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Floating platforms made of monolithic closed rectangular tanks

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Abstract. The paper concerns closed monolithic rectangular tanks produced in one stage (one technological process without interruptions or dilatations) that function as floating platforms in inland waters. It presents an analysis of static work of the above-described tanks subject to the hydrostatic load of walls and bottom as well as the uniform load of the upper plate. Calculations were made with the use of the finite difference method in terms of energy, assuming the Poisson's ratio $\nu = 0$. Based on the obtained results, charts are provided that illustrate the variation of bending moments for the characteristic points of the analysed tanks as per specific workloads. The paper also provides test calculations for buoyancy, stability and the metacentric height for one type of the tank that was produced for the study. In this case, in addition to the above-mentioned loads, the calculation also took into account load temperature and ice load floe. The paper presents photographs taken when launching a pontoon prototype.

Key words: floating platforms, rectangular tanks, hydrostatic load, temperature load, ice floe load, bending moments, definite difference method.

1. Introduction

Rectangular tanks are typical spatial systems made of plates that are their constituent elements. The theory of plates is now practically completely developed. There is a wealth of literature on this subject that is duly specified in paper [1].

However, literature on the static work of rectangular tanks and related calculations is still relatively deficient. Few publications include the results of static calculations on specific open rectangular tanks or analyse the distribution of internal forces induced by various loads, such as e.g. temperature [2]. Due to the lack of full insight into the static work of rectangular tanks, these structures are often defective in practice. Numerous cases are described in monograph [3]. Paper [2] specifies e.g. a certain characteristic, which consists in changing the sign of the bending moment occurring in the upper part of the corner of the tank subject to thermal loading. Although it is known as the reason for the formation of cracking in the walls of the tank, the literature has not referenced it. Paper [2] also indicates that the temperature–borne bending moments occurring in rectangular tanks have higher values than those calculated from existing formulas given in the literature. The above ascertainment implies that the knowledge of statics of monolithic rectangular tanks remains insufficient, which also refers to closed rectangular tanks. Since solutions for monolithic closed rectangular tanks have not been found in the technical literature, this paper constitutes a vital contribution to a better understanding of such structures' statics.

The application of reinforced concrete tanks in the construction of floating platforms is still barely known and rarely described in the literature. Thus, to ensure the safe and comfortable use of water bodies, yacht ports and marinas shall need to be adequately designed and equipped. Berth of vessels and their maintenance should be carried out with scrupulous attention and aimed at protecting aquatic environment. Each yacht port, in order to be able to fulfil its assigned functions, must be equipped with certain hydro–technical structures for mooring, removing from and leaving vessels in water or completing their necessary repairs.

This paper concerns inter alia the issues related to equipping yacht ports with floating platforms. Wood, steel, aluminium, reinforced concrete, fiberglass and plastics are all among the various types of materials used for their production. The pontoon that is the subject of detailed calculation included in the paper was treated as a reinforced concrete rectangular tank produced in one stage at a prefabrication plant [4]. The technical literature and the manufacturers' commercial marketing materials present some concrete pontoon structures consisting of at least two mounting elements [5]. These pontoons are usually constructed from a box and a separately produced upper plate that are assembled at a later stage. Such method invariably opens up the possibility of inaccuracies during assembly works, followed by leaks and premature wear of the structure. The paper demonstrates that it is possible to design closed reinforced concrete tanks – pontoons – that can be implemented as monolithic structures in one production cycle (one step). The approach reduces the risk of leakage and assembly inaccuracies and shortens the time of putting the structure into use.

2. Calculation method

Monolithic rectangular tanks are characterized by three–dimensional static work. This expression implies that the load on one part of a structure causes displacement and stress in all compo-

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nents of the structure, even those that have not been exposed to loads. For instance, the load of the upper plate of the tank induces the formation of bending moments in both the bottom as well as in tank walls. Therefore, simplified methods should not be applied for calculation. Rectangular tanks should not be calculated as individual plate elements and from individual plates with later alignment of moments in individual cross–sections of the tank, for example by the Cross method. Static calculations for monolithic rectangular tanks can be made with the use of the finite difference method (FDM) or finite element method (FEM). FDM and FEM are equivalent methods applied to calculate plate statics, however, it seems that the form of static calculation results produced by FDM is better suited to carry out parametric analysis of the distribution of cross–sectional forces. With a built–in matrix of displacement equations, it is possible to obtain a solution for any structural parameters, e.g. any plate thickness, any value of E and ν, as well as for any loads, which are the second terms on the right side of displacement equations. Meanwhile, when using FEM, a change in one parameter would require complete new calculations.

Calculations presented in the paper were carried out with the use of the finite difference method in terms of energy. The method allowed for taking account of three–dimensional static work of the structure. The description of the method is included in numerous publications [6–11].

The analysis of static work in each case was carried out using the results of calculations obtained with the use of the energy functional stored in the deformable system, with the assumption of the Poisson's ratio $\nu = 0$, taken from [9], as shown in the formula set forth below (1).
Assuming $\nu = 0$ and the designations below:

$$w_{xx}^2 = \left(\frac{\partial^2 w}{\partial x^2}\right)^2, \quad w_{xy}^2 = \left(\frac{\partial^2 w}{\partial x \partial y}\right)^2, \quad w_{yy}^2 = \left(\frac{\partial^2 w}{\partial y^2}\right)^2,$$

$$w_{xx} = \frac{\partial^2 w}{\partial x^2}, \quad w_{yy} = \frac{\partial^2 w}{\partial y^2},$$

the formula is as follows:

$$V = \frac{D}{2}\iint\limits_A \left\{\left(w_{xx}^2 + 2w_{xy}^2 + w_{yy}^2\right) + 2\frac{\alpha_t \Delta T}{h}\left(w_{xx}^2 + {} \right.\right.$$
$$\left.\left. {} + w_{yy}^2 + \frac{\alpha_t \Delta T}{h}\right)\right\} dA + \frac{1}{2}\iint\limits_A K w^2 dA - \iint\limits_A p w dA \tag{1}$$

where:
w – deflection,
ν – Poisson's ratio,
$D = \left(Eh^3\right)/12$ – flexural rigidity of the plate,
ΔT – difference in temperature between lower plate T_d and upper plate T_g, determined by correlation: $\Delta T = T_d - T_g$,
α_t – coefficient of thermal expansion of the plate material,
h – plate thickness,
E – elasticity modulus of the plate material,
K – rigidity modulus,
A – plate area,
q – load perpendicular to the median plane of the plate.

Designing rectangular tanks that are intended to serve as floating platforms involves meeting the conditions of load–bearing capacity of structures as well as their buoyancy, stability and the metacentric height requirements.

3. Results of static calculations

Calculations included four types of closed rectangular tanks with the following proportion of axial dimensions:
– for tank No. 1 dimension ratios are $l_x : l_y : l_z = 1 : 1 : 0.5$,
– for tank No. 2 dimension ratios are $l_x : l_y : l_z = 2 : 1 : 0.5$,
– for tank No. 3 dimension ratios are $l_x : l_y : l_z = 3 : 1 : 0.5$,
– for tank No. 4 dimension ratios are $l_x : l_y : l_z = 4 : 1 : 0.5$,
where:
l_x – length of the tank,
l_y – width of the tank,
l_z – height of the tank.

The hydrostatic load of walls and bottom of the tank (a) and the uniform load of the upper plate of the tank (b) were assumed as standard loads. A schematic drawing of loads is shown in Fig. 1.

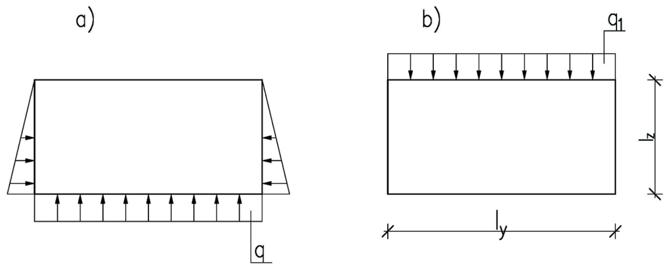

Fig. 1 Schematic drawing of the hydrostatic load of walls and bottom of the tank (a) and the uniform load of the upper plate of the tank (b) included in static calculations

Calculations assumed the same thickness of all walls of the pontoon. The walls were divided into mesh lines for elementary subdivisions. The mesh side length of the applied division mesh was $s = l_y/12$. The symmetry of the tank was applied to construct the matrix of displacement equations. Consequently, it reduced the number of unknowns in the resulting equation systems. For the particular tanks included in the series of types, equations with 247, 439, 631 and 823 unknowns, respectively, were obtained. Solving the equation systems provided the values of coefficients proportional to deflections (w_i) for each point of the applied division mesh. Based on these values, bending moments according to acting loads (M_{xi}, M_{yi}) were calculated for the selected points. The results are presented in Tables 1 and 2. A schematic drawing of the tank with the applied numbering of characteristic points is shown in Fig. 2.

Table 1
Summary of the values of coefficients proportional to deflections (w_i) and bending moments (M_{xi}, M_{yi}) at the selected points of the tank due to the hydrostatic load of walls and bottom, including multipliers related to tank dimension l_y

Analysed value	Multiplier	Dimension ratios $l_x : l_y : l_z$			
		1 : 1 : 0.5	2 : 1 : 0.5	3 : 1 : 0.5	4 : 1 : 0.5
w_1	$10^{-4}ql_y^4/D$	–0.0845	3.2329	5.0548	5.5228
w_2		18.8596	42.8607	47.4399	47.9231
w_3		–0.4793	–4.2560	–5.3191	–5.4956
w_4		–0.4795	–1.1199	–1.1337	–1.1335
M_{A1}	$10^{-2}ql_y^2$	0.0293	0.4881	0.4780	0.4537
M_{A2}		–3.7414	–6.2879	–6.6321	–6.6461
M_{B1}		0.0295	–0.0240	–0.0367	–0.0367
M_{B2}		–3.7413	–4.4726	–4.4770	–4.4768
M_C		–0.11076	0.21278	0.22140	0.22132
M_{x1}		–0.0052	0.1063	0.0523	0.0134
M_{y1}		–0.0052	0.2185	0.3880	0.4386
M_{x2}		2.1636	0.7598	0.1244	0.0119
M_{y2}		2.1636	5.2182	5.8006	5.8599
M_{x3}		–0.1329	–0.1255	–0.0297	–0.0047
M_{z3}		0.1272	–1.0935	–1.4625	–1.5259
M_{y4}		–0.1329	–0.2235	–0.2256	–0.2255
M_{z4}		0.1272	–0.0457	–0.0495	–0.0494

Table 2
Summary of the values of coefficients proportional to deflections (w_i) and bending moments (M_{xi}, M_{yi}) at the selected points of the tank due to the uniform load of the upper plate of the tank, including multipliers related to tank dimension l_y

Analysed value	Multiplier	Dimension ratios $lx : ly : lz$			
		1 : 1 : 0.5	2 : 1 : 0.5	3 : 1 : 0.5	4 : 1 : 0.5
w_1	$10^{-4}q_1ly^4/D$	21.2244	46.9597	51.9222	52.4582
w_2		1.7849	6.6893	8.8950	9.4193
w_3		–2.5512	–7.2013	–8.4011	–8.5982
w_4		–2.5512	–3.2691	–3.2844	–3.2842
M_{A1}	$10^{-2}q_1l_y^2$	–3.3122	–5.9025	–6.2673	–6.2830
M_{A2}		0.3893	0.8240	0.7926	0.7658
M_{B1}		–3.3122	–4.0909	–4.0961	–4.0958
M_{B2}		0.3890	0.2906	0.2769	0.2769
M_C		0.99115	1.35939	1.36897	1.36888
M_{x1}		2.3275	0.8145	0.1349	0.0133
M_{y1}		2.3275	5.5325	6.1573	6.2227
M_{x2}		0.1248	0.1571	0.0630	0.0149
M_{y2}		0.1248	0.4814	0.6931	0.7502
M_{x3}		–0.3277	–0.1474	–0.0334	–0.0053
M_{z3}		–0.7037	–2.2621	–2.6793	–2.7500
M_{y4}		–0.3277	–0.4292	–0.4314	–0.4314
M_{z4}		–0.7037	–0.8976	–0.9017	–0.9017

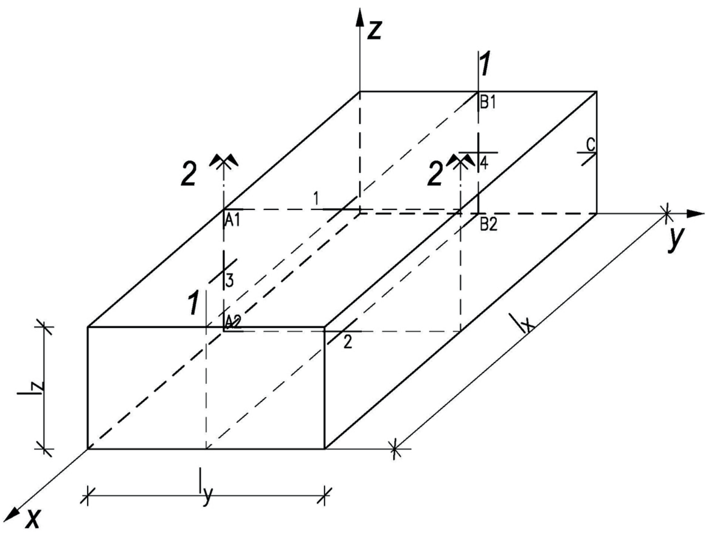

Fig. 2. Schematic drawing of the tank with the applied numbering of characteristic points and location of cross-sections

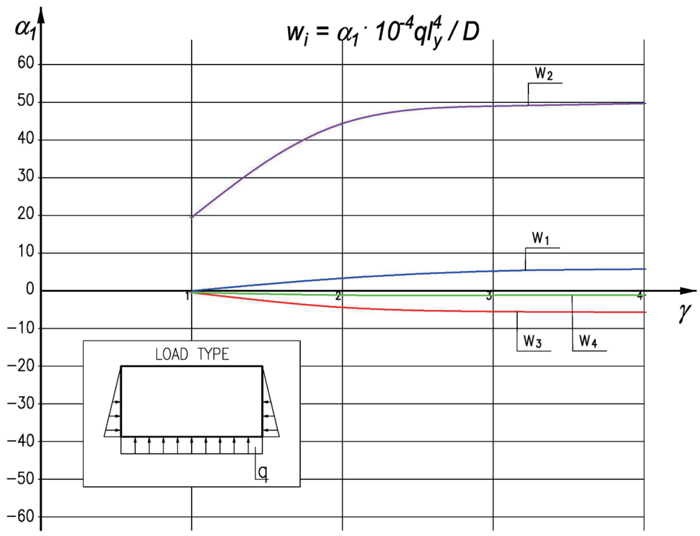

Fig. 3. Variation of deflections due to the hydrostatic load acting on walls and bottom (Fig. 1a) for four types of tanks with dimension ratios $l_x : l_y : l_z = \gamma : 1 : 0.5$ (numbering of points as per Tables 1 and 2)

On the basis of calculations made for the series of tanks with the same cross–section but different lengths, charts were drawn showing the variation of values for deflections and bending moments for the selected characteristic points of the tanks. The variation of deflections for the analysed loads (Fig. 1) is shown in Figs. 3 and 4, and the variation of bending moments

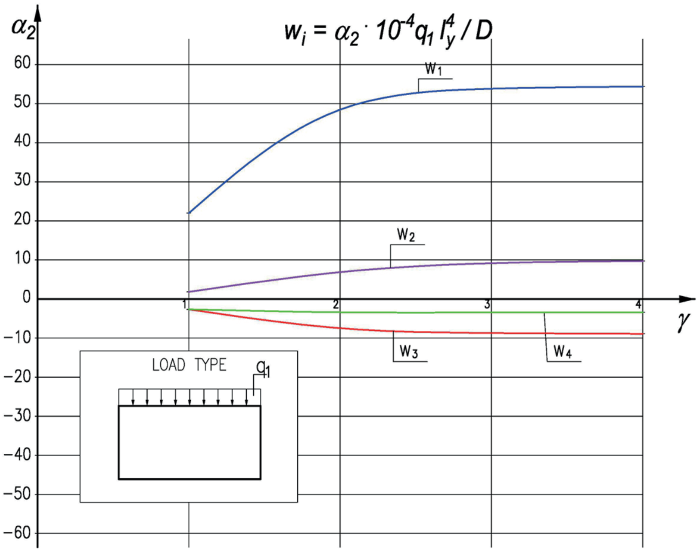

Fig. 4. Variation of deflections due to the uniform load acting on the upper plate of the tank (Fig. 1b) for four types of tanks with dimension ratios $l_x : l_y : l_z = \gamma : 1 : 0.5$ (numbering of points as per Tables 1 and 2)

in Figs. 5 and 6. The charts include the ordinate axes that present the coefficient values proportional to deflections (α_1 and α_2) and to bending moments (β_1 and β_2), respectively. The abscissa axes show the values of coefficient γ that depends on the proportion of the length of the tank to its other dimensions ($l_x : l_y : l_z = \gamma : 1 : 0.5$).

By analysing the charts drawn up for the load acting on walls and bottom of the tank with the hydrostatic thrust (Fig. 1a), it is found that the largest deflections and bending moments occur in the bottom plate. Deflections at point 2 and bending moments M_y^2, M_{A2}, M_{B2} both take almost constant values for coefficient $\gamma > 3$. The same observations apply to the upper plate of the tank that was loaded uniformly (Fig. 1b). Deflection at point 1 and bending moments M_{x1}, M_{y1}, as well as clamping moments M_A^1 and M_B^1 also take almost constant values for coefficient $\gamma > 3$. The above indicates that these plates (bottom and top plate) after taking value $\gamma > 3$ start working in one direction. For the purpose of further analysis of the static work of closed monolithic rectangular tanks with the same cross–section but different length, the charts of bending moments in longitudinal (1–1) and cross–sections (2–2) were made. The locations of bending moments are shown in Fig. 2. These charts are made

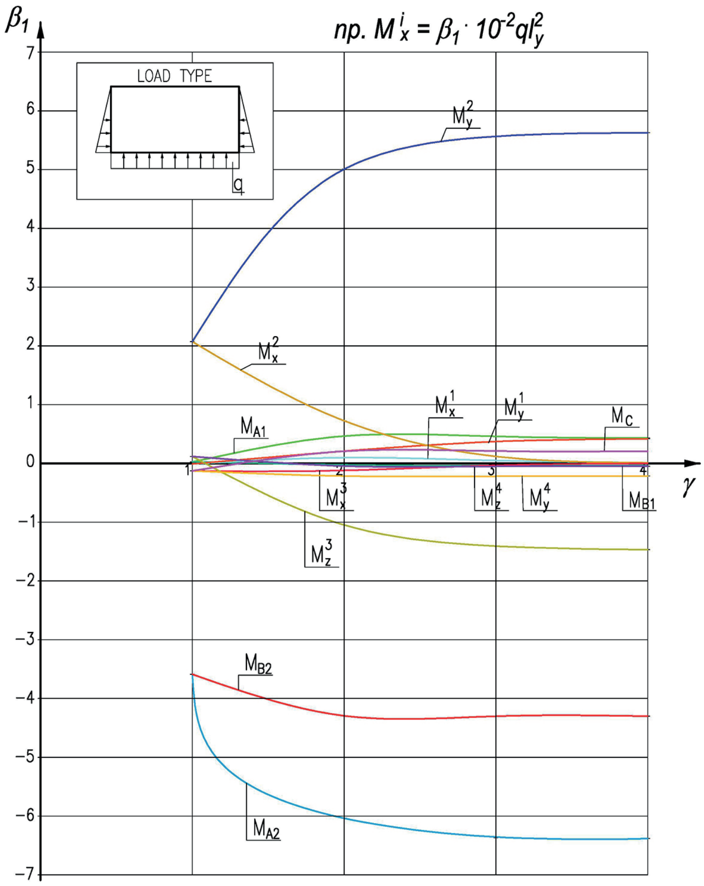

Fig. 5. Variation of bending moments due to the hydrostatic load acting on walls and bottom of the tank (Fig. 1a) for four types of tanks with dimension ratios $l_x : l_y : l_z = \gamma : 1 : 0.5$ (numbering of points and designation of bending moments as per Tables 1 and 2)

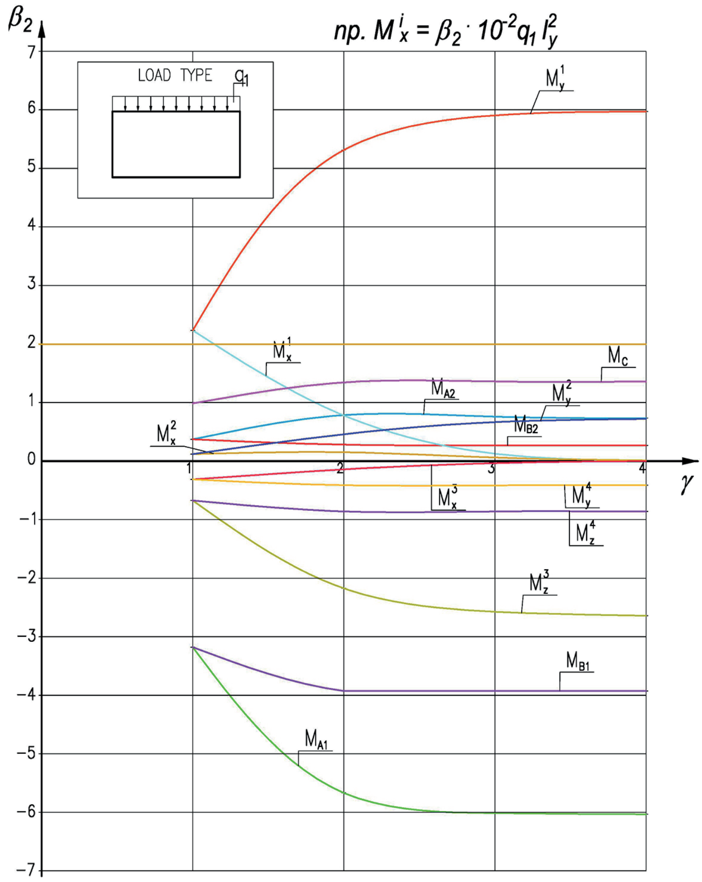

Fig. 6. Variation of bending moments due to the uniform load operating on the upper plate of the tank (Fig. 1b) for four types of tanks with dimension ratios $l_x : l_y : l_z = \gamma : 1 : 0.5$ (numbering of points and designation of bending moments as per Tables 1 and 2)

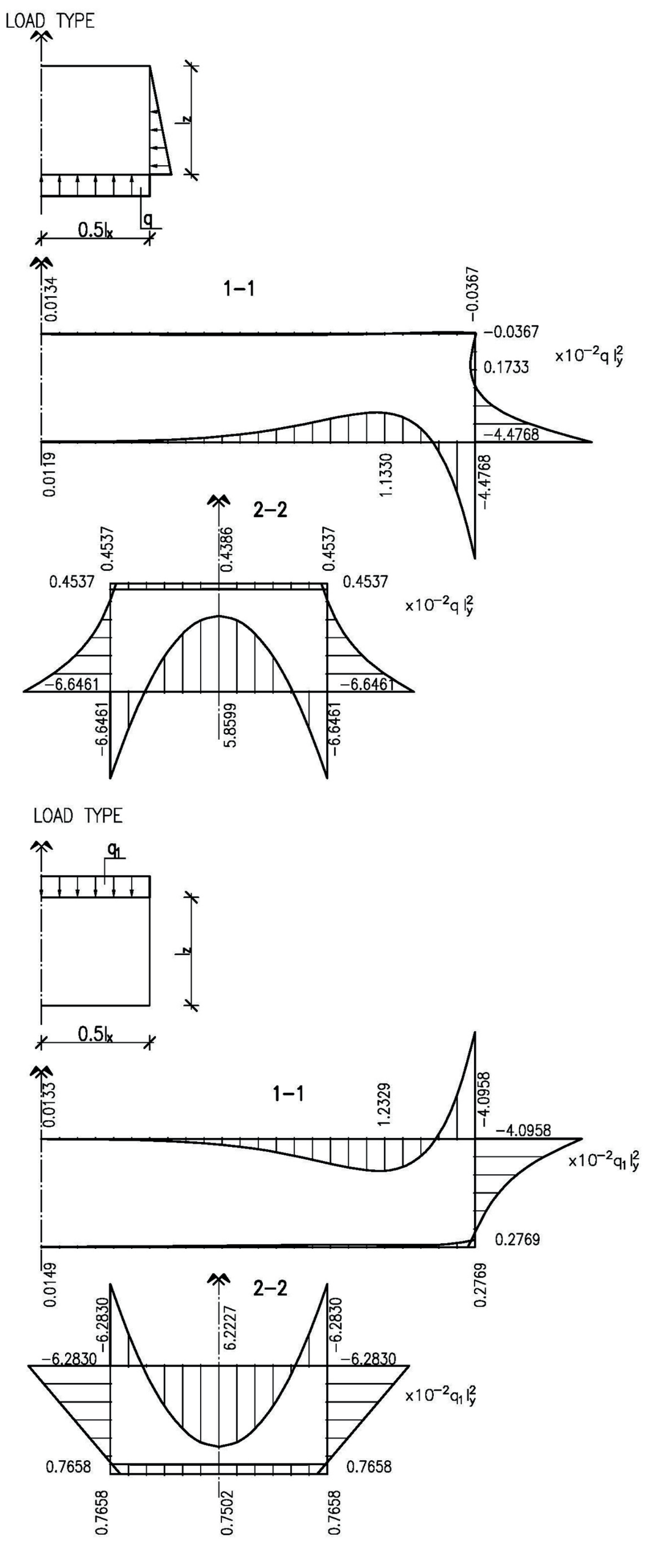

Fig. 7. Charts of bending moments for tank No. 4 due to the hydrostatic thrust acting on the walls and bottom as well as the uniform load acting on the upper plate of the tank in cross–sections 1–1 and 2–2, illustrated in Fig. 6

both for the hydrostatic thrust acting on walls and bottom (Fig. 1a) as well as for the uniform load acting on the upper plate of the tank (Fig. 1b). Figure 7 shows exemplary charts for tank No. 4 with dimension ratios $l_x : l_y : l_z = 4 : 1 : 0.5$.

By analysing the charts shown in Figs. 5 and 6, it can be concluded that when we take into consideration long tanks of dimension ratios $l_x : l_y : l_z = \gamma : 1 : 0.5$ for $\gamma > 3$, the impact of dislocations due to the interaction of end walls disappears in their central part. Thus, the central part works as a closed frame, in the same way as in a strut and tie model.

4. Prototype pontoon calculations

Design of floating platforms requires determining the dimensions and weight of the structure that provide for its adequate buoyancy and stability. An additional criterion to be met is a minimum freeboard height for a specific type of platform. In order to verify the theoretical considerations, a prototype pontoon with dimension ratios of $10 \times 2.5 \times 1.25$ m and wall thickness of 8 cm, was designed. It was also equipped with an internal partition. Under normal circumstances, the following loads act on the pontoon:

– hydrostatic load of walls and bottom of the tank when it is fully immersed,
– uniform load of the upper plate of the tank due to its dead weight and possible load resulting from a great number of people,
– uniform load of the bottom plate of the tank due to its dead weight,
– ice floe load of side walls during winter,
– thermal load of the upper surface of the tank.

The prototype pontoon was also tested for its buoyancy, stability and metacentric height on the basis of Australian standard AS 3962–2001 [12]. Polish regulations [13, 14] provide that pontoon buoyancy shall be tested assuming the crowd load of 3.0 kN/m^2 applied to the entire width of the platform, while its stability shall be verified with the value of 1.0 kN/m^2 applied to the half–width of it. The distance between the water level and the upper surface of the platform (a freeboard) should be at least 0.05 m, with the tilt angle of no more than 6° (according to [13]) and 10° (according to [14]). Calculations simplified by Australian standards [12] can be carried out for the tilt angle not exceeding 15°. A schematic drawing of the pontoon (cross–section) used in buoyancy testing is shown in Fig. 8.

During buoyancy testing of the designed pontoon with $h = 1.25$ m under its dead weight load and service load, the values of immersion depth $h_d = 1.02$ m and freeboard height 0.23 m were both calculated. A schematic drawing of the pontoon (cross–section) used in stability testing is shown in Fig. 9.

The stability of a pontoon determines the location of the metacentric point of the pontoon and its tilt angle. The metacentre is a theoretical point of intersection between the buoyancy force vector of a tilted vessel and its plane of symmetry. The distance between the point and the gravity centre of a floating body (e.g. a pontoon), the so–called metacentric height, is the stability centre of such a floating body.

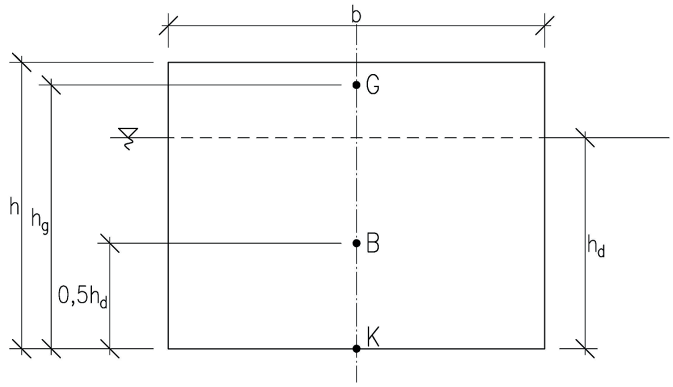

Fig. 8. Schematic drawing of a pontoon under constant load. Designations adopted in Fig. 8: G – gravity centre of the pontoon, B – buoyancy centre of the pontoon at rest, K – keel, h_d – immersion due to dead weight load, h_g – location of gravity centre

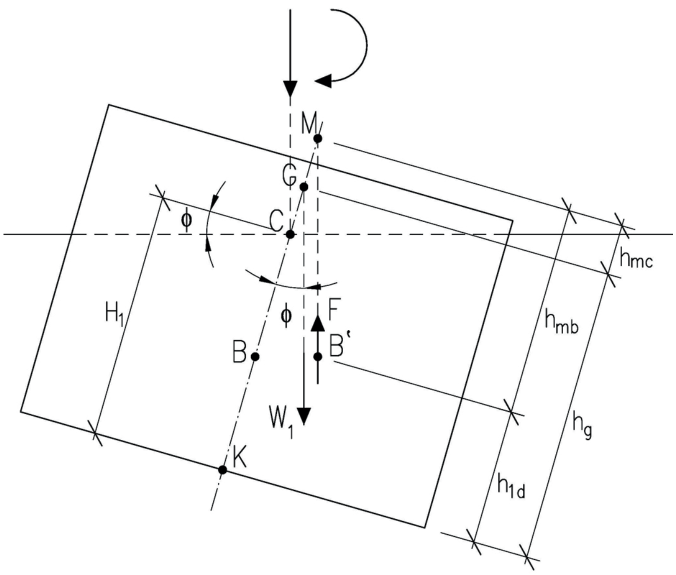

Fig. 9. Schematic drawing of a pontoon under constant and variable load. Designations adopted in Fig. 9: C – centre of the visible area of the water surface, G – gravity centre of the pontoon, M – metacentre, B – buoyancy centre of the pontoon at rest, K – keel, W_1 – total weight of constant and variable loads, B` – buoyancy centre of a loaded pontoon, F – floating forces in water, h_g – location of gravity centre, h_{mc} – metacentric height above the gravity centre, h_{mb} – metacentric height above the buoyancy centre, h_{1d} – height of the buoyancy centre

The gravity and buoyancy forces in a floating object (e.g. a pontoon) are applied to different points. When a floating object is not tilted, these two forces are in one line that is perpendicular to the level of water. When a floating object tilts under the influence of acting loads, the point at which the buoyancy force is applied dislocates in the direction of tilt occurrence. The vertical line, perpendicular to the water level and passing through the buoyancy force application point, determines the point that is called a metacentre at the intersection point with the symmetry axis of such a floating body (e.g. a pontoon). If the metacentre is above the gravity centre of the object, i.e. its metacentric height is positive, the balance of the floating body remains stable. If the metacentric height is negative, it alters the balance.

Stability testing of the prototype pontoon was carried out for its dead load and service load with the value of 1.0 kN/m^2 acting at the half–width of pontoon. A positive metacentric height with the value of 0.32 m was obtained for these loads. It means that the stability of the floating body was constant, and the tilt angle amounting to 6.9° met the requirements. The freeboard height was 0.30 m, which also fulfilled the minimum height requirements. The pontoon was made of C35/45 reinforced concrete and AIII (RB 400) reinforcing steel. Reinforcement was designed according to [15–17] as mesh with reinforcing bars of Ø8 mm spaced every 15 cm, placed inside the wall.

The prototype pontoon was tested for the acting load in the form of ice floe pressure.

Design linear load (strip load) caused by ice floe load was taken in accordance with recommendation Z20 [18]. Thus, in pursuance of [18], it is assumed that due to the expansion of solid ice resulting from changes in ice temperature, specific horizontal action q_{lk} from ice load acting on a hydro–technical structure in sheltered fresh waters is calculated based on the following formula (2):

$$q_{lk} = 200 \cdot h_1 \cdot k_r \tag{2}$$

where:
- h_1 – highest measured thickness of solid ice [m],
- k_r – impact coefficient of solid ice size (for an ice sheet width of less than 50 m $k_r = 1.0$, and for an ice sheet width of 90 m $k_r = 0.8$).

Design load values should be obtained by multiplying characteristic load values by load coefficient $\gamma_f = 1.3$. By comparing the maximum bending moment value resulting from the linear load applied in the middle of the tank height with the moment defining the load–bearing capacity of the tank wall resulting from the reinforcement and concrete class, the allowable thickness of ice floe was determined as 6.9 cm. Due to difficulties in predicting accurate weather conditions during the winter, recommendations for removing pontoons from the water for the season should be considered valid. The recommendation is provided by [5]. The referenced article [19] provides the values of cross–sectional forces of ice floe load acting on the pontoon, the load–bearing capacity of the tank wall resulting from the reinforcement and concrete class as well as the allowable thickness of ice floe.

The prototype pontoon was additionally tested for the load–bearing capacity of its walls assuming that the upper plate would be subject to the temperature load (a pontoon submerged in water is exposed to solar insolation only on the upper plate). Assuming, in accordance with standard [20], maximum temperature $T_{max} = 50°C$ and water temperature $T_w = 20°C$ for Wielkopolska in the summer, it was calculated that for a plate that is 8 cm thick, the difference in temperature between the upper and the lower surface is $\Delta T = 8.4°C$. On the basis of calculations, it is found that such temperature difference does not cause bending moments larger than the load–bearing capacity of the pontoon walls. The prototype pontoon is going to transfer acting loads, including temperature load, in a safe manner. In order to protect the pontoon's walls against cracking, the parameters of the applied reinforcement resulting from formula (7.1) [17] were verified. The required reinforcement surface $A_{s1,\,min}$ for the pontoon was 1.46 cm²/m. The authors used reinforced mesh with bars of Ø8 and 15 cm spacing, placed inside the wall, giving the total reinforcement surface $A_{s1} = 3.35$ cm². The reinforcement area used for the pontoon was approximately twice the value that resulted from formula (7.1) [17]. In order to check the pontoon for cracking occurrence, the values of bending moments appearing in the structure were compared with the value of cracking moment calculated according to formula (116) [16].

The cracking moment during bending is calculated by means of the following formula (3):

$$M_{cr} = f_{ctm} \cdot W_c \tag{3}$$

where:
f_{ctm} – average tensile strength,
W_c – section modulus.
The data for the pontoon walls are provided below:
- wall thickness: h = 8 cm,
- usable cross–section height: d = 4 cm,
- reinforcement: reinforced mesh with bars of Ø8 and 15×15 cm spacing,
- reinforcement surface: $A_{s1} = 3.35$ cm²,
- concrete class: C35/45, $f_{ctm} = 3.2$ MPa.

For the above data the value of cracking moment is $M_{cr} = 3.41$ kNm, whereas the cross–sectional capacity is $M_{Rd} = 4.42$ kNm. The comparison indicates that the value of cracking moment was lower than the value of cross–sectional load. In conclusion, there was no possibility of cracking occurrence in the design pontoon and no cracks were observed in the implemented pontoon.

5. Summary

The prototype pontoon was made of concrete class C35/45 in the formulation that provided appropriate concrete permeability and water absorption below 4%. Pontoon implementation proceeded as follows:
- formwork on the vibrating table was set to the height of the designed pontoon,
- reinforcement of the bottom and walls was made,
- after concreting the bottom, Styrofoam blocks were laid on unbound concrete; the blocks filled the entire pontoon interior,
- before concreting the walls, Styrofoam blocks were weighed down from the top to protect them against uplift pressure,
- after approx. 2 hours, the weight was removed from Styrofoam blocks, reinforcement of the upper plate was applied and concrete was laid,
- after 18 hours, formwork was removed from the pontoon and it was moved to a separate platform. There it matured.

The motivation to thoroughly scrutinise the application of closed rectangular tanks as floating platforms has arisen due to the absence of appropriate solutions in the technical literature. The pontoons used so far in Poland have been produced mainly on the basis of reinforced concrete rectangular tanks implemented under foreign solutions and licenses (Finnish, Norwegian, Swedish). The ideas presented herein demonstrate that such structures can be successfully implemented on the basis of local know–how. The tank (pontoon) produced in natural size with dimension ratios of 10×2.5×1.25 m proves that static calculations and sizing have been made correctly. The concrete formula developed and the technology of implementation adopted have allowed to produce the tank in one technological stage, without cracking and honeycombing. The solutions presented for closed monolithic rectangular tanks have confirmed that static calculations for this type of structure shall be carried out by methods that take into account spatial static work of structures, actual geometrical and material parameters as well as real loads.

6. Photographic documentation of prototype pontoon implementation

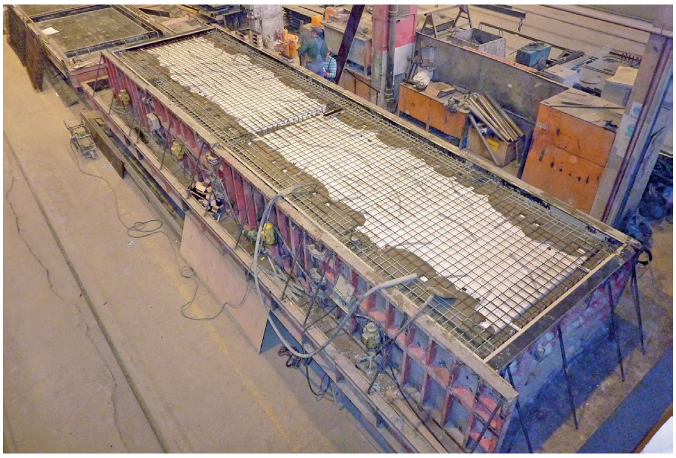

Fig. 10. Concreting of the upper plate of the pontoon

Fig. 11. Placing the pontoon on the adjacent working platform following removal of formwork

Fig. 12. Launching the pontoon

Fig. 13. View of the commissioned pontoon with the platform

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