ИНСТИТУТ ВЫЧИСЛИТЕЛЬНЫХ ТЕХНОЛОГИЙ СО РАН

COMPUTATIONAL MODEL OF DAMAGE ACCUMULATION IN A TANK AT THE FOUNDATION SUBSIDENCE

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INTRODUCTION

Vertical steel tanks (VST) are extensively used in various branches of industry to store liquids and gases of common and production application. Modern tanks are characterized by fluid capacity from 100 to 120 000 m^3. Although the results that recently obtained in the field of tanks manufacturing, at present tanks failures continue to occur. Not only single elements can fail but also the whole structure that bring to damaging closely-spaced tanks, infrastructure, construction machinery and other objects [1-5]. Petroleum, petroleum and chemical product, condensed gas, hot water outflow from damaged tank brings to collapses, material harms, ecological catastrophes and occasionally to human sacrifices. That is why the tanks are the hazardous objects.

Deformation models for cylindrical shells that were developed in elasticity theory [6] are the basic concepts of cylindrical tanks engineering analysis. Over several decades these models were the basis for development and application of standard specifications for tanks design and exploitation. These specifications are founded on analytical techniques and this fact places a limitation on loading cases and conditions of tanks kinematic and force interaction with system environment.

Elaboration of numerical methods and models of deformable solid mechanics enabled to carry out multivariant and many-model computing experiments to investigate tanks behavior in a broad range of operating conditions, including abnormal and emergency effects taking into account fractional damages of load-bearing structures. The conditions of tank buckling at local compressive load were analyzed by Wang et al [7]. Tanks behavior at foundation subsidence was studied by Tarasenko et al [8] and Zhang et al [9]. Papers [2, 3, 10, 11] are devoted to studying multiplex scenarios of catastrophic failures appearance.

The foundation subsidence is one of the causes of emergency situations in the VST operation. The subsidence is caused by foundation compression under the influence of tank structure and its content gravity. The foundation subsidence comes both uniform and non-uniform. The non-uniform subsidence is the most dangerous.

The investigation purpose is to work out and to approve computational model of damage accumulation in a tank at the non-uniform foundation subsidence. The investigation preconditions are case studies of tank failures due to foundation subsidence and the data on engineering factors of tank foundation construction [12]. Using such model enable to analyze structural behavior at the survivability stage, namely character and sequence of damage initiation and accumulation in tank structure.

PHYSICAL AND TECHNICAL REASONING FOR PROBLEM STATEMENT

The VST geometrical model contains cylindrical shell of 4 mm thickness and 7580 mm diameter, and flat bottom of 4 mm thickness. The cylindrical shell is equipped on its overhead contour with reinforcing angle-iron. In the capacity of working loads there are assumed structure proper weight and hydrostatic pressure of liquid content. Deformation of foundation soil is studied by means of elastic support decomposed into some fragments with various foundation stiffness.

The foundation subsidence is under the influence of structure and properties of the soil, the features of the weight distribution in the structure, loading conditions, and external climatic factors. The non-uniform subsidence can show itself as general or partial subsidence on tank bottom outer contour as well as local subsidence under the bottom. It brings to deformation and stress reallocation, elastic-plastic deformation effects, buckling, and general or partial tank tilt.

There are used three approaches to VST foundation modeling that correspond to different scenarios of its subsidence. Within the bounds of the first approach the foundation model is decomposed to parallel bands (Fig. 1a) and foundation stiffness are decreasing in steps from the foundation center to the periphery. In the second model (Fig. 1b) the foundation is decomposed to concentric bands: the largest subsidence appears near the walls, and the smallest one near the center. Similarly to the second approach, the third one (Fig. 1c) uses concentric decomposition of the foundation, but the subsidence center is displaced from the tank bottom center. The foundation stiffness decreases in the direction of subsidence center. All three models have vertical symmetry plane that results in two times reduction for model dimensionality. Table 1 describes the foundation stiffness distributions by fragments. They vary between 0.002 N/mm^3 (low-density soil running sand and so on) and 0.2 N/mm^3 (highly-density soil argillo-arenaceous, artificially packed and so on). Intermediate values correspond with different attenuation degree of the soil because of technological and natural reasons.

For each of three model there are realized four sets of computational experiments that correspond to different levels of foundation subsidence. The stiffness of elastic foundation fragments was controlled under the experiments condition but properly the subsidence was one of the result model parameter.

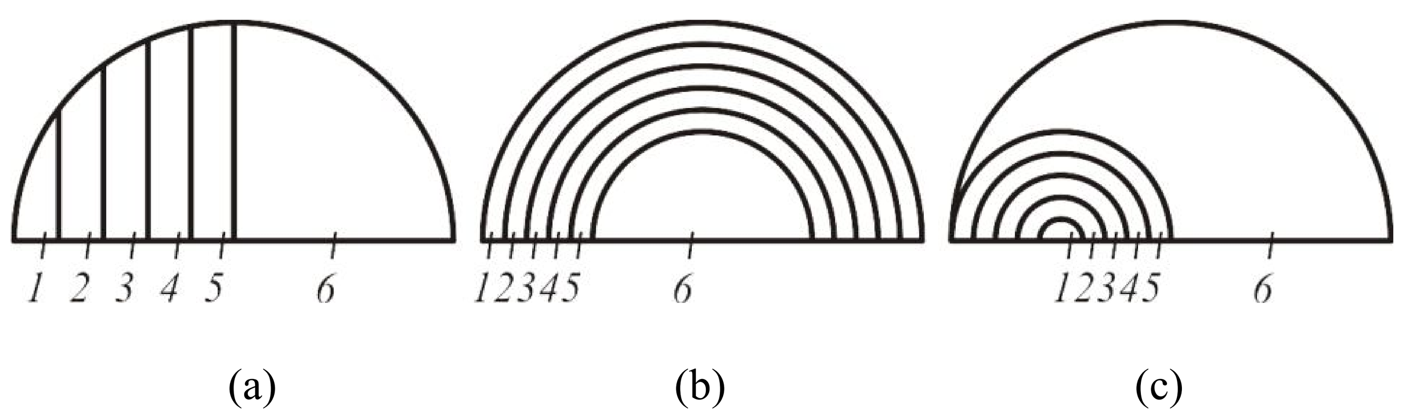

FIGURE 1. Three models of elastic support decomposition to fragments: *1*, *2*, *3*, *4*, *5*, *6* numbers of fragments

TABLE 1. Elastic support foundation stiffness distribution by fragments, N/mm^3

Foundation fragment	Set of experiments			
	1	2	3	4
1	0.002	0.002	0.002	0.002
2	0.0416	0.002	0.002	0.002
3	0.0812	0.0515	0.002	0.002
4	0.1208	0.101	0.068	0.002
5	0.1604	0.1505	0.134	0.101
6	0.2	0.2	0.2	0.2

NUMERICAL MODEL AND RESULTS

Computational model of damage accumulation in a tank at the foundation subsidence involves numerical (finite-element) model of the tank (Fig. 2), resolving equations and algorithm for finite-element displacement method, as well as iterative procedures for solving physically-nonlinear (taking into account elastic-plastic behavior of materials) and geometrically nonlinear (large deflection analysis) problem.

The numerical model is developed with using symmetry boundary conditions and two-dimensional finite element according to Mindlin-Reissner plate theory. Elastic-plastic deforming of the tank structural material was approximated by means of bilinear isotropic hardening law. The Winkler model with constant foundation stiffness was used to determine elastic support behavior.

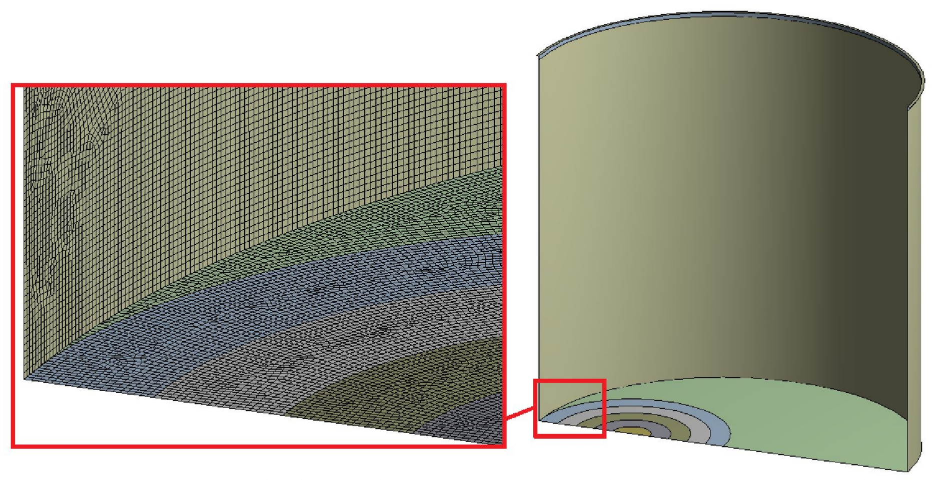

FIGURE 2. Finite-element model of the tank when decomposing elastic support to fragments in accordance with Fig. 1c

The following results are of interest to analyze structure behavior: maximum equivalent stress σ_i, equivalent plastic strain ε_{pli}, buckling load factor L_p, maximum u_{ymax} and minimum u_{ymin} vertical displacement of tank bottom (Table 2).

While foundation subsidence there are possible two kinds of damaging: Elastic-plastic strain appearance and accumulation, and tank elements (bottom and wall) buckling.

Qualitative description of tank deforming involves the bottom local deflection because of foundation attenuation. The deflection results in bending moment both in the bottom and in the welding zone of the bottom and the wall, as well as immediately in the wall. Maximum stresses caused by foundation subsidence are sufficiently large and quickly run up yield stress that results in elastic-plastic strain. The strain magnitude depends on foundation subsidence, namely on its stiffness distribution under the tank bottom.

The main quantitative result of buckling analysis is the buckling load factor L_p. Values $L_p < 1$ are evidence of buckling. Multiplication of working loads by the buckling load factor L_p leads to appropriate mode of buckling. The table 2 contains values of L_p for the lowest mode of buckling.

Table 2 data analysis shows that foundation subsidence under the first scenario is followed by progressive accumulation of elastic-plastic strains and decreasing buckling load factor. While further subsidence the stage of elastic-plastic strains is completed with the stage of buckling. Thus, this scenario is characterized by a consecutive accumulation and a change in the type of damage.

The feature of the second scenario is that conditions of tank buckling prevail over those for appearance of elastic-plastic strain. Only small subsidence leads to buckling risk and appearance of elastic-plastic strain.

When implementing the third scenario the risk of buckling and elastic-plastic strain accumulation grows as foundation subsidence enlarges.

The maximum calculated values of foundation subsidence are equal to 38, 46 and 36 mm accordingly to the first, the second and the third scenarios. They do not exceed values permissible by standards that demonstrate the results realness.

TABLE 2. Numerical results for models 1-3 in dependence on attenuation degree of the foundation

Set of experiments	Model 1				Model 2				Model 3			
	1	2	3	4	1	2	3	4	1	2	3	4
σ_i, MPa	239.1	239.4	240.7	246.0	233.4	210.3	221.0	208.8	123.6	179.2	235.2	242.3
$\varepsilon_{pli}\times10^4$	3.85	4.15	5.46	10.4	0.01	0	0	0	0	0	0.17	6.91
L_p	8.0	2.6	2.3	2.1	0.6	0.1	~0	~0	10.1	3.5	1.8	1.003
u_{ymin}, mm	0.267	0.006	-0.171	-0.220	0.364	0.363	0.362	0.359	0.309	0.300	0.285	0.264
u_{ymax}, mm	21.72	38.08	37.78	37.88	41.84	45.92	44.98	45.84	13.72	25.15	32.65	35.93

CONCLUSION

The elaborated computational model is a tool for analysis of scenarios for damaging structure while it interacts with system environment. There are determined three possible scenarios of damage accumulation for some variants of foundation subsidence. They are: 1 elastic-plastic deformation turning into the buckling; 2 the pure buckling; 3 the buckling turning into elastic-plastic deformation. These scenarios are the essential components of various scenarios for tanks catastrophic failures.

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