On application of rubber-metal seismic isolating supports of a ball tank under seismic load

M Yu Sergaeva¹, A M Lyubykh²
¹Omsk State Technical University, 11, Mira ave., Omsk 644050, Russia
²JSC “Gazpromneft-Omsk Oil Refinery”, 1, Gubkina Pr., Omsk 644040, Russia
mjsergaewa@mail.ru

Abstract. This article considers the possibility of using seismic supports in seismic protection systems for ball tanks for storing liquefied hydrocarbon gases in seismically unstable operating conditions. Attention is paid to the study of support structures, which include rubber-metal vibration isolators. Based on the theory of long-term strength, the issues of the operability of rubber-metal seismic-insulating supports (RMSS) are considered. The use of RMSS reduces seismic loads in the supports of the tank by 1.5-2.0 times. At the same time, the analysis of the stress-strain state (SSS) of the tank body showed that the structural elements retain their operational characteristics under seismic load and meet the strength conditions in accordance with the requirements of the current standard technical documentation.

1. Introduction
The construction and reconstruction of facilities for the transportation and storage of oil products, including liquefied petroleum gas, plays a significant role in the oil and gas industry. In many cases demanding objects are being built in seismically active regions in connection with the development of the Far East, Baikal, Krasnoyarsk Territory, and the North Caucasus.

At present, the problem of safe operation of storage tanks for liquefied petroleum gas under seismic loads remains an urgent task. Traditionally, the reduction of vibration loads on the foundation, supports and tank shells has been achieved by increasing the bearing capacity of the structure. This approach requires certain material and financial costs, and in many cases it is ineffective, since it entails an increase in the rigidity and weight characteristics of the structure.

Solving the problem of a significant reduction in the overall level of seismic loads on structures led to the creation of seismic isolation systems. “When using such systems, seismic isolators are installed between the structures of the construction and the rigid foundation, thereby changing the natural frequencies of the building as a whole, and hence the values of seismic loads” [1]. This increases the operational reliability of structures, reduces material consumption and cost, and significantly reduces the degree of risk from destruction.

In Russia, in the early 70s of the last century the practical issues of seismic isolation began to be actively dealt with under the leadership of Ya.M. Eisenberg [2, 3]. Thanks to the works of I.I. Goldenblat, B.G. Koronev, N. Newmark and others there were developed scientific approaches in the field of seismic protection of structures, a large number of experimental and theoretical studies were carried out [4, 5]. There has been a transition from "static theory" to "dynamic models" applied in the development and study of various options for vibration isolation systems of structures in connection with the development of dynamic calculations, various methods of mathematical modeling [6].

The currently used methods of seismic protection of structures are extremely diverse, so their classification is very difficult.
Most of the seismic isolation systems that have received practical application are combined, various technical solutions have been combined there. At the same time, experts distinguish their main types [7]:

1. Systems based on rubber-metal seismic-isolating supports (RMSS).
2. Systems with seismic sliding supports.
3. Systems with rolling friction units.
4. Systems with elastic shock absorbers.

Despite certain structural differences between RMSS, in the general case, such a support is a structure consisting of alternating thin metal plates with a thickness of 0.1 ... 5.0 mm and layers of rubber, their number and dimensions are set based on the required values of the bearing capacity and rigidity.

The change in stiffness, and the frequency of natural vibrations respectively, in different directions can be carried out by changing the size of the rubber element (figure 1, a), complicating the shape of the rubber mass (figure 1, b) or by introducing additional metal reinforcement (figure 1, c).

![Figure 1. Constructive solutions for changing the stiffness characteristics of vibration isolators](image)

Structurally, the vibration isolator is selected based on the mass of the damped equipment and the ratio between the forced and natural frequencies. In this case, the frequencies of natural vibrations of the damped object are determined by the dynamic stiffness.

2. The problem statement

The solution to the problem of reducing dynamic loads on supporting structures and body elements of a ball tank in seismically active operating conditions can be implemented by studying seismic-isolating supports based on rubber-metal vibration isolators and analyzing the stress-strain state of structural elements of the structure under consideration.

3. Theory

When determining the stiffness characteristics of the applied rubber-metal vibration isolators for the system of seismic protection of a ball tank, we will use the provisions of the theory of long-term strength. The RMSS compression stiffness can be considered as the ratio of the increment in the compressive force to the corresponding decrease in the total thickness of the rubber layer. For engineering calculations, the RMSS compression stiffness can be determined by the formula

$$C_{cmp} = \frac{E_c \cdot A}{n \cdot t_r}$$

where $C_{cmp}$ is RMSS rigidity in compression; $E_c$ is Young's modulus; $n$ is the number of rubber layers; $t_r$ is the thickness of the rubber layer; $A$ is the RMSS area in the plan.

In this case, the RMSS compression deformations is determined by the dependence

$$\varepsilon_{cmp} = \frac{P_{cmp}}{C_{cmp}}$$

where $P_{cmp}$ is the compressive force.

To determine the RMSS shear stiffness we use the following ratio

$$C_{sh} = \frac{G \cdot A}{n \cdot t_r}$$

where $G$ is the shear modulus.
As shear is the most dangerous phenomenon of the stress-strain state of the considered operating conditions of objects, the shear stresses arising in RMSS rubber during horizontal displacement \( x \) will be determined by the formula

\[
\gamma = \frac{x}{n \cdot t_r}
\]

In addition to compression, for the rubber layer of the vibration isolator, the allowable stress from RMSS tensile deformation is taken into account, taken as a conditionally elastic tensile stress \( \sigma_t \) and determined from the inequality

\[
\sigma_t \leq 2G.
\]

The value of the RMSS critical stress \( \sigma_c \), is defined as the compressive stress at zero displacement, at which the support loses its stability, is determined by the formula

\[
\sigma_c = \frac{\pi}{4} \cdot \xi \cdot S \cdot \sqrt{\frac{E_b}{G}}
\]

where \( E_b \) is Young’s modulus at bending; \( \xi \) is a coefficient depending on the shape of the RMSS (for a round support \( \xi = 1 \)); \( S \) is the shape factor.

The deformation capacity of RMSS depends on the shear deformation and volumetric deformation of the rubber, as well as the deformation of the metal plate. The rigidity of RMSS depends significantly on the mechanical properties of the material, the geometric shape and the stress-strain state arising under the action of an external load.

RMSS should be designed to provide operational reliability in the ultimate state obtained from the full compressive load, resistance to wind, snow and seismic load [8].

The limiting state of RMSS can be represented in the form of a diagram using the ratio between the compressive and shear stresses arising in the critical case (figure 2).

![Figure 2. Limit state diagram of RMSS](image)

Two areas are determined from the diagram of the limiting state of the RMSS:

a) loss of stability in bending;

b) loss of strength upon destruction.

The limiting state equation for the loss of stability of the RMSS in bending

\[
\gamma \leq S \left(1 - \frac{\sigma_{emp}}{\sigma_c}\right)
\]

The equation for the ultimate strength of RMSS at destruction

\[
\gamma \leq \gamma_d
\]

where \( \gamma_d \) is shear stress at destruction.
Having obtained experimentally or based on the calculation of the limit state diagram, we can guarantee the creation of RMSS to limit the displacements to a value that allows the isolated and non-isolated parts of the ball tank not to contact during a possible seismic load.

4. Specifications of the investigated object

As part of the seismic protection system for ball tanks, rubber-metal vibration isolators are operated under conditions of high static loads, therefore their dynamic stiffness is determined by the values of these loads and the physical and mechanical properties of the rubber used. In the design of a rubber-metal vibration isolator, its general view is shown in figure 3, the rubber elastic element is vulcanized firmly to the metal reinforcement. “The required stiffness parameters are selected by changing the number and thickness of alternating layers of rubber and metal, to manufacture vibration isolators with different elastic characteristics” [9].

![Figure 3. General view of rubber-metal vibration isolator](image1)

![Figure 4. Diagram of ball tank on supports](image2)

The investigated ball tank is a vessel with a nominal volume of 2000 m³, installed on nine supports (pipes Ø820×24) and designed for storing liquefied petroleum gas. The supports are interconnected by pre-tensioned straps made of Ø54 ropes (figure 4). The technical characteristics of the ball tank are shown in table 1.

| Table 1. Ball tank specifications |
|----------------------------------|
| Parameter                        | Quantity                              |
| Pressure, MPa (kg/cm²):          |                                       |
| – operating, no more             | 1.3 (13.0)                            |
| – calculated                     | 1.8 (18.0)                            |
| – trial during hydrotesting       | 2.3 (23.0)                            |
| – possible residual vacuum        | –                                     |
| Temperature, °C:                 | + 40                                  |
| – operating, no more             |                                       |
| Characteristics of the fluid     | Liquefied gas                         |
| Nominal volume, m³               | 2,000                                 |
| Estimated weight, kg:            |                                       |
| – in installation condition      | 379,000                               |
| – in operating conditions        | 1,316,900                             |
| – during hydrotesting            | 2,379,000                             |
| Established service life, at least, years | 12                                     |
| Conditions of operating          | Seismicity of the site on the MSK-64  |
| scale, no more, points           | 9                                     |

Rubber-metal vibration isolators are a structural element of the ball tank support. In order to ensure the reduction of loads on the foundation, RMSS were used, its specifications are given in table 2.
Table 2. RMSS specifications

| Parameter                          | Quantity       |
|------------------------------------|----------------|
| \( C_p \) – compressive stiffness, \( \text{N/m} \) | \( 0.06 \cdot 10^{10} \) |
| \( C_G \) – shear stiffness, \( \text{N/m} \)     | \( 1.334 \cdot 10^7 \) |
| \( C_B \) – bending stiffness, \( \text{N/m/rad} \) | \( 0.14 \cdot 10^7 \) |
| \( C_Z \) – torsional rigidity, \( \text{N/m/rad} \) | \( 0.134 \cdot 10^9 \) |
| \( a_s \) – support compression factor, mm      | 0.51           |

The vibration isolator must ensure operability under the action of a static compression load (with a filled ball tank) on one seismic-isolating support not exceeding 3042.5 kN, which is evenly distributed between three shock absorbers that are part of one RMSS.

5. Research results

The dynamic calculation of RMSS under the action of static and dynamic forces (dynamics in statics) is of practical interest. The RMSS computational model is shown in figure 5 and consists of three parallel-connected packages, each consists of two series-connected rubber-metal shock absorbers.

The real accelerogram of the Loma Prieta'89 earthquake was taken as the driving motion from the seismic load.

The insulated object is represented by a point mass applied to the top plate and equal to 1/27 of the tank's weight under operating conditions. Since the mass of the tank under operating conditions is 1664.2 tf, and it is installed on nine supports, each support will have 184.9 tf. Structurally, the support is installed on three shock absorber packages, so the load on them is evenly distributed. Since the shock absorbers are connected in series in the packages, therefore the load on each shock absorber will be 61.64 tf.

The dynamic calculation was carried out by the method of finite element analysis [10, 11] under the condition of loading the RMSS model with acceleration in the direction of the largest side of the shock absorber plate. The maximum amplitude of acceleration is 0.49 m/s², the duration of exposure is 39.085 s, and the time interval is taken to be 0.005 s [12, 13].

The results of the finite element calculation of the dynamic loads on the foundation supports under seismic load with a force of 8 and 9 points on the Richter scale, as well as the maximum forces and displacements of the RMSS are given in tables 3 and 4.

Based on the selected structural scheme of the seismic isolation system of a ball tank, two finite element models are considered [14, 15]:

- based on the RMSS;
- without using RMSS.

The design loads acting on the supports (with a combination of normal operating conditions and a seismic loading of 8 points) are given in table 3.
The bims are modeled with two node beam finite element with six degrees of freedom at each node. The tank shell was modeled by finite elements of the type of quadrangular shell elements with six degrees of freedom at each node. To study the stress-strain state of the tank shell from the action of various types of loads, including seismic, the tank shell (figure 6) was modeled by finite elements of the type of quadrangular shell elements with six degrees of freedom at each node [16]. The ball tank supports are modeled as two-node beam finite elements with six degrees of freedom at each node. The bims are modeled with two-node elements with a pretension of 1.5 tf.

Table 3. Loads acting on the supports of the foundation with RMSS

| № of support | Fx, kN | Fy, kN | Fz, kN | Mx, kNm | My, kNm | Mz, kNm |
|--------------|--------|--------|--------|---------|---------|---------|
| 1            | 555.29 | 0      | 3361.28| 0       | 1624.41 | 0       |
| 2            | 817.03 | -310.88| 2910.0 | -665.18 | 1075.93 | 0.65    |
| 3            | 1168.8 | -105.54| 1767.91| -256.0  | 328.45  | 1.01    |
| 4            | 1026.99| 277.94 | 469.18 | 537.62  | 593.66  | 0.88    |
| 5            | 623.42 | -205.34| -378.69| 409.18  | 1407.35 | 0.34    |
| 6            | 623.42 | -205.34| -378.69| 409.18  | 1407.35 | 0.34    |
| 7            | 1026.99| 277.94 | 469.18 | 537.62  | 593.66  | 0.88    |
| 8            | 1168.8 | -105.54| 1767.91| -256.0  | 328.45  | 1.01    |
| 9            | 817.03 | -310.88| 2910.0 | -665.18 | 1075.93 | 0.65    |

Table 4 shows the calculated loads acting on the foundation supports without RMSS.

Table 4. Loads acting on the supports of the foundation without RMSS

| № of support | Fx, kN | Fy, kN | Fz, kN | Mx, kNm | My, kNm | Mz, kNm |
|--------------|--------|--------|--------|---------|---------|---------|
| 1            | 479.58 | 0      | 3386.88| 0       | 3590.63 | 0       |
| 2            | 937.68 | -540.4 | 2929.43| -1059.61| 2654.12 | 1.28    |
| 3            | 1550.31| -175.6 | 1772.22| -455.18 | 1471.49 | 1.98    |
| 4            | 1294.03| 497.81 | 456.69 | 766.91  | 1834.04 | 1.73    |
| 5            | 579.66 | 364.8  | -402.65| 604.45  | 3052.08 | 0.67    |
| 6            | 579.66 | 364.8  | -402.65| 604.45  | 3052.08 | 0.67    |
| 7            | 1294.03| 497.81 | 456.69 | 766.91  | 1834.04 | 1.73    |
| 8            | 1550.31| -175.6 | 1772.22| -455.18 | 1471.49 | 1.98    |
| 9            | 937.68 | -540.4 | 2929.43| -1059.61| 2654.12 | 1.28    |

To study the stress-strain state of the tank shell from the action of various types of loads, including seismic, the tank shell (figure 6) was modeled by finite elements of the type of quadrangular shell elements with six degrees of freedom at each node [16]. The ball tank supports are modeled as two-node beam finite elements with six degrees of freedom at each node. The bims are modeled with two-node elements with a pretension of 1.5 tf.

Figure 6. Finite element model of a ball tank
When calculating the SSS of the finite element model of the tank body in the software package, the following types of loads were taken into account: internal and external pressure; empty weight, weight of product or water during hydrotesting, weight of sites and equipment, wind impact, seismic load. These loads were summarized in the following four combinations of load modes:

- standard operating conditions;
- conditions of hydrotesting;
- installation conditions;
- combination of standard operating conditions and seismic load.

The finite element calculation of the distribution of the principal and equivalent stresses in the wall of the ball tank is performed for all four combinations of loading. Equivalent stresses were determined according to the hypothesis of the specific energy of the Huber-Henki-Mises shape change.

There are diagrams of distribution of principal and equivalent stresses in standard operating conditions in figures 7, 8 as an example.

**Figure 7.** Distribution of common membrane and bending stresses under standard operating conditions, MPa

**Figure 8.** Distribution of equivalent stress under standard operating conditions, MPa

The distributions of the principal and equivalent stresses in the tank wall for a combination of loads are shown in figures 9, 10: standard operating conditions and seismic load.

**Figure 9.** Distribution of the main membrane and bending stresses under operating conditions at seismic load, MPa

**Figure 10.** Distribution of equivalent stress in operating conditions at seismic load, MPa
The calculated strength assessment is carried out in order to establish the conformity of the ball tank to the requirements of the current strength standards and to determine the conditions for further safe operation. A ball tank is considered serviceable if its main elements have safety margins for static and cyclic loading conditions not lower than the values specified in the standard technical documentation. In case of unsatisfactory results of the calculated assessment of the strength of the ball tank, the defective places are subject to repair with mandatory subsequent examination. If it is impossible to eliminate defects, further operation of the ball tank is not allowed [17].

6. Discussion of results
Comparison of the calculated loads on the foundation supports with RMSS (table 4) with similar data without the RMSS (table 3) determines that when using RMSS in seismic isolation systems for ball tanks, the values of bending moments at the base of the supports decrease by more than 2.0 times, and the values of shear forces decrease by about 1.5 times.
The performed analysis of the stress-strain state of the tank shell determines the maximum values in the stress concentration zones (the places where the supports are welded to the backing plates and the backing plates of the supports to the shell), which amounted to:
- under standard operating conditions - 211.94 MPa;
- in operation mode and seismic load - 219.96 MPa.
Comparison of the stress values shown in figures 7-10 with the limit values, establishes that the structural elements of the ball tank meet the strength conditions in accordance with the requirements of the current standard technical documentation [18].

7. Conclusions
In the course of the performed theoretical studies, it was found that the creation of a seismic isolation system based on RMSS reduces the level of loads on the structural elements of ball tanks for storing liquefied hydrocarbon gases under seismic load.
The introduction of rubber-metal vibration isolators into the composition of the supports reduces the values of shear loads and bending moments by 1.5–2 times.
The advantages of the considered seismic-isolating supports include the simplicity of design and manufacture. The elastic characteristics of RMSSs vary by the number and thickness of the layers of rubber and metal plates.
For the considered combinations of loads of operating conditions, hydrotesting and seismic load, the study of the stress-strain state of the tank shell showed that the strength characteristics of the tank elements comply with the standard technical requirements in the case of using RMSS.
The performed computational studies confirm the effectiveness of using RMSS in seismic isolation systems for ball tanks.

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