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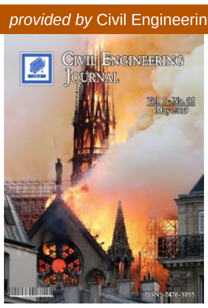

Numerical Evaluation of Foundation of Digester Tank of Sewage Treatment Plant

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Abstract

In the present study the foundation of digester tank, main part of sewage treatment plant, is reanalyzed analytically and numerically to check the adequacy of such foundation to support superstructure loading. The foundation of digester tank consists of raft foundation and bored piles. The diameter of raft is 33 m and thickness of 1 m, while the piles are bored type of diameter 0.6 m and length 15 m. After testing eleven working piles, it is found that three piles cannot support a load of 1.5 times the working load (1305 kN) safely or in other words the factor of safety of these failed piles is less than 1.5. The results of filed pile tests are reanalyzed using two well-known methods, Davisson's method and Brinch-Hansen method to check the ultimate carrying capacity of tested piles. Also, this paper includes analysis of previous soil investigation report and conducting additional soil investigation by drilling three boreholes to secure the soil parameters used in the analytical and numerical analysis of digester tank foundation. SAFE 12 software is used to analysis the foundation of structure as piled-raft instead of pile group to interest from the interaction between soil and raft foundation. The results of analysis showed that the piles failed in the tests can support its share of the superstructure load by a factor of safety 1.8 and the piles success in the field tests can support its share of the superstructure load by a factor of safety not less than 2.86. Also, the settlement under structure will be less than 100 mm, where using piled-raft analysis reduces the settlement to be within allowable limits.

Keywords: Pile; Raft; Foundation; Soil; Tank.

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1. Introduction

The digester tank is considered important structures in comparison with other structures that are consist the sewage treatment plant. The digester tank is reinforced concrete tank and consists of three main parts. The upper part is of a conical shape with outer radius of 12.5 m and height of 6.5 m, the middle part has a cylindrical shape with outer radius of 12.5 m at its upper part (7.3 m height) and 12.8 m at its lower part (6.45 m height) and the lower part of the digester is of an inverted conical shape with outer radius of 12.8 m. The total height of the tank will be 29.25 m. The tank is supported by eight triangular radial walls that fixing the inverted conical base to the tank raft. The foundation of tank is a reinforced concrete raft of 16.5 m radius and 1 m thickness resting at a depth of about 2.5 m below the ground level. This raft is supported by 193 piles distributed in a radial direction. The bored piles of 600 mm diameter and 15 m length were casted in situ using reinforced concrete. The digester is currently under construction and 193 piles were constructed and the raft has been casted as well. The structural designer has defined the working load of each pile as 870 kN [1].

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Hirai [2] presented an analytical solution using Winkler model for the analysis of piled-raft foundation subjected to vertical loading in heterogeneous soils. The coefficient of vertical stiffness of the pile in is derived from Mindlin solution for the displacement of elastic continuum. The coefficient of vertical stiffness for the raft is expressed by the Muki solution for the 3-D elastic analysis. The relation between settlement and vertical load for the piled-raft system is obtained by using the recurrence equation of influence factors of the pile for each layer. The percentage of load carried by both piles and raft is represented by the vertical influence factors. The results calculated by the present method for piled-raft with nodular piles in heterogeneous soils well agreed with those obtained from field test and the finite element method.

Al-Kaisi et al. [3] studied the behavior of free-standing pile groups and piled-raft driven in clayey soil under axial loading. Different configurations of piles were tested such pile diameter, pile length, and spacing between piles. Also, they conducted tests on piles in cohesive soil of different shear strength. It is observed that piles exhibited a very high stiffness at initial loading stages till the settlement reaches 0.5 mm, but then the pile settled rapidly with small increment of the load In addition, most of the load capacity of piles is mobilized at settlement of around (1–2) mm which is corresponding to 5 % of pile diameter. The undrained shear strength of clay has no significant effect on the mechanism of load transfer by piles. The load carrying capacity of pile group is equal to that of piled-raft foundation, where the interaction between piles and raft is not significant. Dezfouli [4] studied the effects of reinforcement elements such as geogrid in the cushion layer of the non-connected pile-raft foundation in sandy soil on the mechanism of load transfer and the shares of piles and raft from the total applied load. The effect of different parameters such as the spacing between piles, thickness of cushion, the number and length of geogrid layers on the load settlement of foundation system had been studied. The results showed that the lowest settlement observed in non-reinforced cases with an optimum cushion thickness and piles spacing, the lowest settlement is observed. Using the geogrid in the cushion layer causes increasing the bearing capacity and the share of the total load carried by the piles.

Many researchers conducted Mali and Singh [5] 3D numerical analysis to understand the settlement, load-sharing, bending moment and shear force behavior of piled-rafts founded on different soil profiles and different loading configurations, and different piled-raft configurations. The results of these studies showed that as the pile spacing increases, the average settlement decreases significantly for different soil profiles soil profile and it is noted to be lesser for uniform piled-raft configurations. Also, the load-sharing ratio increases with increases the pile spacing. The maximum bending moment and shear force are noted to be less in piled-raft foundation than that of raft foundation or pile group analysis [5-9]. The present study is a case study focused on reanalyzed a constructed raft and piles to calculate the allowable carrying capacity of piles and apply SAFE 12 software to analyze the system as piled-raft instead of analysis the system as pile group. This problem raised after testing eleven working piles in the field, it is found that three piles cannot support a load of 1.5 times the design load of 1305 kN safely or in other words the factor of safety of these failed piles is less than 1.5 [10-11]. Therefore, the problem reanalyzed to check if the casted bored piles and raft foundation can support the superstructure load or not. In case the pile group failed to withstand the applied loads will be removed otherwise if it can support the loads with an allowable factor of safety, the construction process will be continued. This project can be considered is trial to analyze the foundation as piled-raft instead of pile group which is considered of of the sustainability development aspects by changing the design criteria.

2. Site Description and Methodology of Analysis

According to the site investigating report and soil tests that performed on samples obtained from 12 boreholes drilled to a depth of 20 m each, the soil stratification can be described as follows [12]:

a) The surface layer starting from the natural ground surface consists of brownish to grayish silty clay soil (with sand CL-CH), soft to medium consistency, this layer extended to a depth of (0.0-4.5) m.

b) A layer of greenish silty sand soil (SW-SP) with clay, loose to medium dense, this layer extended to a depth of (2.5-7.5) m.

c) A layer consists of brownish to grayish silty clay soil with sand (CL-CH), soft to medium to stiff in consistency; this layer extends up to depth of (0.0-15.5) m.

d) A layer of greenish silty sand soil with content gypsum (SW-SP), dense to very dense, this layer extended to the end of boring (14.0-20.0) m.

e) A layer consists of greenish silty clay soil with sand (CL), stiff consistency, this layer extended to the end of boring (18.5-20.0) m.

This consequent changes or sub-soil strata is related to way of sedimentation. The soil investigation suggested using the following geotechnical data:

a) The allowable bearing capacity of shallow foundation at depth ranging from 2 to 3 m below the ground level is ranging from 80 to 98 kPa.

b) The allowable carrying capacity of bored piles of 600 mm diameter and 15 m length is 1092 kN which based on a factor of safety of 2.5, so that the ultimate carrying capacity of such piles is 2730 kN.

The methodology used in the present work can be illustrated in the flowchart shown in Figure 1.

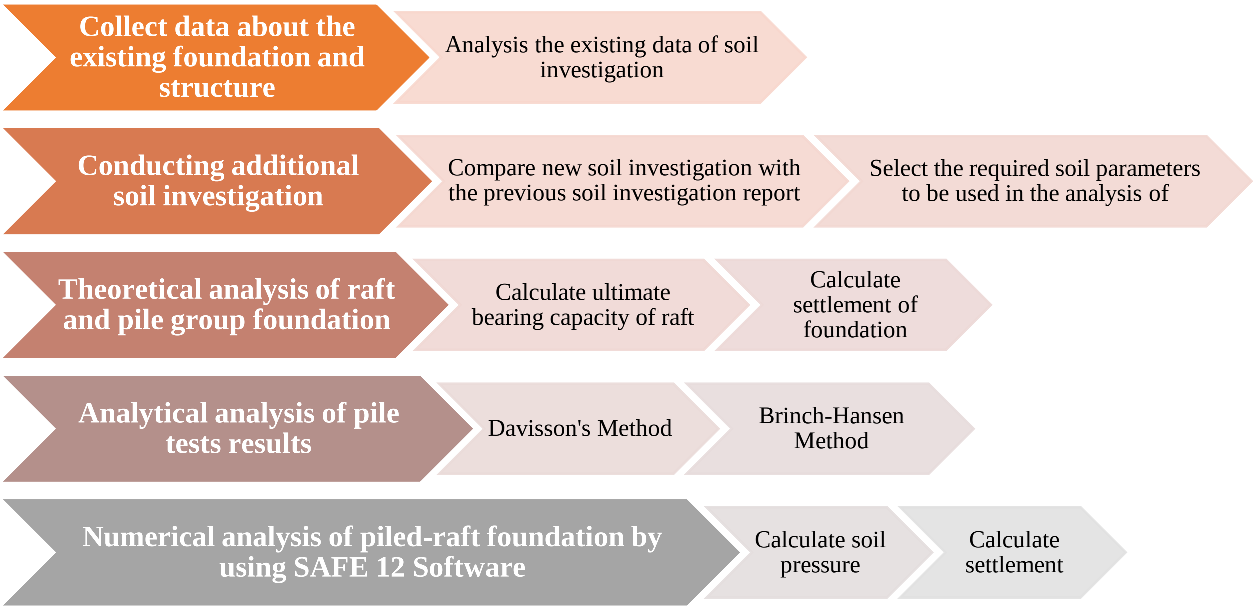

Figure 1. Flowchart of methodology used in the analysis of case study

It is believed that the suggested carrying capacity is overestimated as none of the pile tests indicates such high values for the ultimate carrying capacity. For this reason, it is suggested to perform an additional soil exploration by drilling another three exploring boreholes which may help in obtaining more precise soil parameters to be used in the analysis of the problem in hand. Two of boreholes were drilled to a depth of 20 m and the third borehole was drilled to a depth of 10 m [13].The data obtained from the additional soil investigation suggested that the allowable bearing capacity of shallow foundation at depth 1.5 m is ranging from 55-80 kPa and at depth 4.5 m is ranging from 57.5-110 kPa.Also, the bored pile of 600 mm diameter and 15 m depth has an allowable carrying capacity of 710 kN. This conservative value of allowable carrying capacity is almost consistent with the pile tests results.

3. Geotechnical Parameters of Soil

In order to perform a sound analysis to the problem in hand, it is very important to define reasonable values for the soil parameters that will be used in the analysis. After careful reviewing of the site investigating reports, the parameters given in Table 1 are considered as representative and conservative values for the soil parameters.

Table 1. Geotechnical properties of soil

Property	Value
The undrained shear strength (Su)	34 kPa
The compression index (Cc)	0.10534
The swelling index (Cs)	0.01115
The initial void ratio (e_o)	0.735
The preconsolidation pressure (Pc)	111 kPa
The constrain modulus (E_{oed})	8050 kPa
The dry unit weight (γ_d)	15.26 kN/m^3
The saturated unit weight (γ_{sat})	19.76 kN/m^3
The Poisson’s ratio (μ)	0.4 (assumed)
The water table level	1.5 m below EGL

The calculated soil parameters that will be considered in the analysis are [14]:

- The modulus of elasticity of soil (E) calculated as follows to be is 3760 kPa:

$$E = E_{oed}\ (1 + \mu)(1 - 2\mu)/(1 - \mu) \tag{1}$$

- The shear modulus (G) can be obtained by using three different correlation expressions [14, 15]:

$$G = E/2(1 + \mu) \tag{2}$$

$$G = (100 - 300)Su \tag{3}$$

$$G = 0.6 \text{ x } 25^{Su/100} \ \ \text{(G in MPa)} \tag{4}$$

The first equation gives a value of G about 1343 kPa but it depends on the elastic properties of soil and doesn't account for the undrained shear strength (Su). The second equation and by using its lower limit gives a value of 3600 kPa for G and the third equation results in a value of 1850 kPa for G. By considering the three values of G, a conservative value of G = 2000 kPa is quite reasonable to be considered as a representative value for the soil layer in the analysis.

- Regarding the modulus of subgrade reaction of the supporting soil (Ks) in the site, the geotechnical report assumes that at depth of 2.5 m, Ks is ranging from 2000 to 13000 kN/m^3 [13]. This value is obtained by using the following formula:

$$Ks = 40 \text{ x FS x } q_{all} \tag{5}$$

There is another equation to calculate Ks:

$$Ks = E/B(1 - \mu^2) \tag{6}$$

Equation 6 gives a much-underestimated value of Ks = 136 kN/m^3. For silty clay soils, the value of Ks is ranging from 2000 to 20000 kN/m^3, therefor the lower limit value of Ks= 2000 kN/m^3 will be used in the analysis.

4. Theoretical Analysis of Piled-Raft Foundation

Before starting the theoretical analysis, it is important to calculate the applied load on the soil by the primary digester tank. The main load of this structure is self-weight plus the weight of water inside. The live load which implicitly considered constitutes a very low portion of the total weight of the structure. The total weight of the concrete tank and the water at its maximum capacity is about 160000 kN and the applied stress on the soil will be 187 kPa by considering the raft area of 855 m^2. Regarding the wind load, a calculation was performed by considering a wind speed of about 85 mph and an importance factor of 1.15 [16]. It is found that for such structure of height about 30 m, the wind pressure is ranging from 1.4 kPa at its top to about 1 kPa at its bottom. This will give a resultant horizontal force of about 1000 kN and a resulting moment on the foundation of about 20000 kN.m. To calculate the eccentricity (e) of the total applied loads, thevalue of moment is divided by the axial force (160000 kN) to get the eccentricity value (e = 0.125 m) which is less than 1/6 of the footing width. Therefore, the wind load can be neglected in the analysis. In the beginning, the foundation of the structure will be analyzed as raft foundation at depth 2.5 m. The ultimate bearing capacity (q_{ult}) of such raft can be calculated as follows [17]:

$$q_{ult} = 5\ Su\left(1 + \frac{0.2B}{L}\right)\left(1 + \frac{0.2D}{L}\right) + \gamma D \tag{7}$$

In which B and L are width and length of the raft and D is depth of foundation placement. For circular footing, both L and B are substituted by the raft diameter. Equation 7 gives a value of 220 kPa, where the foundation can carry applied stress with a factor of safety of 1.18. Due to its large diameter, raft foundation usually causes a settlement more than that permissible by different codes of practice. Therefore, the factor of safety should be increased to control the foundation settlement to be within allowable limits. The tolerable settlements, total and differentiable, of different types of foundation constructed in different types of soils based on the experience of many agencies and persons are given in Table 2.

Table 2. Tolerable magnitudes of settlement

Type of footing	Type of soil	Total settlement, mm	Differentiable settlement, mm	Reference
Isolated and Strip	Sand	25	-	[18]
Slab and raft	Sand	50	-	[19]
Isolated and Strip	Sand	40	51	[20]
Slab and raft	Sand	45-65	51-76	[20]
Isolated and Strip	Clay	65	76	[20]
Slab and raft	Clay	65-100	76-126	[20]

It’s recommended to adopt the values presented by Skempton and McDonald [20] in checking the settlement of the foundation. Regarding the circular raft of the primary digester tank, the anticipated settlement can be calculated as follows [21]:

$$\mathrm{Sc} = \frac{\mathrm{Cc}}{1+\mathrm{e_o}}\ \mathrm{H}\log\left(\frac{\sigma_\mathrm{o}+\Delta\sigma_\mathrm{v}}{\sigma_\mathrm{o}}\right) \tag{8}$$

Considering normally consolidated clay of thickness, H = 17.75 m, σ_o= 104 kPa, and $\Delta\sigma_v$ = 116 kPa (structure load transferred to the mid of clayey layer by using method of 2V:1H). The resulting settlement is 350 mm which much greater than that allowed (65-100) mm. In such situation, piles are usually used and the foundation should be considered as piled-raft. The main function of using piles in such foundation is to reduce the settlement of the raft to its allowable limit and to increase the factor of safety of soil bearing capacity. It is documented that when the raft diameter (or width) is greater than the pile length the pile will no longer work as pile group, rather the foundation will work as piled-raft. To analyze the piled-raft foundation, it is important to calculate the pile stiffness and the raft stiffness individually then calculate the piled-raft stiffness. Regarding the piles (diameter = 600 mm and length = 15 m) installed in such soil, the following equation is used to define whether the pile is long (flexible) or short (rigid) pile. For short rigid piles [22-24]:

$$\mathrm{L/D} < 0.25\sqrt{\frac{\mathrm{Ep}}{\mathrm{G}}} \tag{9}$$

L/D is 25 which is less than the right-hand side term (27), therefore the pile is considered as short (rigid) pile and the stiffness of an individual pile (Kp1) is calculated by the Equation 10 [25]:

$$\mathrm{K_{p1}} = \frac{2\mathrm{D}}{1-\mu}\mathrm{G} + \frac{2\pi\mathrm{GL}}{\zeta} \tag{10}$$

Where (ζ) value is ranging from 3-5 and considered as 4 in this analysis. The calculated value of ($\mathrm{K_{p1}}$) is 51124 kN/m. The stiffness of 193 piles ($\mathrm{K_p}$) cannot be considered as the sum of individual pile stiffness ($\mathrm{K_{p1}}$) because of the interaction between piles. The suggested equation to calculate the stiffness of the whole group of piles ($\mathrm{K_p}$) is [19]:

$$\mathrm{K_p} = \mathrm{K_{p1}}\ (\text{No of Piles})^{\beta} \tag{11}$$

A reasonable value of β = 0.66 can be considered in the analysis. This yields a value of $\mathrm{K_p}$ of about 1648500 kN/m [26].

The raft stiffness (Kr) is calculated as follows [26]:

$$\mathrm{K_r} = 2\ \mathrm{D\ G}/(1-\mu) \tag{12}$$

Equation 12 gives Kr = 220000 kN/m. The piled raft stiffness (Kpr) is calculated by using:

$$\mathrm{K_{pr}} = \frac{\mathrm{K_p} + (1-2\,\alpha_\mathrm{pr})\mathrm{K_r}}{1-\alpha_\mathrm{pr}^2\left(\frac{\mathrm{K_r}}{\mathrm{K_p}}\right)} \tag{13}$$

Where (α_{pr}) represents the factor of interaction between piles and raft, its value can be considered as 0.8. The calculated value of Kpr is about 1659190 kN/m. Considering an applied load on the piled raft of 160000 kN, the resulting displacement will be 96 mm which is much less than that of raft alone and within the acceptable limits.

5. Analysis of Pile Test Results

As mentioned earlier, the circular raft is supported by 193 piles of 600 mm diameter and 15 m length. Eleven working piles were tested by considering the working load of each pile is 870 kN. The maximum axial loading reached in the pile tests is 1305 kN that represents 1.5 times the working load. By dividing the total applied load of tank (160000 kN) on the total number of piles, the share of each pile from load is about 830 kN. Accordingly, it is thought that the structural designer presumed that the piles will work as (pile group) with a group efficiency of 95%. The pile test reports indicate that three of the piles cannot carry a working load of 870 kN with a factor of safety (SF = 1.5) and mentioned that these piles are considered as failed piles. The report of pile tests did not refer to the adopted criteria to define neither the pile working load nor its ultimate load. According to the adopted soil parameters, the ultimate carrying capacity of pile can be calculated according to Equation 14 as follows [27, 28]:

$$\mathrm{P_{ult}} = \pi\mathrm{DLSu} + \frac{\pi\mathrm{D}^2}{4}\ \mathrm{Nc\ Su} \tag{14}$$

Where

D is the diameter of pile;

L is the length of pile;

Su is the undrained shear strength of soil;

Nc is the bearing capacity constant.

Considering Nc = 9, the ultimate carrying capacity of pile (P_{ult}) will be about 1047 kN. If the factor of safety is assumed to 2, the allowable carrying capacity will be about 524 kN. Therefore, the assumed working load of each pile (870 kN) could be an overestimated value. To re-analyze the pile test results, two criteria have been adopted to calculate the ultimate carrying capacity of the pile from working pile test results. The used criteria are Davisson's criteria and Brinch-Hansen (1963) criteria. The results of six piles tests are re-analyzed; two of the failed piles, namely Pile No. 138 and Pile No. 184 and four of the piles that passed in working piles tests, Pile No. 20, Pile No. 22, Pile No. 70, and Pile No. 142.

The calculated values of ultimate carrying capacity by Davisson's criteria and Brinch-Hansen criteria of six of the tested piles are given in Table 3. It can be noticed that Davisson's method gives a conservative value for the ultimate carrying capacity and cannot predict that value when it exceeds the maximum load that reached during the pile test. Since the number of tested piles is limited (only eleven piles), it is important to generalize a representative value for all the piles that passed the test and another value for all the failed piles. To be more reasonable, an averaging for the values obtained by the two adopted methods, Davisson and Brinch-Hansen, will be made then another averaging for the tested piles. This will result in an average value for the ultimate carrying capacity for the piles that passed the test of about 1380 kN and that value for the (failed) piles is 815 kN.

Table 3. The values of ultimate carrying capacity as obtained from pile test results

Pile No.	Davisson's Method P_{ult} (kN)	Brinch-Hansen Method P_{ult} (kN)	Remarks
P20	>1305	1643	Passed
P22	1152	1360	Passed
P70	1222	1410	Passed
P138	576	872	Failed
P142	1300	1580	Passed
P184	726	1080	Failed

6. Numerical Analysis of Tank Foundation

In this analysis, the computer program SAFE 12 [26] is used to model and analyze the foundation of tank. Only the piled-raft foundation will be modelled as reinforced concrete material with a unit weight of 24 kN/m^{3}and the tank and eight triangular walls supporting the tank will be represented as vertical loads applied on the circular raft. This simulation disregards the additional stiffness resulting from the structure of tank and could be in the safe side as the adopted stiffness of the raft is less than its actual value. In the program SAFE 12, each pile is modelled as an individual spring of a certain stiffness value K_{p1} and does not taken in the consideration the interaction effect between the piles. Therefore, it is important to define an equivalent value of K_{p1} that consider the interaction between the piles as a whole, pile group. In this analysis the pile test results will be adopted to define this value of pile stiffness because it is more reasonable than that obtained by theoretical analysis. After reviewing the pile test results, it is found that the secant stiffness values are ranging from 40 kN/mm for the failed piles and more than 240 kN/mm for the piles passed in tests. Therefore, an average value of 140 kN/mm will be considered as a conservative value as the number of failed piles is less than half of the total tested piles. To account for piles interaction, the equivalent value of pile stiffness that will be input in the analysis is only 10 kN/mm which is almost equal to $K_{p1} \times (193)^{0.5}/193$ [27, 28]. The value of soil subgrade reaction is also required by the program SAFE 12 and the adopted value is 2000 kN/m^3.

Figure 1 shows the contours of raft displacements resulted from the weight of tank. It can be noticed that the displacement is almost uniform with an average value of 43.8 mm. The maximum value is 44.2 mm occurs not at the raft center, as expected, but at a radial distance of about 7 m from the center which is the edge of triangular wall supporting the tank. This is mainly because of the smaller pile spacing close to raft center. The minimum displacement value occurs at the raft edge as expected with a value of 43.5 mm. The average value of displacement is within the acceptable limits (less than 50 mm) as mentioned earlier in Table 2, more than 90% of this displacement will take place during the period of construction which resulted from the digester tank self-weight and equipment plus the weight of water inside the tank. The differential settlement is about 0.7 mm which is very small and expected to be reduced if the stiffness of the tank is added to the raft stiffness. The contour map of resulting soil pressure is shown in Figure 2. It can be noticed that the distribution of subgrade soil pressure is consistent with the raft displacement. The average value of soil pressure is about 87.6 kPa which is less than the allowable bearing capacity value obtained by the theoretical analysis.

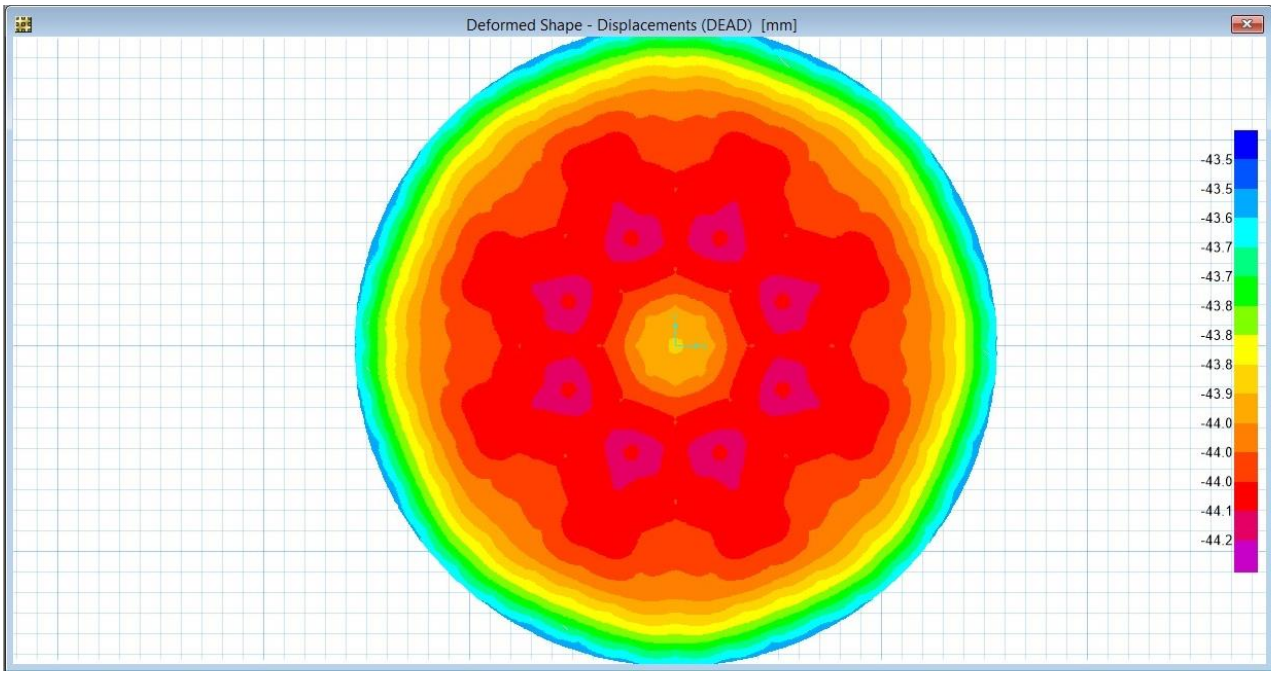

Figure 1. The contours of displacements of raft foundation

Figures 3 and 4 show the value of applied load on each of the 193 piles that supported the raft foundation. Table 4 contains the values of the axial load carried by each pile. It can be noticed that the value of this load varies from 440 kN to about 483 kN depending on the location of pile. Considering the average ultimate load values for both failed and passed piles, the average value of factor of safety (SF) for the failed piles is about 1.85 and that for the piles that passed test is 2.86. These values of factor of safety are based on all piles have the sane stiffness as mentioned earlier, but it is well known that the load carried by each pile is proportional to its stiffness. Therefore, stiffer piles will carry more load and then the factor of safety will accordingly decrease. In the contrast to that, for piles of less stiffness, the carried load will decrease then the factor of safety will increase, which corresponding to the behavior of the failed piles which have a less stiffness value. It is expected therefor that both failed and passed piles will have a reasonable value of factor of safety of 2 or more.

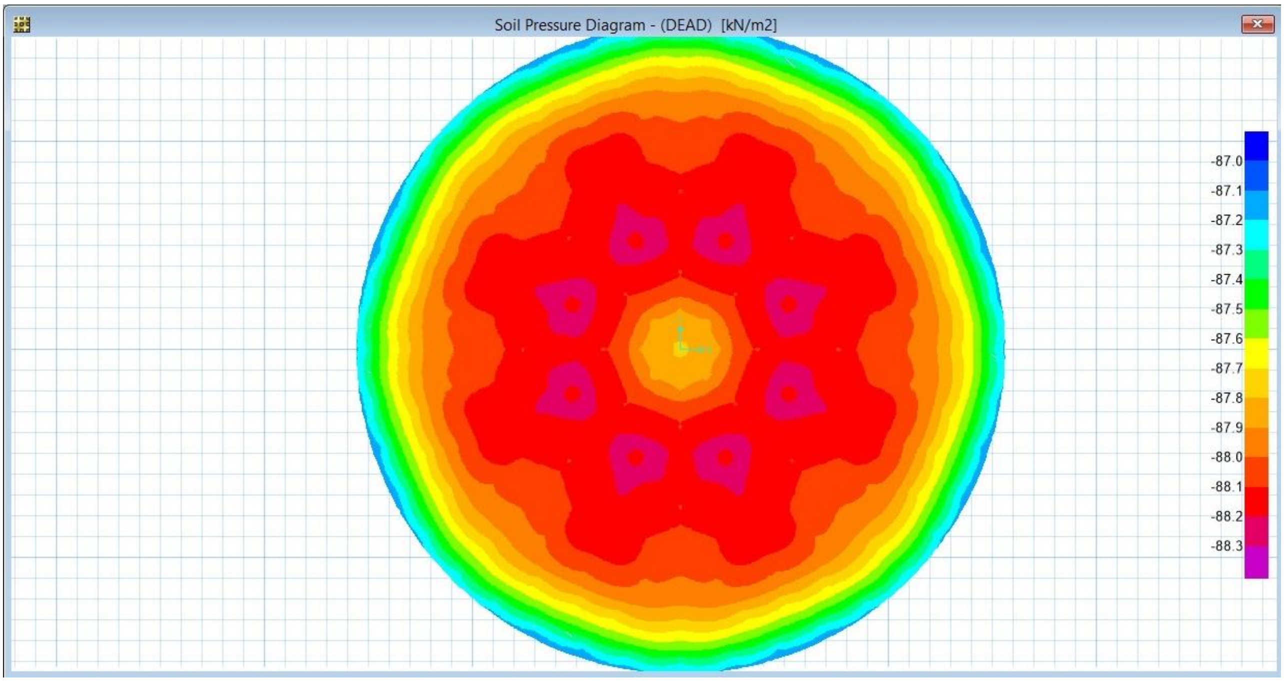

Figure 2. The contours of subgrade soil pressure resulting from digester loads

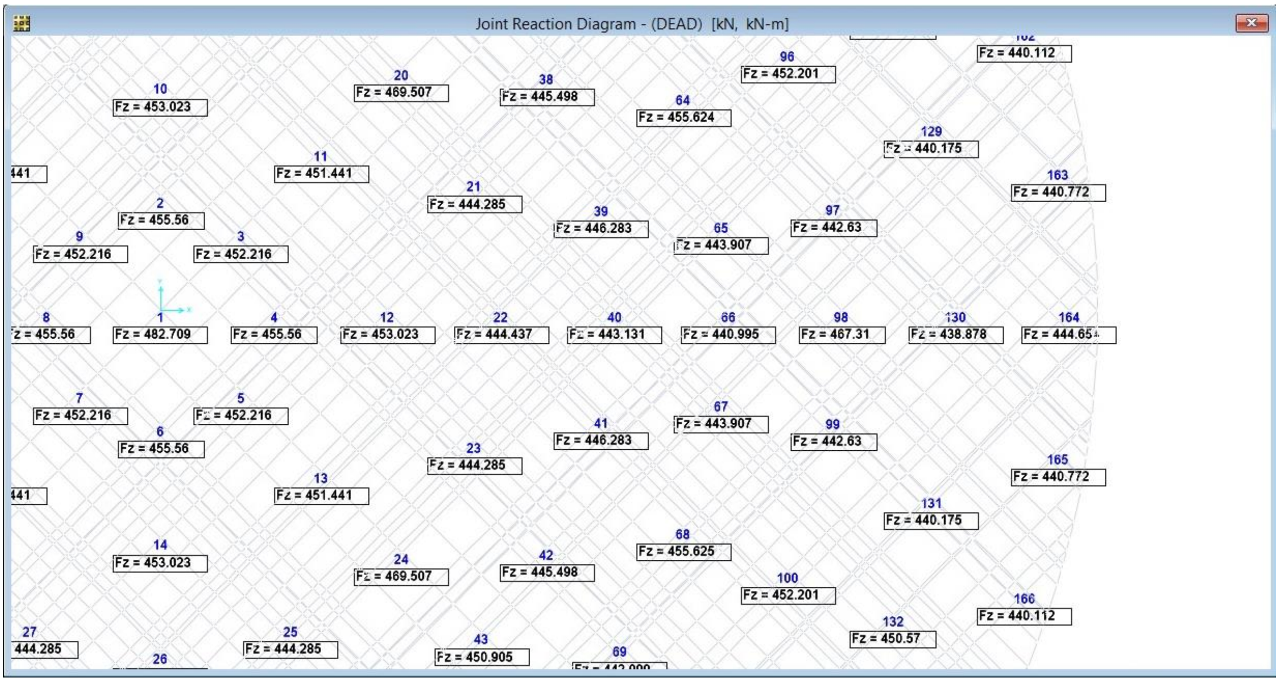

Figure 3. The pile loading (right sector of the raft)

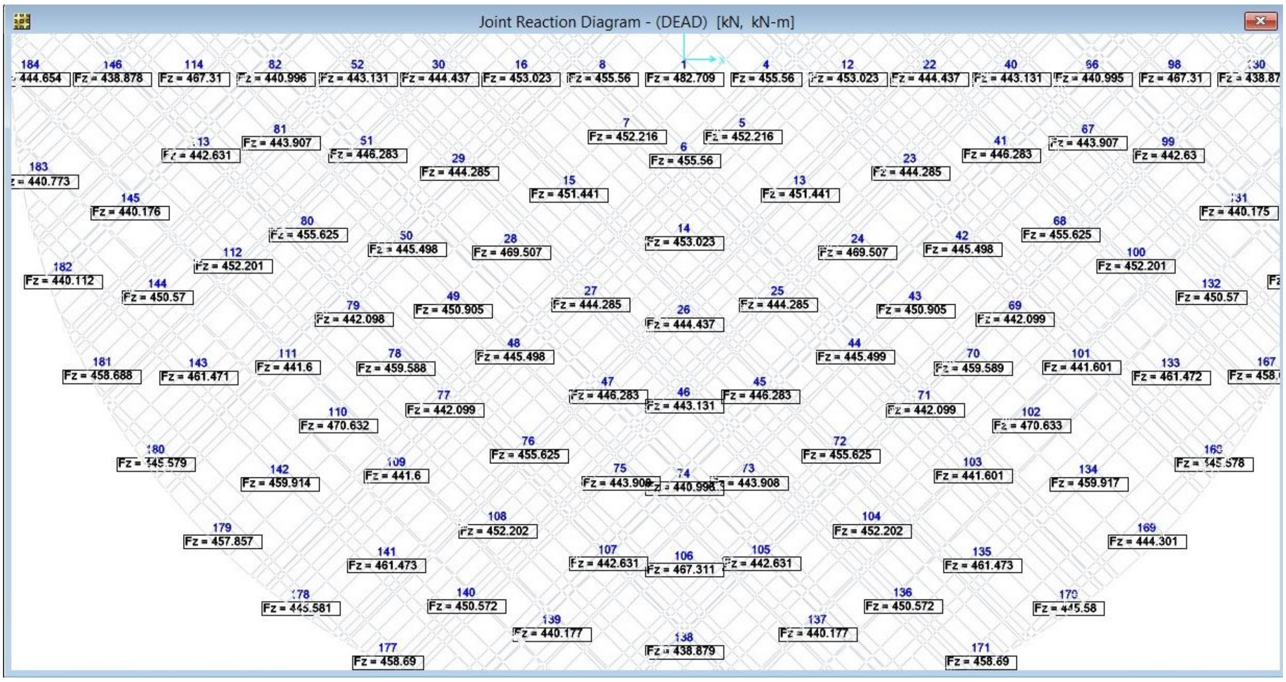

Figure 4. The pile loading (lower sector of the raft)

Table 4. The load carried by each pile obtained from analysis by SAFE 12 software

Pile No.	Pile Load kN	Pile No.	Pile Load kN	Pile No.	Pile Load kN	Pile No.	Pile Load kN	Pile No.	Pile Load kN
1	482.709	40	443.131	79	442.098	118	470.633	157	458.692
2	455.56	41	446.283	80	455.625	119	441.6	158	445.586
3	452.216	42	445.498	81	443.907	120	452.201	159	451.16
4	455.56	43	450.905	82	440.996	121	442.631	160	445.575
5	452.216	44	445.499	83	443.908	122	438.878	161	458.687
6	455.56	45	446.283	84	455.626	123	440.177	162	440.112
7	452.216	46	443.131	85	442.099	124	450.573	163	440.772
8	455.56	47	446.283	86	459.589	125	461.476	164	444.654

9	452.216	48	445.498	87	442.099	126	459.917	165	440.772
10	453.023	49	450.905	88	455.625	127	461.471	166	440.112
11	451.441	50	445.498	89	443.907	128	450.57	167	458.688
12	453.023	51	446.283	90	467.311	129	440.175	168	445.578
13	451.441	52	443.131	91	442.631	130	438.878	169	444.301
14	453.023	53	446.284	92	452.203	131	440.175	170	445.58
15	451.441	54	445.499	93	441.602	132	450.57	171	458.69
16	453.023	55	450.905	94	470.633	133	461.472	172	440.114
17	451.441	56	445.498	95	441.6	134	459.917	173	440.774
18	444.437	57	446.283	96	452.201	135	461.473	174	444.656
19	444.285	58	440.996	97	442.63	136	450.572	175	440.774
20	469.507	59	443.908	98	467.31	137	440.177	176	440.114
21	444.285	60	455.626	99	442.63	138	438.879	177	458.69
22	444.437	61	442.099	100	452.201	139	440.177	178	445.581
23	444.285	62	459.589	101	441.601	140	450.572	179	457.857
24	469.507	63	442.099	102	470.633	141	461.473	180	445.579
25	444.285	64	455.624	103	441.601	142	459.914	181	458.688
26	444.437	65	443.907	104	452.202	143	461.471	182	440.112
27	444.285	66	440.995	105	442.631	144	450.57	183	440.773
28	469.507	67	443.907	106	467.311	145	440.176	184	444.654
29	444.285	68	455.625	107	442.631	146	438.878	185	440.774
30	444.437	69	442.099	108	452.202	147	440.177	186	440.114
31	444.285	70	459.589	109	441.6	148	450.573	187	458.692
32	469.507	71	442.099	110	470.632	149	461.476	188	445.586
33	444.285	72	455.625	111	441.6	150	459.916	189	451.16
34	443.131	73	443.908	112	452.201	151	461.47	190	445.575
35	446.284	74	440.996	113	442.631	152	450.57	191	458.687
36	445.499	75	443.908	114	467.31	153	440.176	192	440.112
37	450.905	76	455.625	115	442.631	154	444.655	193	440.773
38	445.498	77	442.099	116	452.203	155	440.774	-	-
39	446.283	78	459.588	117	441.602	156	440.115	-	-

7. Conclusions

After reviewing the previous soil investigating report and pile tests reports, the foundation of the primary digester tank is decided to reanalyze the foundation of tank. Both analytical and numerical analysis has been performed considering conservative and representative values for the soil parameters in the site. The following points are concluded from this study:

- The circular raft and the supporting 193 piles are analyzed as piled-raft rather than pile group and a circular pile cap. This is mainly because the diameter of the raft is much greater than the pile depth. In the piled raft analysis, both the supporting piles and the subgrade soil will share resistance to the applied load of the structure. The main function of piles in the current foundation is to reduce the anticipated settlement of large diameter raft.

- After re-analyzing the pile tests reports by using two well-known methods; Davisson and Brinch-Hansen methods to determine the ultimate carrying capacity of the tested piles. The analysis results and the theoretical calculations have shown that the adopted ultimate and allowable carrying capacity values by the foundation structural designer and by the soil investigation report are overestimated.

- Using SAFE 12 software to analyze the problem numerically, it is found that the anticipated settlement of the raft is less than 100 mm which is within the acceptable limits. It is also found that the piles can support the applied load with a factor of safety of 1.8 for the failed piles and 2.86 for the piles that passed the tests. This value is believed to be converges to more than 2 for both groups of piles if the actual stiffness of each pile is used in the analysis. This is mainly because piles of high stiffness will tend to carry greater load while piles of less stiffness will carry a less load.

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10. Conflicts of Interest

The authors declare no conflict of interest.

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