.org/10.15587/1729-4061.2021.246751.
65. Ye, Z.; Birk, A.M. Fluid pressures in partially liquid-filled horizontal cylindrical vessels undergoing impact acceleration. *J. Pressure Vessel Technol.* **1994**, *116*, 449–458. https://doi.org/10.1115/1.2929615.
66. Tursunkululy, T.; Zhangabay, N.; Avramov, K.; Chernobryvko, M.; Kambarov, M.; Abildabekov, A.; Narikov, K.; Azatkulov, O. Oscillation frequencies of the reinforced wall of a steel vertical cylindrical tank for petroleum products depending on winding pre-tension. *East.-Eur. J. Enterp. Technol.* **2023**, *3*, 14–25. https://doi.org/10.15587/1729-4061.2023.279098.
67. Zhangabay, N.; Tursunkululy, T.; Bonopera, M.; Azatkulov, O. Laboratory investigation of the dynamic response of a prestressed composite steel cylindrical tank subjected to horizontal loading. *J. Compos. Sci.* **2023**, *7*, 373. https://doi.org/10.3390/jcs7090373.
68. Shapovalov, L.A. *Modeling in Problems of Mechanics of Structural Elements*; M. Mechanical Engineering; Mashinostroenie Publ.: Moscow, Russia, 1990; 288p. Available online: https://www.studmed.ru/shapovalov-la-modelirovanie-v-zadachah-mehaniki-elementov-konstrukciy_a574d9420b2.html (accessed on 30 August 2023).
69. Patent of the Republic of Kazakhstan for Invention. *Method for Increasing the Seismic Stability of Vertical Steel Cylindrical Reservoirs Using a Pre-Tensioned Winding*; No. 35915; Astana, 2022. Available online: https://qazpatent.kz/ru (accessed on 30 April 2023).
70. Patent of the Republic of Kazakhstan for Utility Model. *Cylindrical Shell for Storage and Transportation of Liquid and Hydrocarbon Raw Materials*; No. 6208; Astana, 2021. Available online: https://qazpatent.kz/ru (accessed on 30 April 2023).