NUMERICAL EVALUATION OF BEARING CAPACITY AND SETTLEMENT OF RING FOOTING; CASE STUDY OF KAZEROON COOLING TOWERS

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ABSTRACT

Nowadays, more and more ring footings are used in practice special for axi-symmetric structures. In this paper, a numerical analysis was performed using PLAXIS software for calculating bearing capacity and settlement of ring footing. The parameters used in this analysis are the results of geotechnical studies of Kazeroon cooling tower. The analysis was carried out using Mohr-Coulomb's criterion for soil. The Bearing capacity was calculated for smooth and rough ring footing and then the bearing capacity factors were calculated. The analysis indicated that the bearing capacity of rough ring footing is obviously higher than the bearing capacity of smooth footing. Finally, the results were compared with those available in the literature.

Keywords: *ring footing, radius ratio, bearing capacity, settlement, cooling tower*

1. INTRODUCTION

The bearing capacity and settlement for both strip and circular footings have already been one of the most highly interesting areas in geotechnical engineering for researchers and practical engineers. Defining the correct bearing capacity of the footing is a very important factor in economical terms. A lot of observations have been made in the literature in order to calculate bearing capacity of strip and circular footings using the limit equilibrium method [1, 2]. In recent years, numerical methods, such as finite element method (FEM) [3, 4] and the finite difference method [5, 6], have been widely used to compute the bearing capacity of strip and circular footings. Nowadays, more and more ring footings are used for axi-symmetric structures such as silos, chimneys, and storage tanks and so on. The use of ring footings decrease the amount of material used and is more economical. This has lead to an increasing use of circular footing in countries which construction material on more expensive. Proposed different relations for prediction of the bearing capacity and settlement of strip, circular and square footings aren't suitable for the ring footings. Therefore, the theoretical prediction of ultimate bearing capacity and settlement for ring footings is a requirement in the design. Solutions to calculate the elastic settlements of ring foundations are available in the literature [7, 8]. Some experiments have also been performed to compute the bearing capacity of ring footings [9, 10]. Kumar and Ghosh [11] investigated the bearing capacity factor N_γ for both smooth and rough ring footings by using the method of characteristics assuming that the interface friction angle between the footing base and the underlying soil mass increases gradually from zero along the footing centerline to along the footing base. Hataf and Boushehrian [12] performed a series of laboratory tests on model ring footings and found that for a ratio of internal to external radius of the ring (n) equal to 0.4 the bearing capacity reaches its maximum for sand. Hataf and Razavi [13] found that n value for maximum bearing capacity of sand is not a unique value but is in the range of 0.2–0.4. Zhao and Wang [14] utilize a finite difference code FLAC to study bearing capacity factor N_γ for ring footings in cohesionless soil. The value of N_γ is found to decrease significantly with an increase in radius ratio (n), which is the ratio of internal radius to external radius of the ring. The value of N_γ for a rough ring footing, especially for lager values of friction angle, is obviously higher than that for a smooth footing. In this paper the settlement and bearing capacity of ring footings are observed, Centralization on the ring footings of the cooling tower in Kazeroon cooling towers.

2. GEOLOGICAL AND GEOTECHNICAL STUDIES

Kazeroon power plant site is situated on the 10 kilometer of the Cameroon- Farashband road and the 4 kilometer of Kazeroon powerhouse private road. The mentioned area is geologically part of Zagros wrinkled sector which is situated in the south west of Iran. The area of this sector is estimated between 150 to 250 kilometers. The geotechnical consultant of Kazeroon site performed extensive geotechnical exploration and testing at Kazeroon site. The first three borings were performed by wash borings. Later nine additional borings were carried out by continuous boring. The field and laboratory tests including plate test, pressuremeter test, cone and standard penetration test, triaxial test, oedometer test and… were carried out. Table (1) demonstrates the Mohr- Coulomb parameters which are driven from the geotechnical report of Kazeroon cooling towers.

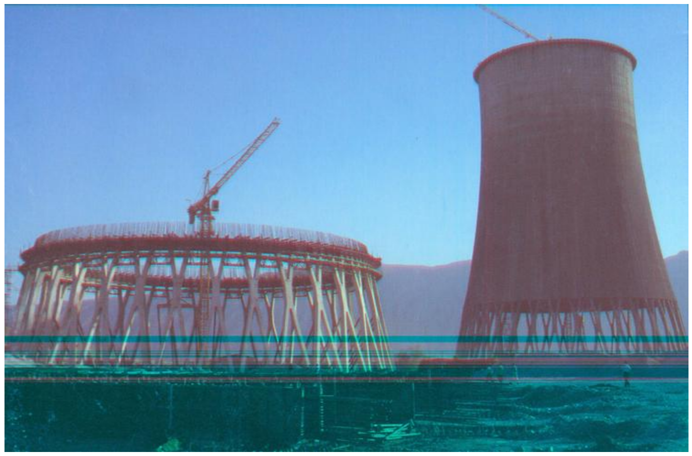


Fig.1 Layout of Kazeroon cooling towers

Table1. Parameters of soil of Kazeroon power plant site [15]

parameter	First layer	Second layer	Third layer
Cohesion (drained),KPa	5	5	5
Cohesion (undrained), KPa	80	70	100
Friction angle(drained)	26	25	28
Friction angle(undrained)	8	5	5
Unit weight(saturated) , KN/m^3	20.1	20.1	20.15
Unit weight(unsaturated), KN/m^3	20	20	20
Modulus of elasticity, KPa	30000	20000	40000
Dilatancy angle	0	0	0
Poisson's ratio	0.4	0.4	0.4
Overconsolidation ratio	1.5	1.5	1.5
Void ratio	0.6	0.6	0.6
Compression coefficient	0.13	0.15	0.14
Swelling coefficient	0.01	0.015	0.01
Permeability in horizontal direction, m/day	0.112	0.199	0.051
Permeability in vertical direction, m/day	0.328	0.207	0.259

3. MODELING

The numerical modeling is implemented using the PLAXIS software. The 15 nodes element will result a more precise calculation of the stress and strains. A tiny mesh is used for the models. The calculations of bearing capacity were performed on a 200 meter thickness of soil. Because the layer was presumed as a one with infinite depth, so that the results could be compared with the bearing capacity theories which are often proposed for the semi infinite layer. The external radius was assumed as 50 meters on the internal radius as 0, 7.5, 15, 22.5, 30, 37.5 and 45 meters so that the dimensions are close to the real dimensions of the Kazeroon cooling tower. Figure (2) shows the numerical model assumed for the bearing capacity calculations. Fixed supports were considered at the bottom of geometry and roller supports were on the vertical boundaries.

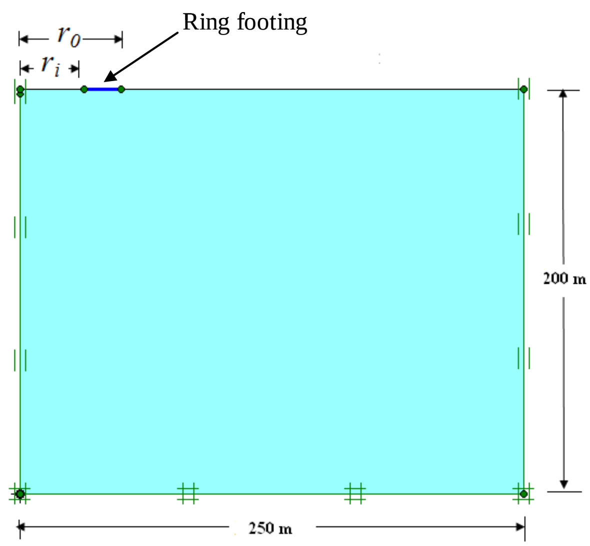


Fig.2. Simulation of ring footing in the numerical analysis

The soil has the tendency to a nonlinear behavior. The soil's nonlinear stress-strain behavior in different levels can be model. The Mohr- Coulomb model is one of the first soil behavior models which is elasto-plastic model. This model uses five parameters which consist of elasticity modulus (E), Poisson's ratio (ν), internal friction angle of soil (φ), cohesion (C) and angle of dilatancy (ψ). In this model an average stiffness is assumed for each level of the soil. Using this constant stiffness for each layer the calculations are done considerably faster than normal. Table (2) shows parameters used for the calculations of bearing capacity. These parameters are an average chosen from table (1).

Table2. Parameters used in the calculations of bearing capacity

E(Kpa)	*ν*	*φ(˚)*	*Ψ(˚)*	*c(Kpa)*	γ_{dy} *(kN/m²)*	γ_{sat} *(kN/m²)*
20000	0.4	26	0	5	20	20.1

A drained behavior is assumed for the materials for the bearing capacity calculations. Initial stresses in the soil are driven from the material weight and their historical of development. In the PLAXIS software the horizontal stress in static state is calculated using Jacky's formula,

$$k_0 = 1 - \sin\varphi \quad (1)$$

4. CALCULATIONS OF BEARING CAPACITY

In this research in order to calculate the bearing capacity, the rigid footing was chosen and the settlement under the rigid footing is assumed as uniform one. A uniform vertical displacement was prescribed to the model until failure was accrued (displacement controled method). Applying the vertical displacement, two different conditions can be presumed; in the first condition, it is assumed when vertical displacement is applied to the footing, the soil under the footing could move horizontally. In other words the friction between the soil and the footing is ignored (smooth footing).In the other condition, it is assumed that when the vertical displacement is applied to the footing, the soil could not move horizontally. In other words the friction between the soil and the footing is infinite (rough footing). Figure (3) shows the stress diagram versus displacement for a footing with a radios ratio of 0.9. From this diagram the ultimate bearing capacity could be calculated. The results showed that the calculated bearing capacity is much higher in rough footings than in smooth footings. In practical conditions, the friction between the soil and footing is between the smooth and rough footings. So, the bearing capacity is on amount between the bearing capacity of smooth and rough footings.

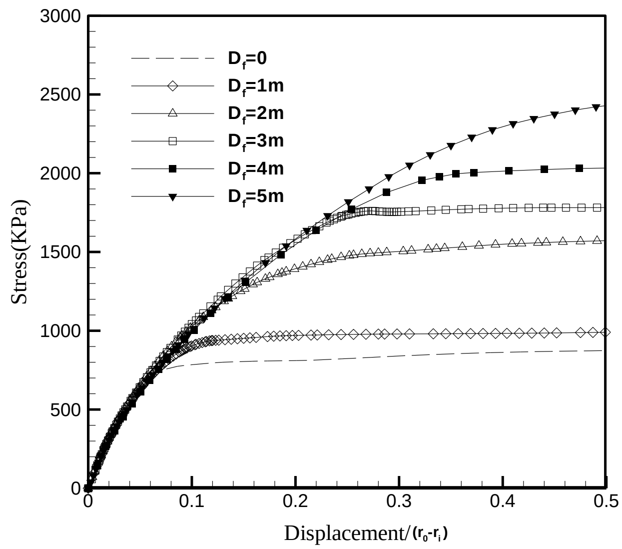


Fig.3. Curves of stress against settlement in different depth

5. CALCULATION OF BEARING CAPACITY FACTORS

Figure 4 shows the changes of bearing capacity according to the depth of the footing, for the radios ratio of 0.9. It can be seen that this relation is almost linear. It is assumed that the bearing capacity for a ring footing is calculated from the below theoretical relations:

$$q_u = (r_0 - r_i)\gamma N_\gamma^* + cN_c^* + qN_q^* \quad (2)$$

Where N_c^*, $N\gamma^*$, N_q^* are bearing capacity factors that shape factors have been considered to modify effect the shape of the footing. The mentioned formula could also be written below:

$$q_u = [(r_0 - r_i)\gamma N_\gamma^* + cN_c^*] + (N_q^*\gamma)D_f \quad (3)$$

In the equation (3) if the depth of the footing (D_f) is the only variable assumed, it could be calculated that this equation is a line, and therefore the slope of the line in figure (3) would be $N_q^*.\gamma$ and then N_q^* could be calculated. Table (3) shows the N_q^* changes versus the radios ratio. There is a relation between N_q and N_c in most references. In the equations proposed by Hanson [16], Meyerhof [2] and Vesic [17], the relation between those two factors are as follows:

$$\frac{N_q}{N_c} = 0.533 \quad (4)$$

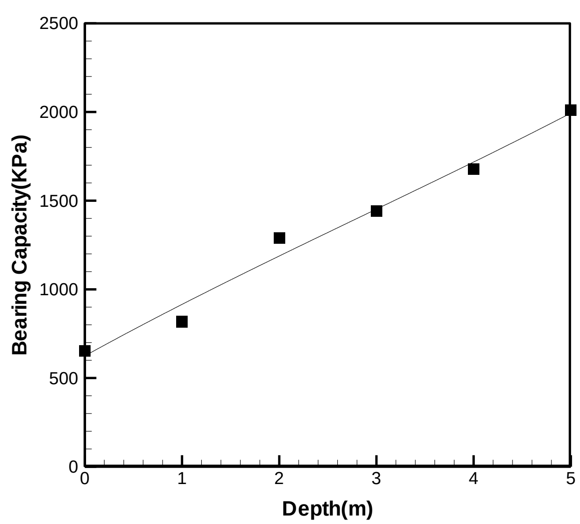


Fig.4. Variation of bearing capacity with depth of footing

If it is assumed that the mentioned equation between N_q^* and N_c^* is true, then the amount of N_c^* is easily reached according to the table (4). $N\gamma^*$ could be calculated after calculating N_c^* and assuming the bearing capacity of the footing in $D_f = 0$, as followed:

$$N_\gamma^* = \frac{(q_u - cN_c^*)}{(r_0 - r_i)\gamma} \qquad (5)$$

Table (5) shows the results obtain from what mentioned.

Table3. Bearing capacity factor N_q^* with r_i/r_o for ring footings

r_i/r_0	N_q^*	
	smooth	rough
0	24	30.75
0.15	22.94	17.92
0.30	20.61	23.36
0.45	17.49	19.44
0.60	14.76	13.92
0.75	14.76	11.60
0.90	13.56	9.52

Table4. Bearing capacity factor N_c^* with r_i/r_o for ring footings

r_i/r_0	N_c^*	
	smooth	rough
0	45.02	57.63
0.15	43.04	52.38
0.30	38.68	43.82
0.45	32.82	36.47
0.60	27.69	26.11
0.75	26.77	21.76
0.90	25.45	17.86

Table5. Bearing capacity factor N_γ^* with r_i/r_o for ring footings

r_i/r_0	N_γ^*	
	smooth	rough
0	4.10	9.40
0.15	3.63	7.67
0.30	2.75	6.11
0.45	2.94	5.75
0.60	3.84	4.50
0.75	4.10	9.29
0.90	5.25	14.59

Tables 3 and 4 show that the bearing capacity factors with increase of radios ratio is decreased. The mentioned results seem logical if we assume that a ring footing with external radios of r_0 and internal radius of r_i has a behavior similar to a strip footing with the width of $(r_0\text{-}r_i)$. Terzaghi [1], Meyerhof [2] and De Beer [18] have proposed equations which show that by decreasing the B/L (width over length), the bearing capacity factors N_q^*, N_c^* will decrease. This is because of influence of the overburden pressure that changes from a 3 dimension to a 2 dimension state. Therefore considering that by increasing the radios ratio, the B/L decreases, then N_q^* and N_c^* should decrease, and the obtained results show the same thing. N_γ^* decreases for all amounts up to 0.6 radios ratio, but increases after 0.6. Terzaghi [1] and De Beer [18] believe that with increase of the B/L, N_γ^* increases. In this analysis, this is true for radios ratio after 0.6. This shows that the behavior of the ring footing is different to strip footing, especially in lower radios ratios.

By considering the some good research performed on the circular footings; initially, the results obtained from the numerical model have been compared with the existing theories for the circular footings. Table (6) shows that the results obtained from this work are logical.

Table (6) - Comparison of bearing capacity factors for circular footings (smooth and rough)

		N_q^*	N_c^*	N_γ^*
PLAXIS	smooth	24	45.02	4.1
	rough	30.72	57.63	9.4
Meyerhof [2]	-	17.55	30.04	4.8
Vesic [17]	-	17.55	30.04	7.5
Hansen [16]	-	17.55	30.04	4.74
Manoharan [19]	smooth	19.5	37.4	12.8
	rough	25.3	45.4	6.3
Zhao and Wang [14]	smooth	-	-	3.95
	rough	-	-	16.84

Figure 5 shows a comparison between the numerical model and the existing theories. It shows that in smooth footings the results obtained from the numerical model are in accordance to the results of Zhao and Wang [14] and have some differences with Komar and Goosh's [11] results. Zhao and Wang's bearing capacity calculations were implemented on a sand soil, which means that the soil was assumed frictional. The accordance of numerical results with Zhao and Wang's method for smooth footings shows that bearing capacity factors are not much influenced by the type of the soil. But for rough footings the results show considerable difference with Zhao and Wang's method and this show that the type of soil has considerable influence on bearing capacity factors for rough footings.

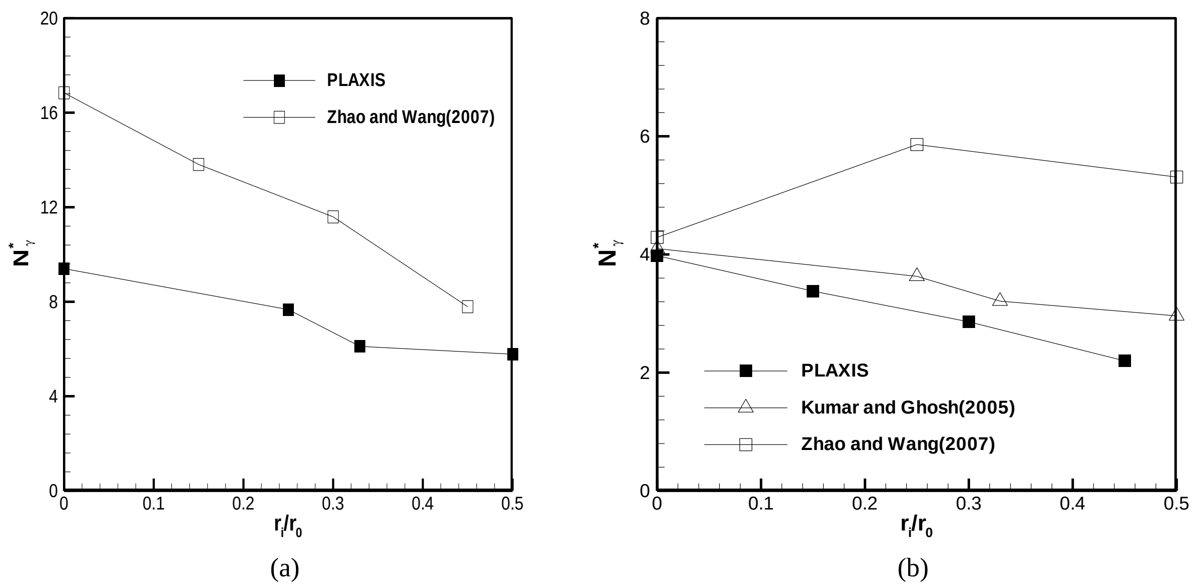


Fig5. Comparison of N_γ^* for ring footings (a) rough footing (b) smooth footing

6. SETTLEMENT CALCULATION

The ring footing settlement of Kazeroon cooling tower has been calculated under different stresses. The immediate and consolidation settlement were calculated in this analysis. This is because of the existence of saturated clay in the site.

Two types of calculations were implemented consisting the plastic and consolidation calculations. Immediate settlement could be driven from plastic calculations, and consolidation settlement can be calculated from consolidation. The consolidation settlement is time-dependent but ultimate settlement is calculated in here. Figure (6) shows the immediate and consolidation settlement versus stress. The calculation of consolidation settlement was implemented in 50, 100, 150, 200, 250, 300 and 350 KPa.

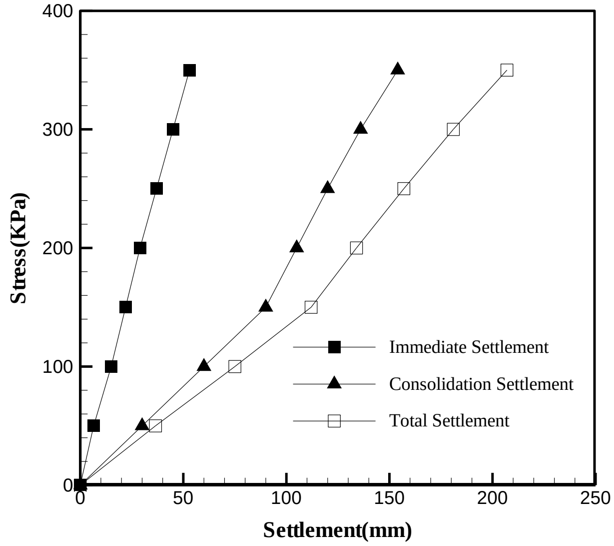
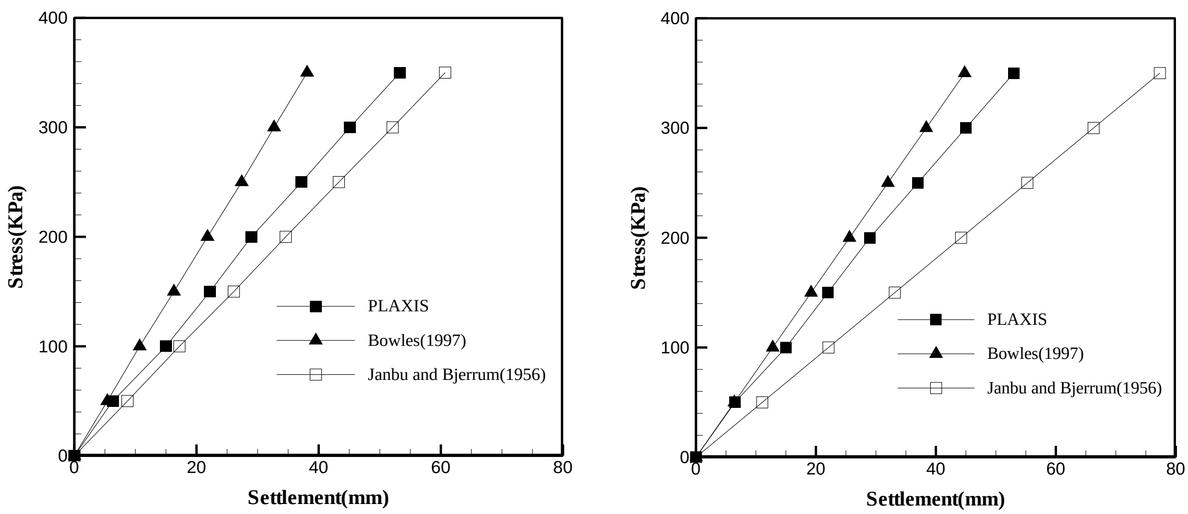


Fig 6 Immediate and consolidation settlement versus stress

Settlement calculations are observed in two states. In the first state, it is assumed that the ring footing is a type of circular footing with the diameter of ($2r_o$-$2r_i$) and latter, it is assumed that the ring footing acts like a strip footing with the width of (r_i-r_0). In figure 7 the results of numerical modeling have been compared with proposed methods by Janbu and Bjerrum [20] and Bowles [21].



(a) (b)

Fig .7 Comparison of calculated settlement with existing theories (a) B=5m (b) B=10m

a sa demussa si gnitoof eht nehw erom si tnemelttes detaluclac eht taht denoitnem eb dluohs tIstrip footing than the state that it was assumed as a circular footing. The results of circular footing state are closer to numerical results. It could be said that it is better to use the width of the footing equal to ($2r_0$-$2r_i$) when calculating the immediate settlement in a ring footing using the Janbu's equations and when using the Bowles's equations, it is better to use the width of the footing equal to (r_0-r_i).

Clay soil is saturated when it is situated beneath the underground water. In this analysis, the second and third layers of the soil were situated beneath underground water and were saturated. However the first layer was not saturate and the saturation degree was between 70 to 90 percent. The consolidation settlement calculations are implemented according to the equations proposed for complete saturated soils. In order to calculate the unsaturated layer of soil in this analysis, the relations for saturated soils were used, but the factor of pore pressure (B) was applied. The factor of pore pressure is related to saturation degree of the soil. Considering that the soil is 70 to 90 percent saturated, the

factor of pore pressure is between 0.1 and 0.6[22]. Here for the average of these two amounts, 0.35, is assumed as factor of pore pressure.
The relations of consolidation are proposed with the assumption of one dimensional consolidation for the soil. In this state the loading surface is bigger than the depth. In this analysis the loading surface is small compared to the depth and so, Skempton-Bjerrum's correction factor [23] was used.
Figure 8 shows the results obtained from numerical work and consolidation theory. The obtained results are similar to each other in B=10 and B=5.

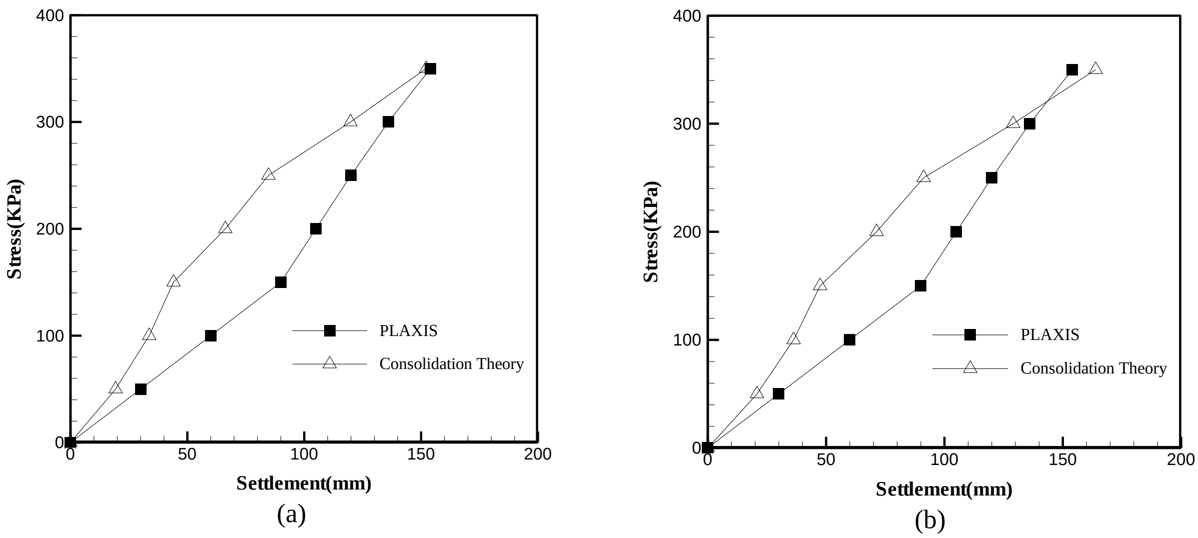


Fig.8. Comparison of settlement with consolidation theory

7. ALLOWABLE BEARING CAPACITY CALCULATION

As mentioned before, calculations of bearing capacity of ring footings showed that by increasing the radius ratio, the behavior of the ring footing moves towards a strip footing. Considering that the ratio of the ring footing in Kazeroon cooling tower is 0.9, hence the bearing capacity of this footing can be calculated using strip footing relations. The existing soil under the cooling tower is not homogenous and therefore an equivalent amount of cohesion and friction angle was assumed for the soil. The ultimate bearing capacity for the ring footing was calculated by assuming it as a strip footing with the width of 5m and depth of 5 m. A safety factor is needed in order to calculate the allowable bearing capacity. The safety factor is usually between 3 and 5 in bearing capacity calculations. Considering that the friction angle in calculations of the bearing capacity is 26 degrees and the average friction angle of the soil under the cooling tower is calculated as 26 degrees, therefore the results obtained for the calculation of bearing capacity could be used for bearing capacity calculation of the ring footing in Kazeroon cooling tower. Allowable bearing capacity calculations of ring footings are shown in table 7. Another factor which influences the allowable bearing capacity of a footing is the allowable settlement of the footing. The allowable settlement increases as the width of the footing increases. Usually in mat foundation, the allowable settlement is about 125 millimeters [24] and so according to figure 7 the allowable bearing capacity of the footing is about 200kpa. It can be observed in table 7 that the allowable bearing capacity calculated from bearing capacity calculations is almost twice the amount of the bearing capacity calculated according to allowable settlement. So it should be said that settlement is the important factor in determination of the allowable bearing capacity.

Table (7) - Comparison of allowable bearing capacity (KPa) for ring footings

Meyerhof [2]	Vesic [17]	PLAXIS (smooth footing)	PLAXIS (rough footing)	PLAXIS (allowable settlement)
338-563	383-638	498-831	402-670	180

CONCLUSION

The numerical simulation for computing the soil ultimate bearing capacity and settlement of ring footing was presented. The soil beneath rigid ring footings is limited to perfectly smooth and rough surface footings, respectively. The soil was modeled as an elastic–plastic material obeying a Mohr–Coulomb model. Based on these results, the following conclusions are made:

1. Variation of bearing capacity versus the depth of the footing is almost linear and from this, N_q^* could be calculated.
2. With increase of the radius ratio, the Nq* and Nc* are decreased.
3. N_γ^* reduces up to the radius ratio of 0.6, but after this amount, N_γ^* increases.
4. The behavior of ring footings moves towards strip footings as the radius ratio increases, especially after the radius ratio of 0.6, it becomes completely like a strip footing and in order to calculate the bearing capacity, the relations regarding strip footings can be used.
5. Comparing the results of current work with bearing capacity results of a ring footing on a sand soil, it can be denoted that the material of the soil has a significant effect on bearing capacity factors, especially for rough footings.
6. The allowable bearing capacity calculation of the cooling tower has shown that settlement is the important factor in determination of the allowable bearing capacity.

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