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Effects of Soil Modulus and Flexural Rigidity on Structural Analysis of Water Intake Basins

Hassan Akbari [a*]

[a] *Department of Civil Engineering, Tarbiat Modarres University, Tehran, Iran.*

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Abstract

A water intake basin is a buried box that functions as a water reservoir near shorelines. Number of these structures has been increased in the recent years and for a safe design, it is necessary to know their behaviour under applied loads. In addition to common dead, live and seismic loads, the bottom of such a basin is usually located below sea water level and endures uplift pressure as well as reaction of supporting soils. Uncertainty of these special loads complicates the structural response of this buried basin to the applied loads. Therefore, the unreliability in the soil parameter and in the rigidity of the basin structure is studied in this research by calculating the generated internal bending moments. Different loads and load combinations have been taken into account and finite element analysis is carried out for modelling nonlinear behaviour of different types of supporting soils. It is concluded that the geometry and flexural stiffness of the basin affects the analysis more than the soil parameters because the contribution of the soil modulus in the total stiffness of the system is negligible than the structural rigidity of the basin structure. In addition, inner walls and geometry of the basin should be modelled in detail to obtain acceptable results.

Keywords: Soil Modulus; Water Intake; Rigidity; Bending Moment.

1. Introduction

In recent years, water consumptions have been increased due to development of industrial activities as well as extension of urban areas. Although demand of potable water has been expanded, the source of water is limited and its consumption should be done with special attentions. Desalination plants near seas are cost effective and reliable methods for establishing the required source of water [1]. In these systems, the sea water comes to a water intake basin through marine pipes and then the water is pumped from the basin to the required destination. Destination can be a plant or a crowded area with industrial or urban activities. Seawater intakes can be classified to submerged and buried intakes [2]. In a submerged intake, water comes to a basin through offshore pipes and in a buried intake system, water passes through screens and drilled wells. The capacity of the latter case is limited; however, a submerged system is applicable in different conditions and it is a common practice for providing required waters for industries. A chamber structure is usually used at offshore and water comes to inland basin through pipes. A desalination system has different parts including a water intake and an effluent outfall. There are some criteria and studies for the intake and outfall conditions [3, 4] and different shapes of the offshore chamber is investigated [5], but studies for the structural behavior of the intake basins is limited. This basin is actually a buried structure because its bottom level is under the sea level and the water comes to the basin by gravity. The basin acts as a box with interior walls and soil pressure as well as water pressures exert on the exterior walls. In addition, the bottom slab should resist against uplift force and soil reaction. Analysis of this structure is complicated because it is a combined system of solid, water and soil. The thickness of the bottom slab is usually uniform and the soil beneath the intake basin support the basin with reaction forces. In addition to the bearing capacity of the base soil, differential and total settlements also control the design [6]. Although the thickness of the bottom slab affects differential settlement and bending moments, its effect on the total

* Corresponding author: akbari.h@modares.ac.ir

settlement is little. The maximum bending moment may be increased with increasing the slab thickness [7], but, the effect of the slab thickness on the maximum bending moment is decreased by increasing the slab thickness nearly more than 1.5 m [8].

Since modeling the soil beneath the basin structure can affect the total behavior of the basin, it is important to know the sensitivity of the analysis to the assumed soil parameters. It should be noted that there are usually considerable uncertainties in the soil parameters. Therefore, the effects of soil modulus on the behavior of an intake basin are investigated in this study by analyzing the basin under different loading conditions and by assuming different soil parameters. In addition, the effect of the rigidity of the bottom slab is studied. The soil beneath the basin is modeled via nonlinear springs and the results are also compared with the results of simplified models which assume a fixed support condition instead of nonlinear soil reactions.

2. Analysis Procedure

2.1. Geometry and Modelling

To study an actual case, the geometry of the basin is selected based on an actual case. The 3D geometry of the basin with two horizontal sections is presented in Figure 1. Plan view and dimensions are shown in Figure 2. As presented in this figure, Length, width and height of the analyzed sea water intake are 48.55 m, 22.3 m and 13.0 m, respectively. Inner walls of the basin act as separators for water flows and their lengths are different based on their locations. Sea water comes into the basin from the side with smaller width and pumps are located at the side with the larger width. The thicknesses of roof, floor, inner walls and outer walls are 0.8 m, 1.5 m, 0.6 m and 1.0 m, respectively, yet the thickness of the bottom slab is also changed to study the effect of the its rigidity. Four node, isotropic shell element are used in the utilized finite element software (Sap2000-14.2.4) for modeling both interior and exterior walls as well as roof and floor slabs. Dimensions of the Basin and modeling conditions are presented in Table 1.

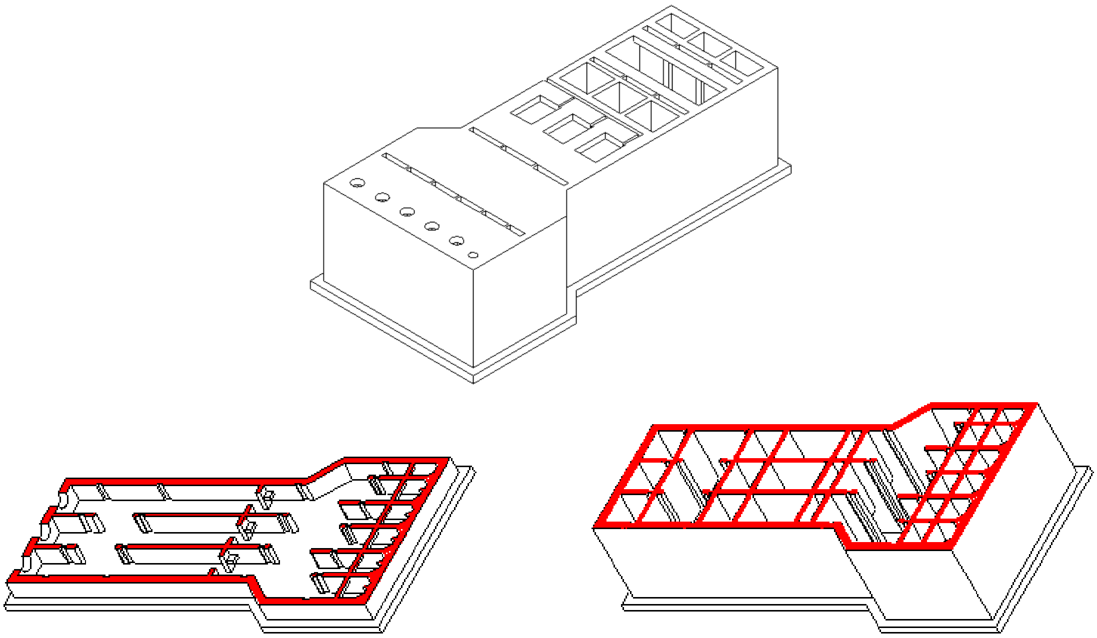

Figure 1. 3D geometry of the basin and two horizontal sections at different levels of the basin

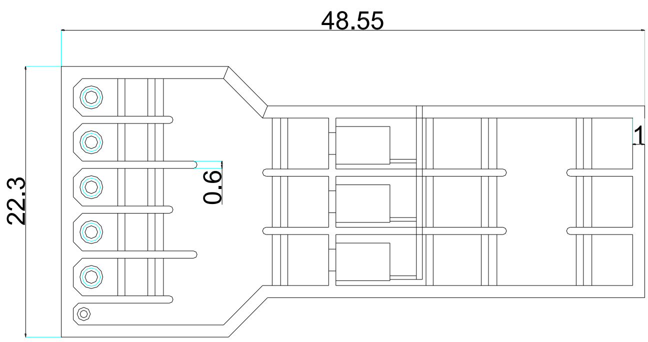

Figure 2. Plan view of the basin with dimensions

Table 1. Geometrical dimension of the basin and elements used for modeling

Geometry	**Length of sea water intake**	**48.55 m**	
	Width of sea water intake	22.3 m	
	Top of floor level	-7.0 m (CD)	
	Top of roof level	+5.5 m (CD)	
Model	Shell elements for modeling	Thickness	No. of elements
	Roof	0.8 m	9337
	Floor (supported on springs)	1.5 m	10481
	Inner walls	0.6 m	27185
	Outer walls	1.0 m	21521

Since the basin floor is located on the bed, the soil beneath the basin structure is modeled via nonlinear springs with a compressive behavior. According to the physical nature of contact between basin floor and bed, the springs can only endure the compressive forces and they cannot act in tension. The following Figures show the model geometry. To consider the effect of concrete cracking in analysis, module of elasticity has been decreased by a factor of 0.35 according to [9]. The model geometry is shown in Figure 3. and the applied classification for the shell elements i.e. inner walls, roof, exterior walls and foundation, respectively are shown in Figure 4.

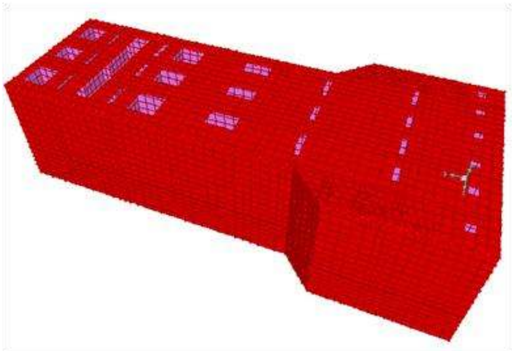

Figure 3. 3D modeled geometry of the basin

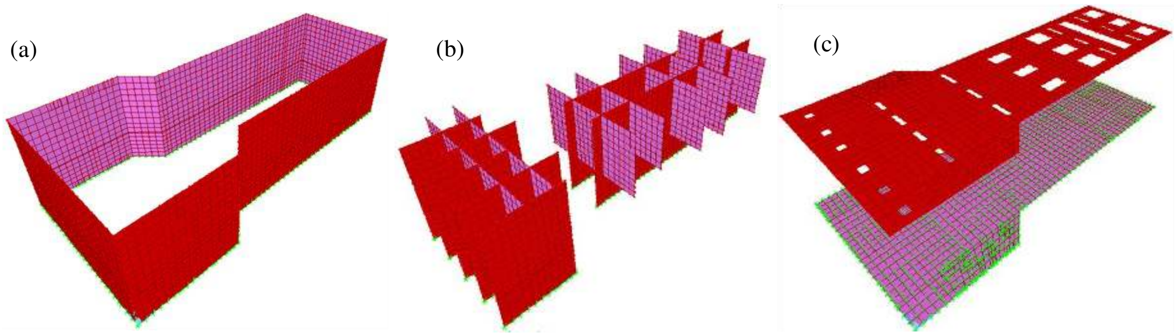

Figure 4. Classifications of shells in the modeled basin; a) outer walls, b) inner walls, c) roof and floor

2.2. Modulus of Soil Sub-grade Reaction

Soil beneath the basin supports the vertical and lateral movement of the structure. Assuming a fixed support is the simplest way for modeling the soil support. However, the better way is to model the actual behavior of the soil by making use of either nonlinear Winkler foundation or elastic continuum [10]. In Winkler model which is implemented in this study, the base soil assumes to behave like infinite number of springs that their stiffness is the modulus of subgrade reaction. By modeling the soil strata, the soil pressure beneath the basin will be obtained by analysis. Since assuming a rigid foundation is a common assumption in conventional modeling of mat foundations, the reliability of conventional methods is investigated in the present study for different soil parameters. To do this, the Finite element analysis is utilized as an effective and accurate way for analyzing the basin under applied loads. Since the sensitivity of the results depend on the soil parameters, different values of soil modulus have been taken into account. A wide range of values has been recommended for the modulus of subgrade reaction for various soil types and, the exact value of subgrade module at each location should be determined by field test [11]. If not, it can be calculated based on the equations derived based on plate load test [12] and estimates the subgrade modulus as a function of soil parameters [13, 14]. Several equations have been suggested for evaluating subgrade modulus, one of them is the empirical equation recommended by [15] as $k = (40\ to\ 50) \times su$, for clay and $k = (70\ to\ 100) \times NSPT$, for sand. In these equations, k is subgrade modulus [t/m^3], su is undrained shear strength (t/m^2) and NSPT is value of Standard Penetration Test. Finally, typical values for different types of soils can be evaluated as the values in Table 2.

Table 2. Typical values of modulus of sub-grade reaction (ks) for different types of soils

Type of Soil	Loose sand	Medium dense sand	Dense sand	Clayey medium dense sand	Silty medium dense sand
ks (MN/m^3)	5 to 15	15 to 60	60 to 130	30 to 80	20 to 50

In this study, to consider uncertainty of soil condition, different values of soil modulus are modeled in a way to cover different types of soils. For this purpose and based on the typical values, soil modulus are selected as 10, 50, 100 and 130 MN/m^3. A fixed support condition is also modeled as the highest possible stiffness of the base soil.

2.3. Loading

Several combinations of dead, live, hydrostatic, seismic, soil pressure and thermal load act on the structure. Dead loads include the weight of basin structure, attached equipment and accessories. The weight was calculated based on the density of the reinforced concrete as 2400 kg/m^3. Live load is the load superimposed by the use and operation of basin. The following items were considered as live load: Maintenance and equipment hatch load (uniform load) = 1000 kg/m^2, Personal load (uniform load) = 500 kg/m^2. The Hydrostatic load varies linearly with height of the water and it acts perpendicular to the surfaces. The uplift pressure applied to the basin floor is the maximum water pressure with a uniform distribution. Seismic load is evaluated based on Iranian standards for marine structures [16].

Static method is utilized for calculating the inertia effects of earthquake on internal forces and displacements. For conditions of earthquake occurrence, it is considered that the basin is in operation state and it is full of water. The Earthquake coefficient for this condition is considered to be 0.16 ($= 0.13 \times 1.2 \times 1.0$) [17]. This coefficient cross the effective weight generates the earthquake force that is applied to the structure in two directions. Dead load plus 20% of live load is considered as the effective weight in calculating seismic load. In addition, seismic load may generate unbalanced water pressures inside the basin. To consider this effect, 30% of the dead weight is added to the above mentioned effective weight during earthquake and the total weight cross the earthquake coefficient is applied as the earthquake force. It should be noted that the weight of the water inside the basin is applied in the model in the seismic condition when the weight of the structure becomes important. Soil pressure around the basin is evaluated based on the supposed specific gravity and apparent gravity of the soil. Soil pressure is assumed equal in both seismic and ordinary conditions. The lateral soil pressure coefficient is assumed as k_0=0.45. Thermal Loads are defined as a force caused by variation of temperature and it is not considered in this study.

All the loads are combined based on [9] as presented in Table 3. An envelope combination is also determined to show the maximum stresses among different load cases. In addition to common load combinations, some special notes have been taken into account. For example, it may be required during operation to close the stop logs an empty the basin for maintenance or cleaning the basin. In this case, the uplift exerted on the bottom of basin can generate a critical state that governs design of the floor section of the basin foundation. In another case, the internal water pressure is not applied on the exterior walls and only the outer face of these walls are subjected to the hydrostatic pressure from the water outside the basin. In this manner, water pressure acting on the outer face of the exterior walls will not be balanced with the interior pressures and a critical condition is obtained that governs design of the exterior walls. To consider the worst case, MLHW level is considered for evaluating the lateral water pressure on the exterior and interior walls. Therefore, 3.0 m of the basin top is located above the sea water level. In a normal operating condition, hydrostatic pressures act on both sides of an interior wall and it do not generate a bending moment in the interior walls. However, when a section needs repair and it is done by closing the sluice gates, the hydrostatic water pressure is applied to the interior walls of the full sections of the basin. Meanwhile, the external forces applied to structure in this state are as same as the previous condition. The bending moment due to this condition can govern design of internal walls.

Table 3. Load combinations that are used for structural analysis of basin

Load Comb.	Dead Load	Live load	Water Pressure outside	Water Pressure inside	Uplift Pressure	Soil pressure	Earthq. X or Y Dir.
1	1.40						
2	1.40	1.70			1.70		
3	1.40	1.70	1.70		1.70		
4	0.90		1.275		1.275		
5	1.40	1.70	1.70		1.70	1.70	
6	1.40	1.70	1.70	1.70	1.70	1.70	
7, 8, 9, 10	1.05	1.275	1.275	1.70	1.275	1.275	±1.40
11, 12, 13, 14	0.90						±1.40
Envelope	Maximum output of all other combinations						

3. Effect of Soil Modulus

The structure of the basin is analyzed under different load combinations and the maximum bending moment in each element is obtained from the envelope combination. A sample output corresponding to the subgrade reaction modulus of 100 MPa/m is presented in Figure 5. that shows the distribution of the maximum bending moments in two perpendicular directions i.e. M11 and M22 in different elements of the bottom slab. As shown in this figure, the maximum bending moment per unit length of the bottom slab is nearly 200 tonf.m/m. The average value of the maximum bending moments as well as the standard deviation of these values can be calculated. The average value of the bending moment in this case is nearly 17 tonf.m/m and it can be useful in evaluating the adequacy of the thickness of the bottom slab. These maximum, averaged and standard deviations of the maximum bending moments in the bottom slab are calculated for different cases with different subgrade modulus.

The results are shown in Figure 6. According to these results, the averaged value of the bending moment is significantly less than the maximum value which is generated in a local point of the bottom slab. Since the soil modulus are selected based on loose to hard conditions, it can be concluded that the maximum bending moment in the bottom slab is not too sensitive to the soil modulus, however, a harder soil condition results in a lower bending moment value. The limit condition happens when a fixed support is modeled for the base reaction modeling. The averaged value is more sensitive to the changes in soil condition and it has been changed from the maximum value of 19 tonf.m/m in a loose soil to a minimum value of 10 tonfm/m in a hard soil condition. On the other hand, the standard deviation of a hard soil condition is clearly less than softer soil conditions. The effect of soil modulus on the averaged bending moment in different walls is presented in Figure 7. As shown in this figure, the bending moment in the bottom slab is clearly a function of soil modulus. The reason is that the slab is directly supported on soil and its behavior is more sensitive to the soil condition. However, the averaged bending moment in outer walls, inner walls and roof is independent to the soil modulus because stiffness of the intake is dominant to the soil condition.

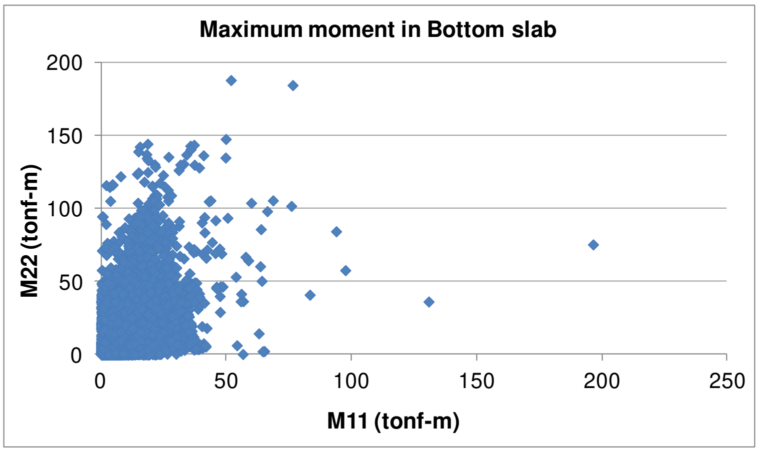

Figure 5. Bending moment in elements of the bottom slab in the envelope load combination

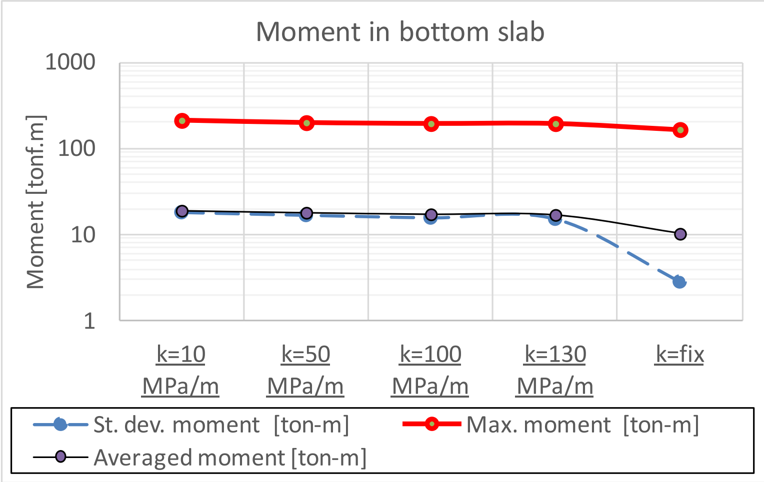

Figure 6. Averaged, standard deviation and maximum bending moment in the bottom slab with different subgrade modulus

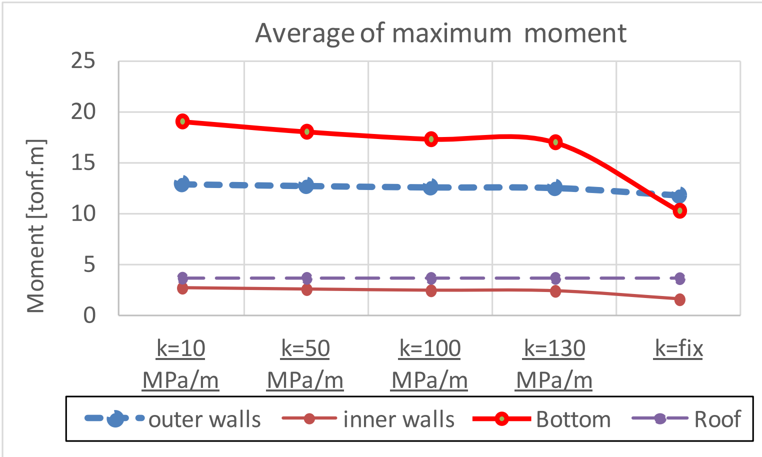

Figure 7. Averaged bending moment in different walls with different subgrade modulus

4. Effect of Bottom Slab Rigidity and Inner Walls

To study the effect of the existence of inner walls on the generated bending moment in the basin, two different structures with and without inner walls are analyzed by taking into account two different soil conditions with soil modulus of 10 and 100 MPa/m. The results i.e. averaged bending moment in different walls and slabs are presented in Figure 8. As shown in this figure, in the case of removing the inner walls, bending moment in all the shells (outer walls, roof and bottom slab) has been increased. The maximum effect is yet in the bottom slab where the averaged bending moment in the case of a structure without any inner wall is nearly twice the averaged bending moment in the case of existence of inner walls. The bending moment in the roof is also increased significantly by removing the inner walls. The minimum effect, however, has been occurred in the outer walls. Actually, the inner walls increase the rigidity of bottom slab and roof sections clearly and the length between the stiff supports will be decreased accordingly.

The outer walls are not supported on the inner walls and therefore, they experience fewer amounts of changes due to removing inner walls. On the other hand, the effect of soil stiffness on the averaged bending moment is little especially in outer walls and roof slabs. The bottom slab is the only shell element type that its bending moment is a function of soil stiffness. However, the effect of inner walls on the generated bending moment is clearly more than the effect of the soil condition. It is worth mentioning that the effect of soil condition on the averaged bending moment is limited only to the bottom slab and this effect is yet less than the effect of inner walls. In a soft soil condition, the existence of inner walls is more important in controlling the bending moment in bottom slab because the contribution of inner walls in the total stiffness is higher than its contribution in a stiff soil condition. As shown in Figure 9, the averaged bending moments in the bottom slab of a structure with inner walls are nearly the same for two soil conditions. However in the case of removing inner walls, the bending moment in the bottom slab has been increased nearly 30% in the case of the softer soil condition.

In addition to the inner walls, rigidity of the bottom slab depends on the thickness of the foundation. To evaluate this item, two different thicknesses i.e. 0.5 m and 1.5 m have been modeled for the shell elements at the bottom slab.

The results are presented in Figure 9. The thickness of the bottom slab does not affect the averaged bending moments in other walls and its effect is limited only to the bottom slab itself. A thicker slab absorbs a higher bending moment in a way that by increasing the thickness by three times, the generated averaged bending moment has been increased by the same order.

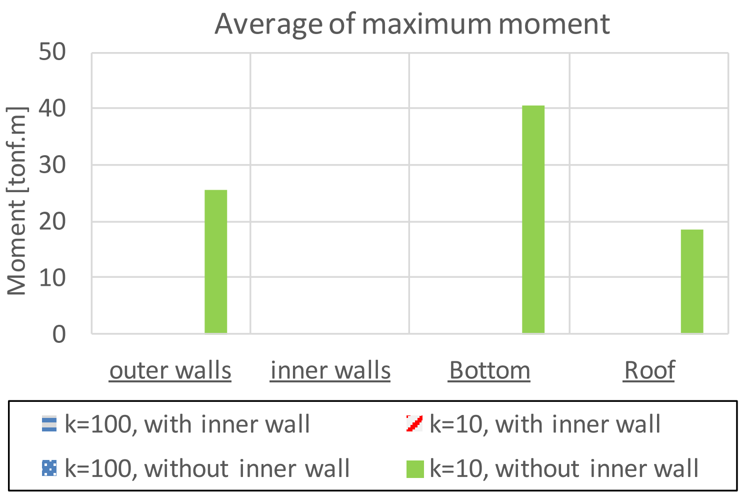

Figure 8. Averaged bending moment in different walls with and without inner walls and two different subgrade modulus

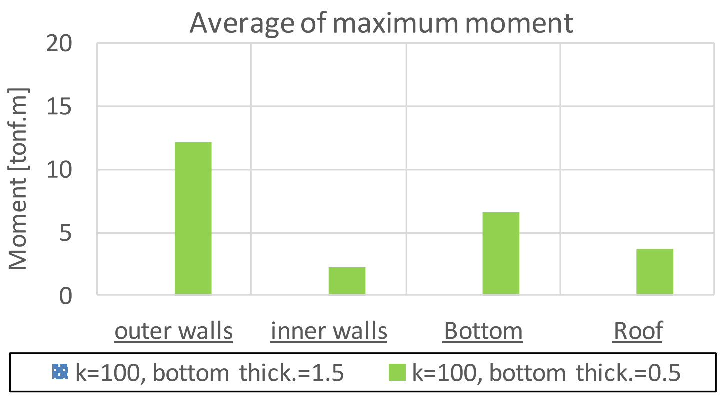

Figure 9. The effect of rigidity o the bottom slab on the averaged bending moment in different walls

5. Conclusion

The structural behavior of a water intake basin is studied under different applied loads. Since the basin is a buried structure which is supported vertically by the soil layers, the effect of the soil modulus on the internal bending moments is investigated by making use of a FEM analysis. Different soil parameters from a soft to a stiff condition have been taken into account to cover the unreliability of the soil parameters. In addition, the rigidity of the foundation is studied by making use of different thicknesses and removing inner walls. Based on the results, it is concluded that:

- The maximum bending moment in the basin structure is not too sensitive to the soil stiffness and the maximum effect of the soil modulus on the maximum bending moment is nearly 25% that occurs in the bottom slab located directly on the soil.
- In comparison with the maximum bending moment, the averaged bending moment in the bottom slab is more sensitive to the soil parameters and the averaged bending moment would be underestimated if a stiff soil condition was considered. In another word, the averaged bending moment in the bottom slab will be increased by assuming a softer soil condition. On the other hand, the averaged bending moment in other walls except the bottom slab is nearly independent to the soil modulus.
- The bending moment will be increased in all of the basin elements in the case of removing internal walls. Among the basin elements, the roof and bottom slabs are more sensitive because they are actually supported by inner walls.
- The effect of inner walls on the bending moment depend on the soil parameters and in a case of removing inner walls, the averaged bending moment in the bottom slab can be increased nearly 30% from a stiff to a soft soil condition. The effect of inner walls on the generated bending moment is more than the effect of the soil

condition and in a soft soil condition; the averaged bending moment in the bottom slab may be doubled in the case of removing internal walls.

- The thickness of the bottom slab defines its rigidity and by thickening the foundation slab a higher bending moment will be obtained. However, the bending moments in other walls i.e. outer wall, roof and inner walls are not a function of the foundation thickness.
- As a result, design of the basin walls based on the maximum bending moment can be done with making an acceptable assumption for the soil modulus. However, it is necessary to model the geometry of inner walls accurately when evaluating the structural behavior of a basin. It can be concluded that the contribution of the soil modulus in the total stiffness of the basin is less than the contribution of the geometry of the basin.

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