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Analysis of structural solutions of reinforced concrete tanks used in agricultural farms

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Abstract

The article presents the types of the most common underground or partially sunken tanks used on farms. The analyzed tanks were designed for the storage of zoonotic fertilizers. Solid or semi-liquid fertilizers should be stored in livestock premises in sealed tanks, protected from leakage into the ground. Basic static schemes of tanks and types of loads acting on tanks were considered. The durability and leak-tightness of the tanks were also addressed, and the insulation used to protect the walls and bottom plate of the tanks was discussed. A computational example presents the values of loads acting on the various elements of the tank at two computational schemes, and compares the results obtained by two computational methods, i.e., the separated plate method and the finite element method. The discrepancies in the obtained results were pointed out. Recommendations were formulated for the design of tanks in terms of meeting the tightness criterion. FEM calculations were made for two cases: with and without consideration of the soil stiffness.

Keywords: organic waste tank, reinforced concrete structure, tightness, durability, FEM

1 Introduction

One of the European Union's requirements for farms is to reduce soil and groundwater pollution caused by nitrates from agricultural sources and to prevent further such pollution. Among the many environmental hazards arising on the farm, special attention should be paid to solid and liquid animal excrements. Natural fertilizers in solid form should be stored in livestock housing or on impermeable slabs, protected from leakage infiltration into the ground and equipped with a system that drains leakage into sealed tanks. Natural fertilizers in liquid form (slurry) should be stored only in sealed tanks. Each made tank needs a document confirming its good quality, especially in terms of its tightness.

The main requirements for the construction of the tank are as follows (according to Eurocode 2 [1], BN-84/8814-07 [2], PN-B-03264:2002 [3]):

- the tank should be designed in a way that ensures its tightness and durability [1, 4, 5],
- liquid manure is a medium or weakly aggressive environment towards concrete, which corresponds to exposure class XA1 or XA2 [4],

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- materials used for the construction of the tank should meet the requirements of relevant standards or technical approvals,
- the minimum class of concrete for the environment XA1 and XA2 according to (PN-EN 206:2014) [5] is C30/37, according to (PN-B-03264:2002) [3] for XA1 - C25/30, XA2 - C35/ 45, while according to (BN-84/8814-07) [2] it is C16/20 (recommended C20/25), and according to the Announcement of the Minister of Agriculture and Rural Development [6] class C16/20,
- the minimum required degree of waterproofness is W6,
- contacts between components of prefabricated tanks should be properly secured and sealed,
- structural reinforcement in the form of bars made of steel class A-IIIN, the ductility class C is recommended,
- reinforcement cover for XA1 and XA2 exposure class due to corrosion protection should be at least 40mm,
- permissible crack widths according to (PN-B-03264:2002) for elements operating in the XA1, XA2 environment to protect against corrosion are 0,2 mm, and for tanks that are required to be tight they are 0,1 mm,
- permissible crack widths according to (PN-EN 1992-3:2008 Eurocode 2) for tightness class 1 depend on the height of the water column h_0 and the wall thickness h (w_{k1}=0,2 mm for $h_0/h \leq 5$; w_{k1}=0,05 mm for $h_0/h \leq 35$) and deformation fluctuations resulting from changes in load and temperature $\Delta\varepsilon \leq 150 \cdot 10^{-6}$.

The work will present the currently used types of tanks for organic fertilizers, basic static schemes, types of loads acting on the tank, tank insulation solutions and a calculation example of a monolithic tank with variant consideration of the soil stiffness.

2 Currently used tank solutions

For the storage of animal manure in liquid form on farms, underground or partially buried tanks are most often used. The advantage of these tanks is the possibility of gravity discharge of manure from buildings and manure slabs into the tank. The ceiling above the underground tank can be used as an area for manure storage. In such a case, ventilation and inspection hatches should be provided in the upper plate and slopes of min. 1% to allow liquid feces to be discharged. The difficulty in the construction of these tanks is the fact that in the case of a high level of groundwater, it is necessary to lower their level for the period of the tank construction, as well as to make appropriate seals, which is associated with additional costs. Tanks for storing natural fertilizers can have the shape of a rotating solid - a cylinder with a vertical axis of rotation, the so-called cylindrical tanks or they can be rectangular tanks. The slab covering the tank intended for manure storage should be provided with retaining walls located on the edge of the slabs. The analyzed tanks are made of various materials and can be divided into monolithic reinforced concrete, prefabricated reinforced concrete, steel, PVC-based plastics or reinforced fiberglass. The most common are monolithic and prefabricated reinforced concrete tanks.

3 Computational static schemes and loads of monolithic reinforced concrete tanks

The following computational static schemes of underground tanks for animal waste can be distinguished: distribution scheme (Fig. 1a), spatial scheme (Fig. 1b).

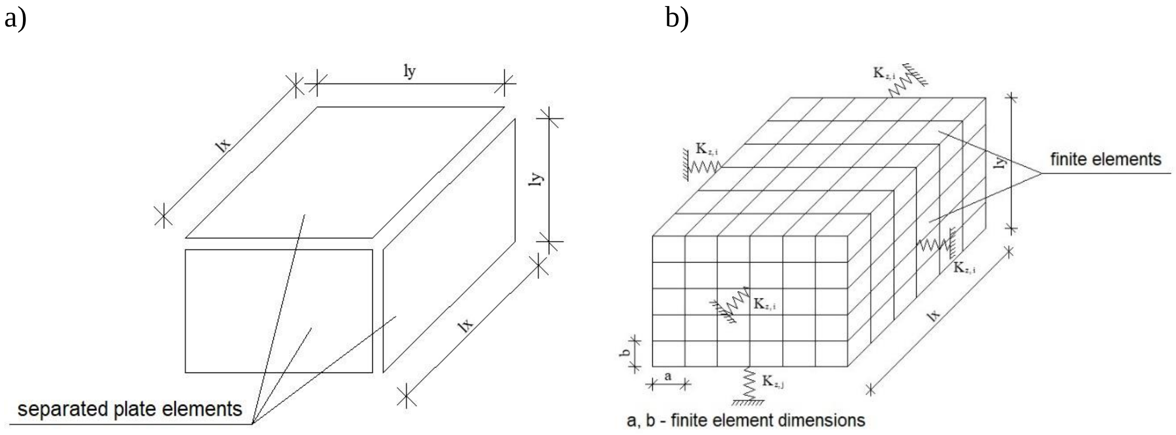

Figure 1. *Distribution diagram (a) and spatial diagram with finite element mesh (b)*

In the distribution scheme, the calculations are carried out using the isolated plate method. The analysis consists in considering the structural elements of the tank (walls, bottom plate, top plate) as bidirectionally bent plates, assuming, depending on the expected technology of execution, free support, or complete fastening of the relevant edges. Thanks to this method, it is possible to determine the bending moments and deflections of rectangular slabs with different support conditions resulting from the adopted design solution. It is also important to remember about the need to equalize the edge moments in the case of rectangular tanks with different dimensions of the adjoining walls.

Monolithic rectangular tanks should be calculated using methods that allow for considering their spatial static work [7] as well as actual dimensions and material data. Finite difference method (FDM) or finite element method (FEM) can be used here. Using the finite element method (FEM), a finite element mesh is created and, by performing a computational analysis, the values of forces, bending moments and deflections are determined at any point in the structure (Fig. 2).

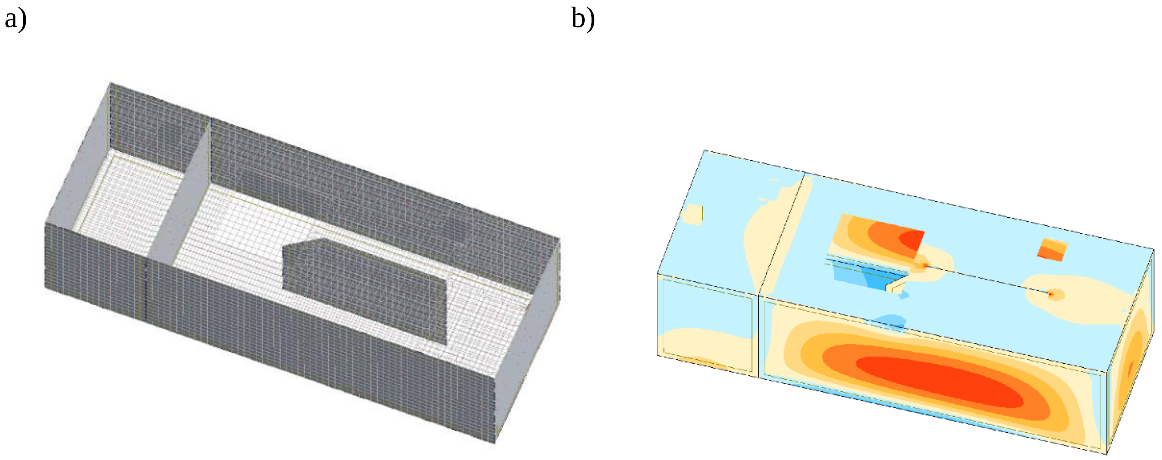

Figure 2. *Scheme of a two-chamber tank: a) spatial arrangement of elements, (b) diagram of bending moments*

When calculating the tank using the finite element method (FEM), one should consider the soil stiffness, supports with one-sided constraints, differentiation of stiffness, change in stiffness caused by cracking, stiffness degradation, various types of loads [8], including possible explosion loads [9].

For both static schemes, the following types of connections can be distinguished between structural elements of the tank (Fig. 3):

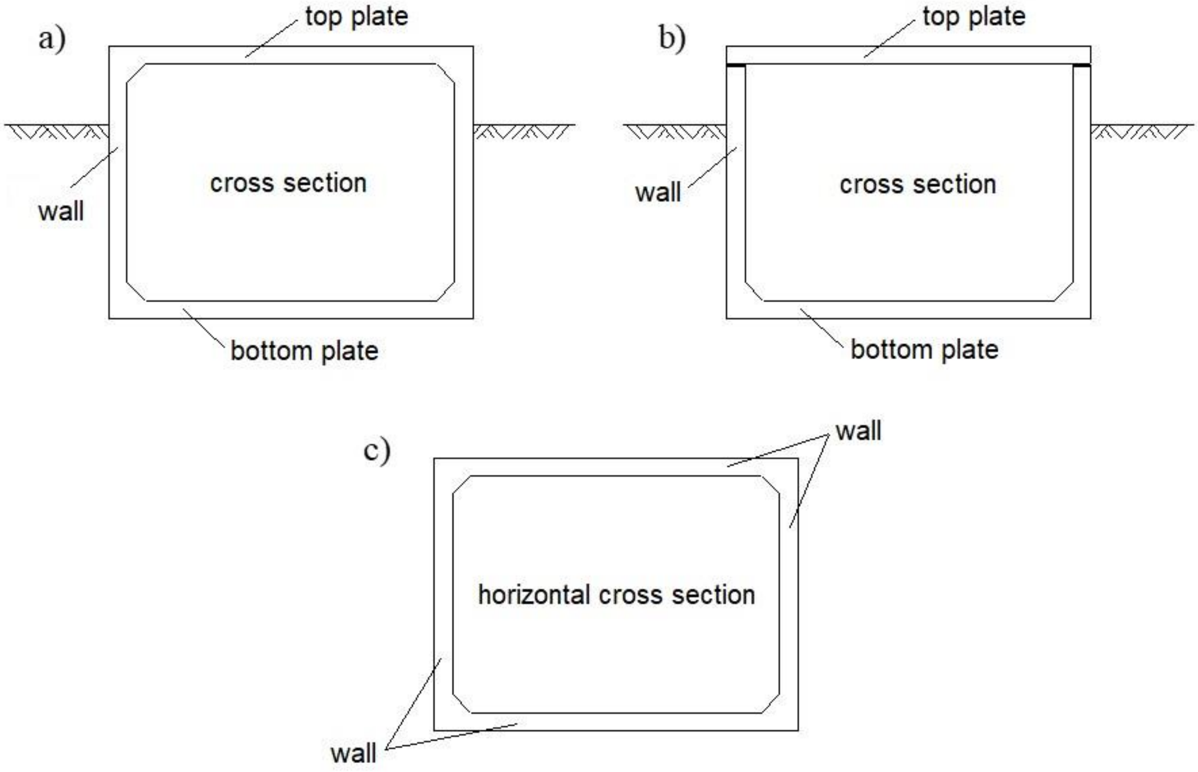

Figure 3. *Types of connections between structural elements of a monolithic tank:*

a) rigid connection of the tank walls with the bottom plate and the top plate, b) rigid connection of the tank walls with the bottom plate and hinged connection of the tank walls with the top plate, c) rigid connection between the tank walls

When designing underground tanks for liquids, we can consider two main load schemes. The first scheme concerns an uncovered tank filled with liquid, while the second one concerns an empty tank covered with soil. For the first scheme, the following loads acting on the tank should be considered:

- load of the cover plate with its own weight,
- liquid (slurry) load on the walls of the tank and the bottom plate,
- loading of the bottom plate with the ground resistance caused by the tank's own weight.

For the second scheme, the following loads must be considered:

- loading the top plate with its own weight,
- loading the top plate of the tank with soil (if the top plate of the tank is buried in the ground),
- operating load, and in the case of vehicle traffic, the load caused by vehicles according to [10], the standard [11] is also helpful,
- load of the top plate with snow,
- load on the walls of the tank with backfill soil, in the calculations, it is assumed that resting pressure acts on the tank,
- load of the bottom plate with soil resistance.

In the case of high groundwater levels, it is very important to check the tank for its stability due to water buoyancy. In addition, the load on the bottom plate and walls caused by water pressure should also be considered [12].

An important factor causing additional forces that should be considered when designing tanks is concrete shrinkage and ambient temperature fluctuations [4, 7, 13, 14, 15 18, 19]. Higher class concretes are characterized by greater shrinkage. This is important for the proper selection of reinforcement. It should be noted that according to the standard [5] slurry tanks should be made of concrete of at least C30/37 class, and according to the Announcement of the Minister of Agriculture and Rural Development [6] of concrete of C16/20 class.

4 Solutions that ensure durability and tightness

The external and internal protection of the structural elements of the tank depends primarily on the exposure class, the degree of aggressiveness of groundwater, ground and water conditions and the type of stored liquid.

To ensure adequate durability and tightness of the tanks, the basic activity is to determine the exposure class depending on the environmental conditions according to [5], and then select the concrete class and cover thickness according to [1]. In addition, the standard [5] indicates the minimum amount of cement, and the standard [4] specifies the maximum crack width. These issues are described in [16].

It should be noted that the requirements set in [4, 5] due to the durability of tanks are much more stringent than in [2, 10] or [6]. The construction of tanks based on the requirements set out in [1, 4, 5] ensures longer durability of the objects, which was discussed in the article [17, 20, 22].

To ensure durability and tightness, in addition to the standard requirements, it is worth following the rules [23]:

a) protection against penetration: ensuring adequate concrete tightness, impregnation, application of coatings, transmission of cracks through joints, use of membranes, and in the case of damaged tanks, surface crack closure, crack filling,
b) limiting moisture,
c) increased resistance to physical factors: possible abrasion, impacts,
d) resistance to chemical agents.

The basic action to ensure adequate durability and tightness of tanks is to limit the width of cracks or prevent their formation [24, 25]. A detailed method of checking cracks is given in [26].

In tanks buried in the ground, coatings applied to structural elements can be used, which can provide additional protection or protection of the structure against the aggressive impact of the environment. The inner surface of the tank is protected by various types of reactive resins, which form a tight coating on the inside of the tank. The cured coating is flexible, abrasion resistant and resistant to weathering and chemicals, especially slurry. On the outside, two coats of bitumen are generally sufficient. When the ground water table is high, waterproofing compounds are used.

If gravity drainage is possible, drainage around the tank and the entire bottom is generally used. Drainage is used to drain groundwater seeping from the ground level and rainwater. Drainage is necessary when you want to permanently lower the level of ground water or protect against its periodic rise above the level of the tank bottom [26].

A particularly dangerous situation may arise when the tank is located on cohesive soils and the backfill of the tank is made of non-cohesive soils. The incoming groundwater can completely fill the space between the cohesive soil and the tank, filling the pores in the backfill soil, so that the tank, which does not consider the additional pressure on the walls and bottom plate caused by groundwater, may be damaged or pushed upwards.

5 Example of the calculation of the tank in the monolithic version

Calculations were made for a tank completely submerged in the ground of a monolithic structure with the following axial dimensions: width 4,5 m, length 6,0 m, height 2,0 m. A retaining wall 1,5 m high made on the top plate of the tank was also provided. The structural elements of the tank: the top plate, walls and retaining wall are 20 cm thick, and the bottom plate is 30 cm thick. It is a slurry tank. The foundation level of the reservoir was set at -2,00 m below ground level. The tank is placed on dusty clay in a plastic state with a degree of plasticity $I_L = 0{,}43$. After the tank is completed, the walls will be covered with medium sand with $I_D = 0{,}49$. The tank was calculated by two methods. Two load schemes were adopted when calculating the tank using the separated plate method (Fig. 4a). In the finite element method (FEM), the elastic work of the subsoil was additionally considered for the tank walls and the bottom plate (Fig. 4b).

When calculating for scheme I, the following load values were considered:

- top plate (snow load, dead weight of the top plate),

- walls (pressure of liquid - slurry),
- bottom plate (snow load, dead weight of the top plate, liquid-slurry pressure, load from the dead weight of the retaining wall, load from the dead weight of the tank walls).

The method of application of loads is shown in (Fig. 5a).

When calculating for scheme II, the following load values were considered:

- top slab (dead weight of the top slab, manure load),
- walls (ground load from a motor vehicle, soil push load),
- bottom plate (dead weight of the top plate, load from the dead weight of the retaining wall, load from the dead weight of the tank walls, manure load),
- retaining wall (manure load).

The method of applying loads is shown in (Fig. 5b).

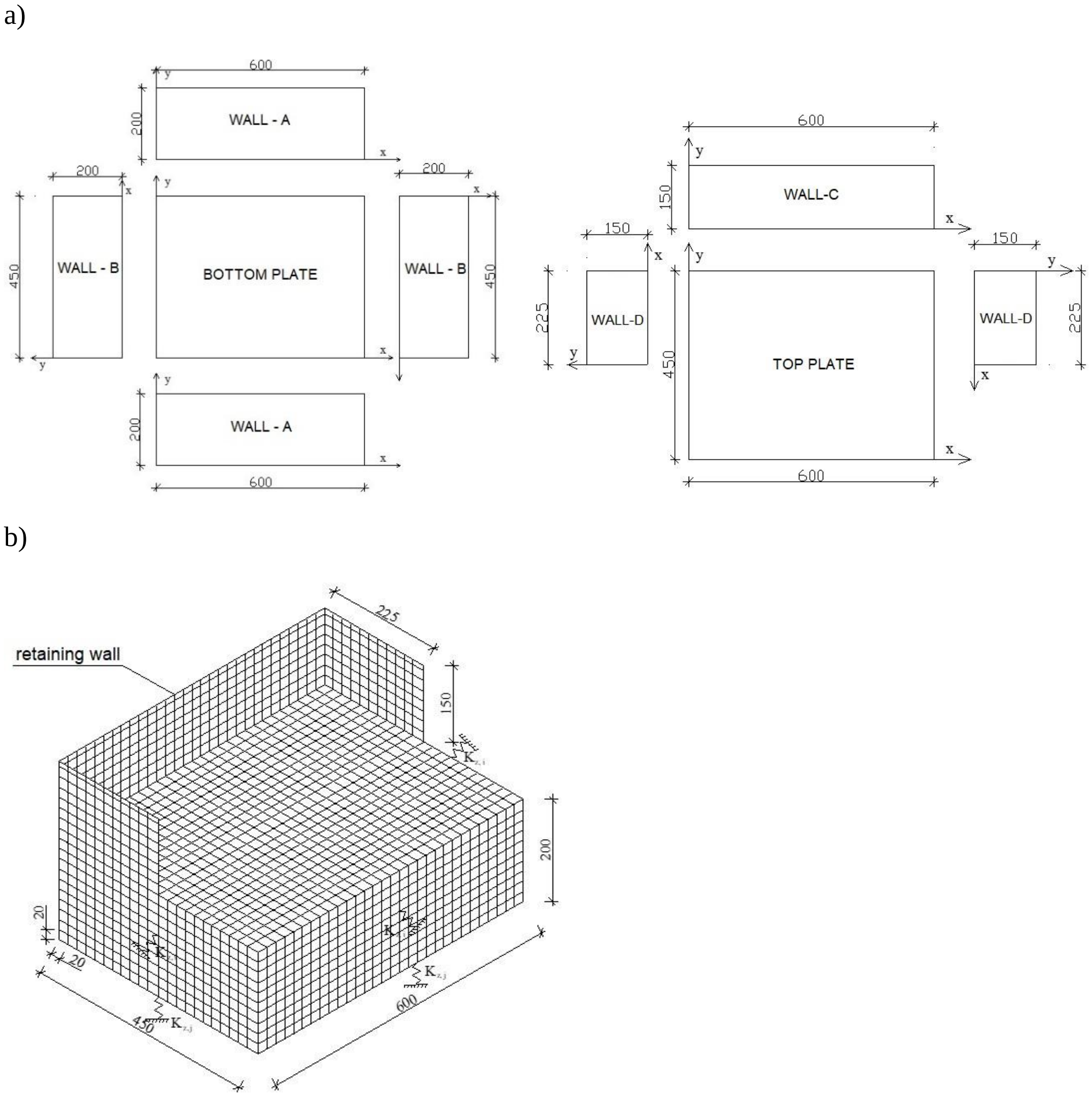

Figure 4. *Structural elements of the tank in the isolated plate method (a) and discretization of the finite element method (b)*

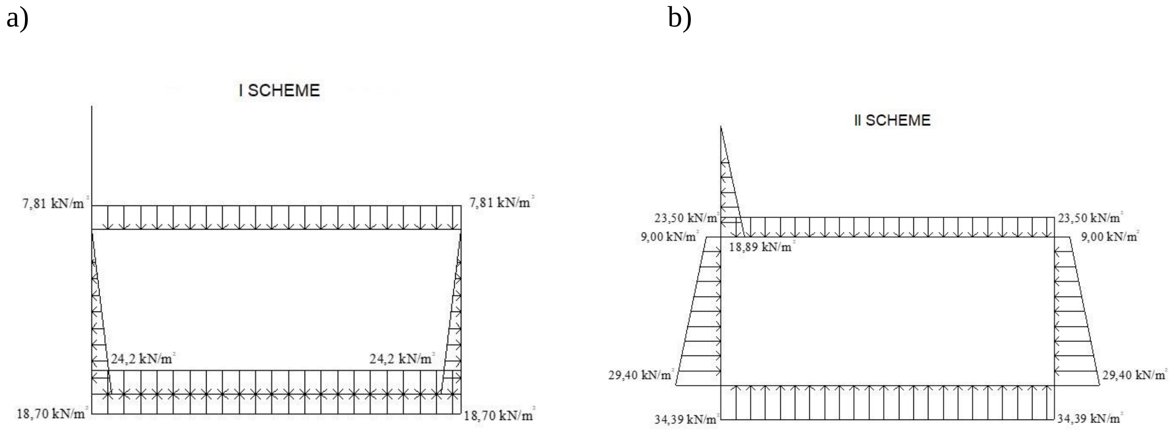

Figure 5. *Loads acting on the tank in the I and II load schemes*

For the calculations, the height of the manure was 1,5 m and the volumetric weight $\rho = 10kN/m^3$. The volumetric density of the backfill soil is $\rho = 17kN/m^3$.

In the case of the second load scheme, a uniformly distributed load with a constant value over the entire surface of the top plate was assumed.

Calculations were carried out using the separated plates method with the equalization of edge moments using the appropriate separation coefficients [27].

A plate fixed at the perimeter was taken as the static schemes when calculating walls, A, B, the top plate and the bottom plate. Slab C was calculated as a slab fixed on three edges with a fourth free, while slabs D were calculated as fixed on two edges with the other two free.

To compare the obtained results, the comparisons shown in tables 1 and 2 were made.

No.	Element	$M_x[kNm]$				$M_y[kNm]$				
		support moment		span moment		support moment		span moment		
		separated plates method	FEM	separated plates method	FEM	separated plates method	FEM	separated plates method	FEM	
I load scheme										1
1.	WALL – A	-2,88	-3,24	+0,50	+1,22	-10,74 -4,70	-8,25	-5,58 +2,11	-	
2.	WALL – B	-2,88	-3,36	+0,50	+1,34	-6,81 -3,20	-6,51	-1,59 +3,67	-	
3.	TOP PLATE	-6,81	-6,67	+4,72	+5,26	-10,74	-7,23	+9,59	+6,25	
4.	BOTTOM PLATE	-3,20	-4,72	+0,60	+1,62	-4,70	-5,22	+1,99	+2,63	
5.	WALL – C	-0,09	-2,08	+0,07	+0,65	-0,06	-2,06	+0,04	-	
6.	WALL – D	-0,09	-2,03	-0,04	+0,32	-0,05	-2,42	+0,03	-	
II load scheme										
7.	WALL – A	-7,72	+5,23	+3,17	+2,64	-29,27	-46,48	-11,39	-	

						-45,01		-24,24	
8.	WALL – B	-7,72	+5,16	+0,87	+1,42	-18,71 -28,56	-33,29	-0,83 -7,89	-
9.	TOP PLATE	-18,71	-20,12	+11,66	+12,87	-29,27	-24,08	+24,25	+18,38
10.	BOTTOM PLATE	-28,56	-32,97	+19,39	+20,80	-45,01	-45,54	+39,50	+42,65
11.	WALL – C	-1,75	-2,25	+0,36	+1,16	-2,91	-3,17	+1,20	-
12.	WALL – D	-1,75	-2,20	+0,32	+0,61	-2,39	-4,60	+0,86	-

Table 1. *Summary of moment values calculated by the separated plate method and by the finite element method without taking into account the soil stiffness*

No.	Element	$M_x[kNm]$				$M_y[kNm]$			
		support moment		span moment		support moment		span moment	
		FEM	FEM soil stiffness	FEM	FEM soil stiffness	FEM	FEM soil stiffness	FEM	FEM soil stiffness
I load scheme									
1.	WALL – A	-3,24	-4,63	+1,22	+1,30	-8,25	-9,12	-	+4,59
2.	WALL – B	-3,36	-4,61	+1,34	+1,31	-6,51	-7,64	-	+3,63
3.	TOP PLATE	-6,67	-8,26	+5,26	+6,73	-7,23	-6,21	+6,25	+4,22
4.	BOTTOM PLATE	-4,72	-2,48	+1,62	+0,13	-5,22	-1,93	+2,63	+0,09
5.	WALL – C	-2,08	-2,62	+0,65	+1,00	-2,06	-2,92	-	-1,23
6.	WALL – D	-2,03	-2,63	+0,32	+0,42	-2,42	-3,32	-	-1,13
II load scheme									
7.	WALL – A	+5,23	-1,85	+2,64	+0,07	-46,48	-2,60	-	-0,20
8.	WALL – B	+5,16	-1,73	+1,42	+0,05	-33,29	-2,31	-	-0,24
9.	TOP PLATE	-20,12	-36,32	+12,87	+16,94	-24,08	-29,07	+18,38	+10,04
10.	BOTTOM PLATE	-32,97	-0,06	+20,80	-0,02	-45,54	+0,41	+42,65	-0,08
11.	WALL – C	-2,25	-1,97	+1,16	+0,13	-3,17	-5,81	-	+0,15
12.	WALL – D	-2,20	-1,97	+0,61	+0,22	-4,60	-3,77	-	+0,32

Table 2. *Summary of the values of moments calculated by the finite element method with and without taking into account the soil stiffness*

Graphically, the results obtained using different methods for the top plate and the bottom plate are shown in Fig. 6.

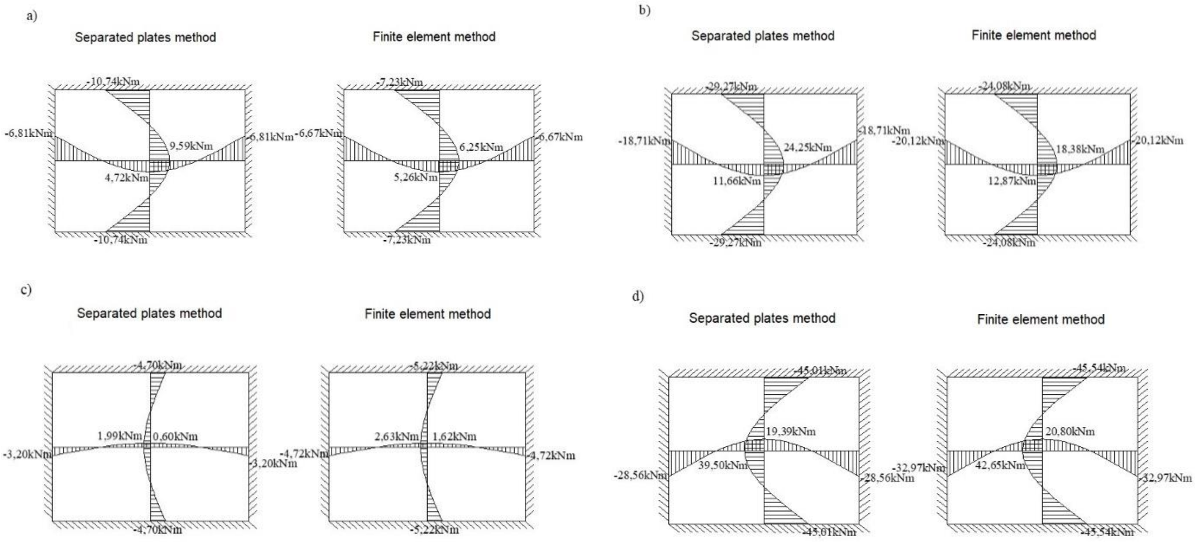

Figure 6. *Comparison of moment diagrams calculated by the separated plate method and the finite element method (FEM) without taking into account the soil stiffness: a) top plate I scheme (it was assumed that the retaining walls are unloaded), b) top plate II scheme (it was assumed that the retaining walls are unloaded), c) bottom plate I scheme, d) bottom plate II scheme*

6 Summary

Comparing the values of moments calculated by the separated plate method and the finite element method without considering the soil stiffness, the results differed by about 10-15%. This difference is because the calculation methods are different, and in addition, different values of Poisson's ratio (ν=0,00 according to [28] and ν=0,20 in the computer program) are included in the calculation program and in the tables [27]. On the other hand, in the second case of finite element calculations without consideration and when the soil stiffness is considered, it is noted that in the elastically supported elements the support moments have reduced their values mainly in the bottom plate by about 30-35%. For safety reasons, it is necessary to design tank elements adopting higher values of moments. Considering the elasticity of the soil substrate significantly alters the strain on these elements and regroups the internal forces. Similar observations can be found in the work of [7] and [8, 28]. It may be difficult to adopt the appropriate parameters regarding the stiffness of the soil under the tank. The right approach will be to calculate the internal forces for several variants, considering different parameters of the subsoil, and then to analyze the impact of the variability of the subsoil parameters on the obtained results.

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