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Structural fabrication quality as a factor of industrial facilities safety

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Abstract. In the conditions of industrial facilities high wear degree, it is very important to ensure the possibility of their safe operation in order to avoid various kinds of accidents and catastrophes. As practice shows, industrial plant collapses can occur suddenly under normal operating conditions. Usually, such accidents can take place at different stages of structures life cycle. One of the reasons for this is the initially low quality of reinforced concrete structures fabrication. The article considers the factors contributing to the collapse of reinforced concrete structures of water purification tanks located on the territory of the Omsk Region. The main surveys results on tank structures after collapse with the use of ultrasonic and physical methods of investigation are presented. On the basis of the obtained data analysis, it was found that the main cause of the accidents was the insufficient load-bearing capacity of typical reinforced concrete structures, caused by defects in their fabrication in the factory conditions because of exceeding the standard displacement from the design position of the working reinforcement. Recommendations are given on the identification of defective structures and the prevention of similar accidents when operating similar tanks at manufacturing plants constructed from standard designs.

Key words accident, reinforcement, caving, reinforced concrete structures, tanks, bearing capacity.

1. Introduction

The current stage of development of Russia is characterized by active construction and reconstruction of objects of predominantly civilian use. Industrial construction is developing to a lesser extent. A similar situation is observed in the analysis of infrastructure facilities construction in cities and industrial enterprises, in particular, water treatment facilities. We have to state that most such objects were built in the middle or the second half of the last century. To date, the structures of old treatment facilities have accumulated a great deal of physical wear, but they continue to function and serve city enterprises. Moreover, the intensity of exploitation increased with the growth in the cities number and the sewage volume. However, in some cases, the dysfunction of tanks, including their collapse, is not resulted from the accumulated normal wear and tear, but from initially hidden defects designs, accepted at the stage of fabrication and is not amenable to visual identification of the construction and normal operation of the facilities. Typical features of existing reservoir structures are:
- application, for the construction of variously designed tanks, of unified prefabricated reinforced concrete structures made according to standard series;
- a large useful volume of tanks, i.e. in case of failure in the event of an accident, it is necessary to redirect the water to the reserve storage, which is extremely difficult in conditions of congestion;
- practical impossibility of complete dehumidification of certain types of treatment facilities due to their continuous operation.

In this regard, the identification of possible defective structures for the purpose of preventing their strengthening and preventing the accident of storage tanks and water treatment is an urgent task.

2. Statement of the problem
In the process of tanks structures fabrication, there is a number of tolerances, within which displacements from design decisions are permissible. It is believed that if the tolerances are observed, the influence of the initial imperfections on the strength and operational properties of the structural elements is negligible. A number of parameters, such as overall dimensions, position of embedded parts, etc. can be determined using simple measuring instruments. However, to assess other parameters of the quality of reinforced concrete products (concrete strength class, class of reinforcement, etc.), more complex measurements are required, which, as practice shows, has not always been carried out in the manufacturing plants.

The problems of reinforced concrete structures fabrication and installation quality were investigated by leading research organizations and scientists both in Russia and abroad. In particular, in 1993, on the basis of a research, a program was developed to determine the destructive loads for the calculation of cylindrical ferro-concrete tanks [1]. The problems of reinforced concrete structures progressive collapse with the development of recommendations for designers [2, 3] are investigated. The experience of research indicates that the violation of the technology of reinforcement and concrete operations in the structures manufacturing and erection can lead to facility collapse, while the development of defects can occur as both controlled and sudden. Thus, the violation in the performance of reinforcement work led to the collapse of the silo building in 1954. [4]. Displacement from the requirements of the project for the reinforcement of the aero-tank bottom in Togliatti led to the destruction in the bottom of the wall panels sealing and the subsequent collapse of 11 wall panels [5]. In addition to the initial defects, specific aggressive conditions of maintenance facilities operation lead to accelerated aging of structural elements. N. K. Rosenthal points out that the presence of air in air tanks containing oxygen and carbon dioxide, a high rate of washing of the aerot-ank structures surface with water, potentially creates the conditions for the occurrence of concrete and reinforcement destruction in the underwater zone [6].

The investigation of the inadequate reinforcement influence on the load-bearing capacity of reinforced concrete tank panels was carried out at two sites, which identified wastewater reservoirs in the city of Omsk and Omsk Region. These objects are selected for research due to massive sudden collapse of building structures. The practical significance of the chosen topic is to substantiate the causes of man-made accidents of structures associated with poor-quality reinforcement of reinforced concrete structures and to develop recommendations for identifying and preventing similar situations.

3. Results of on-site inspections
Inspection of the facility number 1 was carried out according to the requirements [7] in connection with the large-scale collapse of the bearing wall and partitions. The waste water reservoir is located in sewage treatment plants for biological treatment of household and related industrial wastewater in the territory of the Soviet administrative district of Omsk. The construction is 4-corridor with a distributed intake of waste water and variable volume of the regenerator. The object surveyed is a buried rectangular open top structure with dimensions in the axes of 108x72 m and a depth of about 5.0 m relative to the ground level. The structure is interlocked from 2 aero-tanks (left in axes 1-5 / A-B and right in axes 5-9 / A-B), divided by a continuous bearing wall along axis 5. Each aeration tank consists
of 4 sections with a width of 9 m, separated by partitions with technological apertures for water passage. The structure was built in 1974; at the time of collapse, the service life was 40 years. Overhaul of reservoir structures throughout the life of the plant was not carried out.

The main constructional elements of the structure are:
- bearing walls, located along the perimeter of the structure and an internal separation wall along axis 5. The walls are made of prefabricated reinforced concrete panels according to the standard series 3.900-2. The panels are cantilevered into the bottom grooves. Between the individual wall panels there are also monolithic reinforced concrete inserts;
- loading beds made of prefabricated reinforced concrete structures of individual fabrication, installed on partitions in prefabricated reinforced concrete beams.

According to the initial design, the joints of the dividing bearing wall panels between each other and the corner panels are splined and made by injecting the interlit weld with a cement-sand mortar. The joints of the corner panels and dividing partitions are designed to be rigid, located on the welding of horizontal reinforcement bars. The project provides for shotcrete monolithic sections of the walls with thickness of 20 mm.

During the examination, the following basic defects and structural damages were recorded:
- The wall panels of the dividing bearing wall section along axis 5 collapsed (figures. 1, 2);
- the internal dividing partitions collapsed together with the supplying reinforced concrete beds at different sites along the length;
- there were cracks in the panels of the bearing wall and partitions adjoining the destroyed sections;
- almost complete absence of the shotcrete concrete layer of on the panels surfaces (residual layer thickness up to 3 mm at the design value of 20 mm);
- corrosion of working reinforcement of wall panels;
- in separate wall panels there were no reinforcing bars.

Figure 1. Overview of the sewage water reservoir collapse (North side).

Figure 2. Overview of the sewage water reservoir collapse (South side).

The results of the object inspection and the destruction nature allow us to reconstruct the picture of the accident occurred. Immediately before the accident, the right aero-tank was not filled with water, while the left one was in operation. After filling the left aeration tank with water at the full calculated depth, a sudden destruction of 14 panels (a section 39 m long) of the bearing dividing wall occurred along axis 5. The panels collapsed as a result of strength loss of the normal section at the jammed place under the action of unilateral water pressure from the filled aeration tank. After the collapse of the bearing dividing wall section, there was a sharp outflow of water from the filled left aerotank, which resulted in the consequent destruction of the partitions in an unfilled aeration basin (along axis 6 coaxial with the collapsed section, a 39 m long section collapsed, along axis 7 panels collapsed over a length of 21 m) from the hydraulic shock of the formed wave and simultaneously in the filled part.
(first along axis 4 at a length of 56 m, then along axis 3 at a length of 39 m) due to asymmetric pressure provoked by a sharp outflow of water into the break. After the water level in the section in axes 6-7 / A-B of the right aero-tank increased, the partition wall was destroyed at a length of 27 m in 7 / A axes because of the remaining water pressure; thereon, the destruction ceased.

During on-site surveys, the strength characteristics of concrete were determined, the diameters and the pitch of the reinforcement were measured, and the reinforcement class was identified. In order to determine the possible causes of collapse, a comparative analysis of on-site surveys data and design solutions was performed, as a result of which the following structural features of the wall panels were found:

- the actual strength of bearing wall panels concrete corresponds to class B20, which is higher than the strength class B15 provided by the project;
- working reinforcement of load-bearing wall panels has Ø22 mm AIII with an average pitch width of the panel 140 mm (according to the project, it has Ø20 mm AIII with 200 mm pitch);
- the actual thickness of the bearing dividing wall panels of 200 mm corresponds to the design;
- working reinforcement of partitions panels has Ø12 ... 14 mm AIII with a pitch of 180 mm, distribution reinforcement has Ø6 mm AI and Ø8 mm AIII. According to the project, working reinforcement has Ø12 mm AIII, distribution reinforcement - Ø8 mm AI with a pitch of 130 mm;
- in three load-bearing wall, the panels are set up in a row and located in the middle of the collapsed section along axis 5, the actual distance from the edge of the panel to the working reinforcement is from 80 mm to 110 mm (figure 3).
prefabricated reinforced concrete ribbed cover plates are used, supported by steel beams or located directly on wall panels.

During the examination, the following basic defects and structural damages were recorded:
- the load-bearing slabs of the sewage tank No. 4 covering in the axes 6-13 / GD and the wall panels of the bearing wall in the axes 6-13 / D collapsed. The total area of the collapse was 130 m²;
- there was a loss of stability of the coating steel beam along the D axis in the plane and from the plane;
- the unbroken wall panels of sewage tank No. 1 are inclined from the vertical plane to 100 mm in the direction of T axis;
- violation of structural requirements for the construction of a of sewage tank No. 5 steel structure;
- there was no any anticorrosive protection of steel structures; in some areas, the degree of corrosion of beams and columns metal was up to 60% of the cross section;
- working reinforcement corrosion damages in sewage tanks wall panels and slabs;
- overestimation of up to 80 mm on one side and underestimation of the protective layer of concrete of the of the bearing wall collapsed panels on the other side, inadmissible displacement of the reinforcement when the panels embedding in concrete.

Based on the survey results and the damage nature analysis, the overview of the accident that occurred was restored. Immediately before the destruction, sewage tank No. 4 was not filled with water. At the same time, the sewage tank No. 5 adjacent to it was 80% full. At a certain point in time, as a result of strength loss of the wall panels normal section, a part of the bearing wall partitions and the coating in axes 6-13 / G-D under the effect of unilateral hydrostatic water pressure on the side of the filled sewage tank broke down at the point of pinching (figure 4). The situation was aggravated by the fact that the ribbed slabs of the coating did not actually unlock the top of the wall panels, because the corrosion caused complete destruction of the welds and embedded parts.

![Figure 4. Overview of the sewage water reservoir structures collapse](image)

The analysis of the actual constructive wall panels made it possible to find out that:
- the actual thickness of the collapsed panels of the bearing wall is 200 mm;
- the longitudinal working reinforcement of the panels is made with periodic reinforcement ∅18 A-II with an average pitch of 100 mm along the width of the panel;
- The transverse reinforcement is made by different reinforcement of the periodic profile (∅10 A-II, ∅14 A-II) and plain bars (∅12 A-I) with a pitch of about 200 mm;
- the protective layer of concrete is within 25 ... 85 mm (excess allowance of the reinforcement from the design position);
- the strength class of concrete corresponds to class B20.
4. Calculated analysis of the failure reasons

As the survey has shown, the reservoirs had numerous defects and damages, which are mainly resulted from non-compliance of the operational regulations, maintenance and major repairs of structures. However, the immediate cause of the accident in both cases is the sudden failure of the load-bearing wall panels under the effect of unilateral hydrostatic water pressure. A series of calculations was performed to assess the actual bearing capacity and crack resistance of a wall panels section. The calculations took into account the actual characteristics of concrete and reinforcement of the collapsed panels, as well as the displacement of the working reinforcement from the design position.

The calculations were performed according to the requirements of two groups of limiting states from the condition:
- Strength check, i.e. force from external loads and impacts in the section $F$ under consideration should not exceed the ultimate force $F_{ult}$;
- width of crack opening, i.e. the crack opening width from the external load $a_{cr}$ should not exceed the maximum allowable crack opening width $a_{cr,ult}$ [8].

The main results of the calculation analysis of the influence of displacement on the bearing capacity and crack opening in reinforced concrete panels are shown in the graphs (figures 5 and 6, respectively).

The comparison of load-bearing capacity of panels with efforts from unilateral hydrostatic water pressure, as well as with the Norms, regulating the requirements for reinforcement of reinforced concrete structures, indicates the following:

1. During wall panels fabrication, the requirements [9] for placing the longitudinal working reinforcement ($\Delta = 10\text{ mm}$) and the value of the protective layer of concrete ($\pm 8\text{ mm}, -5\text{ mm}$) were grossly violated. The main reason for the defect appearance is a violation of the reinforcement technology: the upper mesh in the case of panel horizontal concrete casting was not fixed and was displaced by the weight of the poured concrete to the center of the panel. The fact of several defective panels setting on the object No. 1 in a row is a typical one, which led to the collapse of the defective site.

2. For the panels of the object No. 1, the reinforcement displacement within the permissible [9] limits did not lead to the wall panels section overload at normal stresses. The limit of the condition for ensuring the strength of the normal section of the wall panels is the working reinforcement displacement by 40 mm relative to the design position. The normal section strength of object No. 2 wall panels is initially provided under the condition of the design placement of the reinforcement and with the obligatory unfastening of the panels tops with ribbed plates. In fact, in conditions of complete destruction of welded seams and embedded parts, the displacement of the working reinforcement, even within the limits of the standard allowance for object No. 2, was critical and led to overloading of the section with loss of strength and structures collapse.

3. By the condition of the cracks opening, the working reinforcement displacement should not exceed 47 mm. At the same time, violation of the maximum permissible crack opening condition can eventually lead to loss of concrete and working reinforcement adhesion, especially taking into account the aggressive influence of the medium, which in turn will affect the load-bearing capacity of the structure. In exploited reinforced concrete structures under the influence of aggressive gas-air and liquid chloride-containing media, one of the most common types of damage is the failure of reinforcement and concrete adhesion as a result of reinforcement corrosion [10, 11].
Thus, the occurrence of an accident at the facility number 1 resulted from violations in the fabrication of wall reinforced concrete panels. For facility number 2, in addition to the reinforcement displacement up to the collapse, there were violations of the repair mode during the facility operation, when the measures to restore and protect the welded joints of the ribbed plates were not carried out in time. According to the classification of A. G. Tamrazyan [12], the accident refers to the categories of accidents caused by poor-quality work and violation of the operation regulations.

5. Conclusion

1. All cases of accidents considered in the article occurred without human casualties. In terms of
the scale and degree of consequences, the examples given refer to the second group [13]. Nevertheless, due to the unsatisfactory quality of the wall panels and the subsequent accident, significant economic damage was caused as a result of the work suspension for up to six months and the need to restore the structures.

2. For the existing aero-tanks structures, a hidden defect of the non-project working reinforcement location is very dangerous, because, in the case of unilateral loading of the tank (for example, during cleaning or reconnaissance of the adjacent one), it can result in sudden collapse of the bearing wall panels.

3. For newly erected buildings with the use of prefabricated reinforced concrete wall panels, it is necessary to strengthen control over the products fabrication, and at the construction site, that over the acceptance inspection. In existing facilities, it is advisable to conduct full-scale inspection of wall panels with the detection of the reinforcement position, its corrosion damage and evaluation of structures bearing capacity. Ultrasonic methods for nondestructive testing can be used to determine the actual position of the working reinforcement.

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