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ANALYSIS AND OPTIMUM DESIGN OF CONCRETE RESERVOIR WALL

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Abstract. The design problems of reservoirs for collection, safekeeping and utilization of aggressive sewage and liquid manure in agricultural production have been discussed. As economic construction of reservoirs are reinforced concrete cylindrical containers. The stress analysis and optimum design of the wall of open monolithic reservoir has been performed. The optimum parameters of reservoir wall are fixed taking into account strength and serviceability limit state requirements. Based on the results obtained, it is determined that economical solutions can be reached by using combinations of concrete and steel with high strength classes.

Keywords: reinforced concrete reservoirs, strength, impenetrability, optimum design.

1. Introduction

Because of economic activity, an increase of processing waste and polluting the environment is taking place. The problem of collecting, storing, keeping and utilisation of aggressive sewage and liquid manure becomes very important. In case of wet technology in the process of removing manure from farmhouses, the water content of manure can reach 95%-97% [1]. In order to protect the environment, the safe keeping of mentioned liquids is possible by using large containers near to farmhouses and agricultural factories.

An economical solution of containers is reinforced concrete cylindrical reservoirs [2-4]. However, they have several disadvantages. In case of prefabricated reservoirs very often a leak between elements takes place [5]. Special systems for early detection from small leaks, especially in underground storage tanks, have to be developed. Under the action of tension, flexure, temperature gradient as well as concrete shrinkage, cracks can form in the vertical and horizontal direction of reservoir wall [6]. That causes a need of expensive repair techniques for treating cracks. In order to assure the impenetrability and durability of the wall it is necessary to check for the material strength and crack formation.

Wastewater and aggressive environment results in corrosion of storage tanks. Chemical resistance of protecting coating is extremely important in case of steel and concrete reservoirs [7, 8]. However, the use of man-made containers instead of natural reservoirs provides protecting impounded water from ash and other contaminants. Reliability problems as well as psychophysical and physiological effects of geometry have to be taken into account in design of storage tanks and distribution reservoirs [9, 10]. Chronological review of papers on the cost optimisation of reinforced concrete, prestressed concrete and fiber-reinforced concrete structures is given in [11]. The relative benefits of fire safety of underground reservoirs, the design and the relative costs of aboveground containers are in dispute [12].

In this study stress analysis and optimum design of the wall of open aboveground monolithic cylindrical reservoir has been performed. The task is to determine the optimum parameters of reservoir wall taking into account strength and serviceability limit state requirements and discrete material properties.

2. Determination of stress state

The objective of this research is to study the stress distribution in monolithic open reservoir. The problem is treated taking into account the effect of circumferential tensile force and vertical moment distribution in reinforced concrete wall thickness.

In case of monolithic reservoir, the connection of the wall to the bottom is moment resisting and there is no radial displacement. As a result, vertical wall acts in flexure and tension. The circumferential tensile force per unit width of the wall with the vertical co-ordinate x is determined by using expression:

$$N(x) = N^0(x) - p_{\max} r[e^{-\varphi}\cos\varphi + e^{-\varphi}\sin\varphi(1 - s/l)], \tag{1}$$

where $p_{\max}$ is maximum hydrostatic pressure, Pa; r is radius of reservoir, m; l is height of reservoir, m;

$\varphi = x/s$ is dimensionless coordinate; $s = 0.76\sqrt{rh}$ is elastic characteristic of the wall; h is thickness, m. The tensile force $N^0(x)$ in the wall without restriction depends on hydrostatic pressure:

$$N^0(x) = p_{\max} r(1 - x/l). \quad (2)$$

Because the radial displacement of the wall w depends only on coordinate x for local bending moment M_x formed near to the bottom of reservoir can be written

$$D_x \frac{d^2 w}{dx^2} + M_x = 0. \quad (3)$$

In equation (3) the moment M_x can be expressed as

$$M_x = C_1 e^{-\varphi} \cos\varphi + C_2 e^{-\varphi} \sin\varphi, \quad (4)$$

where C_1 and C_2 are constants of integration, Nm. Cylindrical stiffness D_x in equation (3) depends on the modulus of reinforced concrete E_x and the wall thickness h: $D_x \approx E_x h^3 / 12$.

Based on equations (3) and (4) the expression for bending moment with the vertical coordinate x is given in the following way

$$M_x = 0.5 p_{\max} s^2 [(1 - s/l) e^{-\varphi} \cos\varphi - e^{-\varphi} \sin\varphi] \quad (5)$$

and the maximum moment at the bottom of reservoir can be expressed as

$$M_{\max} = 0.5 p_{\max} s^2 (1 - s/l). \quad (6)$$

3. Numerical optimisation and discussion

According to the strength limit state based on the safety and load-carrying capacity of the structure [12, 13] the cross-section area of reinforcing steel bars A_θ^s in the circumferential direction θ can be found

$$A_\theta^s = \gamma_f N(x) / R_s, \quad (7)$$

where γ_f is load safety factor; R_s is design resistance of steel reinforcement in tension, Pa.

The cross-section area of vertical reinforcement is given as

$$A_x^s = \frac{M(x)}{\eta h_0 R_s}, \quad (8)$$

where η is design coefficient; h_0 is effective thickness of the wall, m.

In case of reservoirs the serviceability limit state refer to the performance of structure under normal service loads and are concerned with the use and durability of structure taking into account cracking of concrete ([13]). The formation of crack in a normal cross-section of the structure under action of normal force N can be checked by using relationship

$$N(x) \le N_{crc}. \quad (9)$$

The critical tensile force N_{crc} is determined by stresses formed in concrete and reinforcement before cracking:

$$N_{crc} = R_{bt,ser}(A + 2\alpha_s A_\theta^s) - \sigma_\theta^s A_\theta^s, \quad (10)$$

where $R_{bt,ser}$ is design resistance of concrete in tension for serviceability limit state, Pa; $A = b \times h$ is design cross-section area (b - unit width, m); $\alpha_s = E_s / E_b$ is the ratio of steel modulus to concrete modulus; σ_θ^s is stress decrease due to the shrinkage (σ_θ^s = 40–60 MPa).

When the effect of bending moment M_x is examined, the cracks begin to develop in tensile side of the wall. Bending moment at which these cracks begin to form, that is, when the tensile stress equals the modulus of rupture (strength), is referred to as the cracking moment, M_{crc}. In order to prevent the formation of cracks it is necessary to ensure

$$M_x \le M_{crc} = R_{bt,ser} W_{pl}. \quad (11)$$

The plastic cross-section modulus W_{pl} is determined by using the moment of inertia about the modulus weighted centroidal axis of the section I_{red} and distance from the axis to the extreme fibre in tension y_t:

$$W_{pl} = \frac{I_{red}}{y_t} \psi, \quad (12)$$

where ψ = 1.75 - the coefficient of plastic deformation.

The structural optimisation problem considered consists of the weight $W(\xi)$ minimisation of concrete and steel reinforcement used for the reservoir wall. The design variables ξ_i are: the wall thickness ($\xi_1 = h$) at the given volume (geometry) of the reservoir, steel class ($\xi_2 = E_s$, $\xi_3 = R_s$), concrete class ($\xi_4 = E_b$, $\xi_4 = R_{bt,ser}$). The entire problem can be expressed in terms of the design variables as follows: find a vector ξ such that

$$W(\xi) = \gamma_c 2\pi r l h + \gamma_s V_s \to \min, \quad (13)$$

subject it to behavioural constraints

$$G_j(\xi) = g_j^U - g(\xi) \ge 0, j \in Q_R \quad (14)$$

and side constraints

$$\xi_i^L \le \xi_i \le \xi_i^U. \quad (15)$$

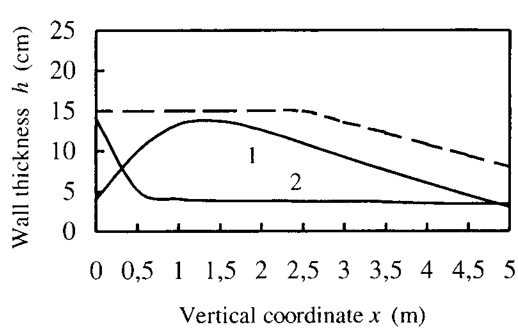
Here Q_R denotes the set of retained constraints, g_j^U is the upper bond to a response quantity $g(\xi)$; ξ_i^U and ξ_i^L are the upper and lower limit of the independent design variables, respectively; V_s is the volume of steel reinforcement, m³; γ_c and γ_s are the specific gravity of concrete and steel, N/ m³, respectively.

The analysis for fixed content and distribution of reinforcement with the vertical coordinate was performed. By using different combination of materials (strength classes of concrete and steel reinforcement), some convenient projects for reservoir with height of 5 m and diameter 10 m have been fixed. In Fig 1 the variants of analytical solution for the optimised reservoir wall thickness and recommended design thickness are shown. The predicted design wall thickness includes covering layer of reinforcement fixed in building codes [14].

The results were found for doubly reinforced wall by using steel bars (class A-II and A-III) with diameter 12 mm and uniform step (200 mm) in the vertical and horizontal direction. Because the price for steel reinforcement is the same for steel class A-II and A-III (≈ 225 USD/t) the optimisation of total weight was performed by using the weight of concrete depending on the strength class of concrete and steel. The weight of concrete is represented by wall thickness of reservoir. In Fig 2 isoclines of the wall thickness h for the lover part of the wall with material strength (R_s , $R_{bt,ser}$) are shown.

Cost is of wider practical importance of the structure, but it is difficult to obtain sufficient data for the construction of a real cost function. Real cost includes the cost of materials, fabrication, transportation, etc. In addition to the cost involved in the design and construction, other factors such as operating and maintenance costs, repair and assurance costs may be considered. Because the cost of the structure is proportional to its weight, the objective function can represent the weight $W(\xi)$.

a)



b)

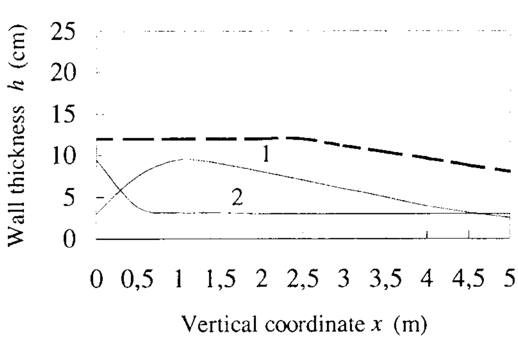


Fig 1. Effect of tensile force (1) and bending moment (2) on wall thickness vs vertical coordinate:
a) steel class A-II, concrete class B25;
b) A-III, B50; - - predicted profile

The selection of materials presents a special problem with conventional materials, as they have discrete properties, eg, a choice is to be made from a discrete set of variables. In practical design, it is necessary to represent design variables as discrete variables with quantities predefined in codes. Based on results shown in Fig 2, there is a possibility to determine the effect of concrete and steel strength on the total volume of concrete. In Fig 3 the relationships of wall thickness with concrete resistance in tension for different grades of steel strength are shown.

In case of steel class A-III in comparison with A-II the economy of concrete volume for the given strength class of concrete is less than 10%. Economical solutions can be reached by using combinations of concrete and steel with high-strength classes. By using concrete of class B50 and steel of class A-III instead of B25 and A-II the decrease of concrete total volume is 39%, although the

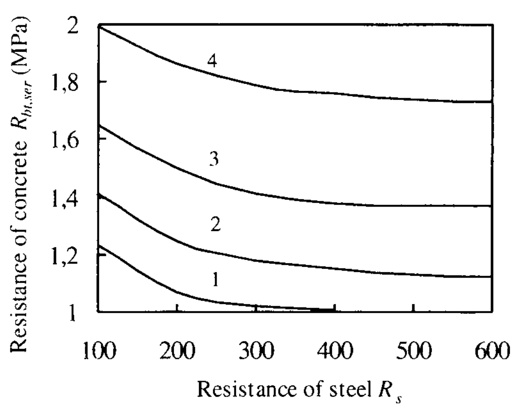


Fig 2. Isoclines of wall thickness h (cm) of reservoir for N_{max} = 250 kN: 1 – h = 21.0, 2 – 18.0, 3 – 15.0, 4 – 12.0

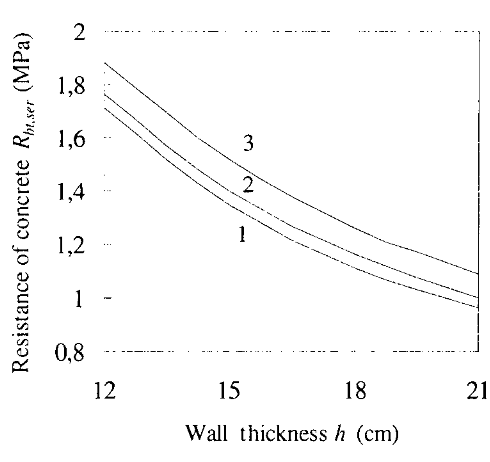


Fig 3. Variation of wall thickness vs concrete resistance in tension depending on steel resistance R_s (MPa): 1 – 600, 2 – 400, 3 – 200

increase of material cost is 8%. Nevertheless, taking into account the costs of transportation and concrete pouring economy is the case with high strength materials.

4. Conclusions

Based on constitutive relationships, the stress state in the wall of reinforced concrete reservoir is determined. The optimum quantities of the main parameters of reservoir wall are fixed taking into account strength and serviceability limit state requirements.

Taking into account discrete quantities for material properties and technological regulations according to building codes, the optimisation of reservoir wall thickness is performed. Based on results obtained, it is determined that economic solutions can be reached by using combinations of concrete and steel with high strength classes.

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