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Reliability Based Design of Pile Raft Foundation

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Abstract

The Combined Piled Raft Foundation (CPRF) is a modern concept in which the total load coming from the superstructure is partly shared by the raft through contact with soil and the remaining load is shared by piles through skin friction and/or base capacities. A CPRF system is economical compared to the traditional "piled foundation" design where the pile cap is assumed to be sustained by piles only.

A "case study" (Basrah elevated water tank project) is studied thoroughly in this work. The 1365 m^3 elevated water tank located at 3 nearby sites was originally designed as a piled foundation with 25 bored piles for each site (0.7m diameter and 24m length). Theoretical analysis reveals that the piles have an allowable capacity of 2245 kN. On the other hand static pile tests were preformed on 17 piles out of 75 piles and it appeared that the allowable capacity demonstrated erratic values below the expected pile capacity.

A re-analysis of the pile raft is performed establishing the CPRF concepts. The case study was modeled by STAAD Pro computer package to determine the loads on both piles and soil with the corresponding settlement values.

The reliability aspects of behavior of both "piled foundation" and CPRF are investigated. In this approach the influence of autocorrelation for the stiffness modulus (of both piles and soil) and raft thickness are considered.

The safety of both systems is obtained in terms of traditional factor of safety (FS) and reliability index (β). The results showed that the "piled foundation" system is "unsafe" for 3 criteria for both FS and β. On the other hand, the CPRF is "safe" for the 4 criteria for FS concept while it is "unsafe" for 3 criteria for β.

الدراسة المعولية لتصاميم الاسس الحصيرية المسندة بالركائز

الخلاصة

تعتبر الاسس الحصيرية المسندة بالركائز (Combined Piled Raft Foundation, CPRF) احد المفاهيم الحديثة لتصرف الاسس حيث يفرض توزيع الاحمال المسلطة الاتية من المنشأ بين اساس الحصيرة (خلال تماسها مع التربة) ومجموعة الركائز (اما من خلال قوى الاحتكاك الناتجة من تماسها مع التربة او من خلال قوة تحمل قاعدة الركيزة او كلاهما). يعتبر هذا النوع من الاساسات اكثر اقتصادية مقارنة مع المفهوم السائد لاسس قبعة الركائز (Pile Cap Foundation) والتي تفرض ان الاحمال المسلطة على الاسس تسند من قبل الركائز فقط.

في هذا البحث تم اخذ مشروع خزان مياه في مدينة البصرة كحالة ميدانية. صممت اسس الخزان سعة 1365 متر مكعب والذي يقع في ثلاثة مواقع عمل متقاربة على المفهوم

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المتعارف لاسس قبعة الركائز والتي تتضمن استخدام 25 ركيزة حفر بقطر 0.7 متر وطول 25 متر لكل موقع عمل. اظهرت الحسابات النظرية لقوة تحمل الركائز وفقا لفحوصات التربة الموقعية ان قوة تحمل الركيزة الواحدة المسموح بها هي 2245 كيلونيوتن. بعد تنفيذ جميع الركائز في مواقع العمل واجراء فحص الركائز الستاتيكي على 17 ركيزة من اصل 75 ركيزة، تبين ان قوة تحمل الركيزة المسموح بها متذبذبة القيم وهي اقل من قوة التحمل النظرية المتوقعة.

تم اعادة تحليل الاسس في مشروع البصرة على مفهوم (الاسس الحصيرية المسندة بالركائز) والذي يوزع الاحمال المسلطة من المنشأ مابين التربة والركائز بنسبة معينة لكل منهما. لغرض هذه الدراسة تم استحداث نموذج نظري يمثل الحالة بواسطة برنامج STAAD Pro لحساب الاحمال المنتقلة لكل من التربة والركائز ومن ثم حساب الهبوط المرافق لهما نتيجة الاحمال.

تم تحديد مدى امان المنظومة وذلك بحساب معامل الامان التقليدي (FS) ومؤشر المعولية (β). اظهرت النتائج ان المنظومة الاصلية المصممة على المبدأ التقليدي لاسس قبعة الركائز تعتبر "غير أمينة" حسب ثلاثة معايير من وجهتي نظر معامل الامان التقليدي ومؤشر المعولية بينما اظهرت الدراسة ان الاسس المقترحة والمصممة على مبدأ (الاسس الحصيرية المسندة بالركائز) اعتبرت "أمينة" حسب المعايير الاربعة لحساب قوة تحمل الركائز للمبدأ التقليدي لعامل الامان (FS) و "غير أمينة" لثلاث معايير على اساس مبدأ المعولية.

1. Introduction

The piled raft or sometimes called “Combined Pile Raft Foundation” (CPRF) is a geotechnical composite construction consisting of three elements: piles, raft and soil. The design of traditional piled foundation (or pile cap foundation), assumes that the loads are carried by the piles only. In the design of piled rafts (or CPRF), the load coming from the superstructure is shared between the piles (through skin friction and/or base capacities) and the raft through contact with soil. The piles are loaded up to their limiting capacities and the excess load (which is the total load minus the ultimate load capacity of a single pile multiplied by number of piles) will be transported to the underlying soil (Reul and Randolph, 2003).

As the demand for a rational treatment of uncertainty in geotechnical engineering has increased, the use of probabilistic methodology has gained importance. Probabilistic risk and reliability methods employ the use of statistics and probability theory in order to formally include and quantify uncertainties in design. In so doing, the probabilistic predictions of performance provide a more realistic interpretation of the actual engineering behavior than the factor of safety (Cameron, 2002).

2. Case Study- Basrah Water Tank

A case study is taken in this research in which 3 typical elevated tanks are constructed in 3 different locations in Basrah city, Iraq. The elevated water tower consists of a concrete tank with inner dimensions of 16.2 m x 16.2 m x 5.2 m which gives a total volume of 1365 m^3. The tank is carried out by 16 columns arranged in 4 x 4 grids with a spacing of 5.6 m c/c. The columns are 650 mm x 650 mm in section. The base of the columns rests on 19.6 m x 19.6 m x 0.7 m pile cap that transmits the loads of the columns to 25 bored piles underneath. The bored piles have a diameter of 700 mm and extend to depths of 24 meters and are arranged in 5 x 5 grids with a spacing of 4.2 m c/c. The height of the base of the elevated concrete tank is 22 meter above the top of the raft (pile cap). The upper level of the pile cap is 2.6 meter below ground level. Figure (1) shows the locations of the columns and the bored piles on the pile cap (Al Tareq Engineering Bureau, 2007a).

It is proposed in this paper to exchange the traditional factor of safety (FS) with more encouraging factor (Reliability Index, β) which takes into account the variability of input parameters of the problem. Results of the reliability-based analysis are presented in terms of the reliability index at various values of initial values of the input variables in addition to their coefficient of variance.

The soil investigation performed showed that the soil profile for the three sites consist mainly of two layers (soft clay layer and dense sand) with properties as shown in the Table (1). Al-Tariq Engineering Bureau report estimated the value of the allowable bearing capacity for the upper layer ranging from 40 to 50 kPa. The water table was found at a depth of 1 meter below ground surface at the time of test.

2.1. Theoretical Pile Capacity

The design capacity of the bored pile was estimated from theoretical static equations where different soil parameters were anticipated from the soil investigation report.

The total ultimate compression capacity of single pile (neglecting the effect of negative skin friction) can be calculated as the sum of the two parts; tip and friction as shown below (Bowles, 1996 for details).

$$Q_{ult} = Q_{tip} + \sum Q_{friction} \qquad \ldots\ldots\ldots (1)$$

$$Q_{ult} = [(c_u\, Nc^* + s'\, Nq^*)\, A_{tip}] + [\sum(\alpha\, c_u + \bar{q}\, K \tan\delta)\, A_{shaft}] \qquad \ldots\ldots\ldots (2)$$

$$Q_{ult} = [(0*159.13 + 243.45*134.53)*0.384] + [(0.45 * 25 + 124.4*1.5*\tan(0))*41.78 + (0.45*0 + 230.95 * 0.535 * \tan(32))*5.5]$$

$$Q_{ult} = 12576 + 894 = 13{,}470 \text{ kN}$$

The allowable capacity of the pile is calculated using rather high factor of safety (=6) instead of the traditional factor of safety for piles (=3) in order to accommodate for all inherent uncertainties involved in this problem.

$$Q_{allowable} = Q_{ult} / FS \qquad \ldots(3)$$

2.2. Actual Loads on Piles

The design loads transmitted to the piles can be calculated by dividing the structure into two parts; super structure and sub-structure. The super structure loads on the pile cap through the 16 columns were analyzed using STAAD Pro Computer Package. Three types of load combinations on the pile cap were taken into consideration and the first one is adopted as the "critical" value for simplicity reasons:

- Full tank only
- Full tank +wind

- Empty tank +wind

The analysis showed that the total vertical load (the sum of loads on 16 columns including the dead weight of the pile cap) equals to 46,547 kN.

The sub-structure (pile cap) analysis was performed using two approaches; conventional analysis and finite element analysis. The pile cap consists of 25 piles (5x5 grid with 4.2 meter spacing). From the superstructure model results, it has been noticed that the sum of horizontal forces (Fx and Fz) is equal to zero and the sum of moments in all directions (Mx, My and Mz) are also zero.

The load on each pile can be calculated using the conventional equation (Bowles, 1996).

$$Load_{pile} = \frac{P}{N} \pm \frac{{}^{*}d_x}{\sum d_x^2} \pm \frac{M_z {}^{*} d_z}{\sum d_z^2} \quad \ldots\ldots..(4)$$

This equation can be simplified to Equation (5) for the case where moments in both directions (Mx and Mz) are equal to zero and symmetry of loads.

Load subjected on each pile = P/N …….(5)

= 46547/25 = 1861 kN < 2245 kN

It can be seen that the average load on the piles (1861 kN) is lower than the “theoretical” allowable capacity of the piles and hence the design is considered to be acceptable.

The second approach of analysis was performed by dividing the pile cap into 784 "brick element" and replacing the piles by a “spring” located at the nodes which are in the same position as the location of the pile. The results showed good agreement with the simplified analysis (Equation 2).

2.3. Static Pile Load Test

Static pile load test was performed on 12 working piles in addition to 5 test piles (Al Tareq Engineering Bureau, 2007b). The total load applied on each pile varied from 2000 kN to 2400 kN and was loaded in 4 to 5 stages. The procedure of loading was NOT according to ASTM- D1143 where it should be loaded to twice the design load [4000 kN] in 8 stages. In some tests, the settlements at their final loads were very high and were considered to be a failure.

It is difficult to define the “failure load” of a pile when it has not been loaded to failure. In the case where ultimate failure has not been reached in a loading test, a “limiting load” may be defined which corresponds to a “limiting settlement” or “rate of settlement”. A commonly used definition of failure load is taken to be that at which settlement continues to increase without further increase in load; alternatively, it is customarily taken as the load causing a settlement of 10% of pile diameter (BSI, 1986).

In order to define the allowable capacity of the piles that can be used in the three sites, one can interpolate the results of the static pile test and to estimate the allowable load from the following three requirements and then choose the minimum or the average. Hence the allowable capacity (Q_{all}) has three definitions which are:

1. Q_{all-1} = load that encounter a total settlement of 10 mm.
2. Q_{all-2} = load that encounter a total settlement of 15 mm./1.5

3. Q_{all-3} = ultimate load / Load factor = ultimate load /2.5

There are several methods proposed by different investigators to estimate the ultimate pile capacity from the results of "static pile load test". Four methods were chosen which are, (Fellenius, 2006):

1. Tangent Method.
2. Chin Method.
3. Davison Method.
4. DeBeer Method.

The data of all static load pile tests are plotted and the capacity of the piles was obtained according to the previous methods.

Table 2 shows the results obtained from the static pile tests on all piles tested in the three sites. It can be noticed that the final allowable capacity for the piles in all projects can be taken as 700 kN. This is due mainly to the "unsupervised" pile construction.

From the tests performed on the piles on the site, the following can be concluded:

1. The tests results show an erratic behavior. This is mainly due to the bad performance of the piling work. Several precautions that should be taken into consideration in the site were not performed.
2. All tested piles show lower values than the theoretical calculations (Qall = 2245 kN).

3. STAAD Pro Model (Reference Example)

The STAAD Pro computer package is used in this work to estimate the loads transmitted from the superstructure to each pile and the soil underneath the pile raft foundation. This load case and the subsequent results are considered as the reference example which will be referred to as "reference example" throughout this work.

3.1. Formulation of the Model

The foundation of the elevated water tower was analyzed using STAAD Pro Computer Package. The Combined Pile Raft Foundation (CPRF) was simulated by plate elements each having a dimension of (0.7 m x 0.7 m) and a thickness of 0.7 meter. A total of 784 elements (28 x 28) forming a (CPRF) with a total dimensions of 19.6 m x 19.6 m (see Figure 2). The total number of nodes at the lower level of the CPRF is 841 which will be connected by two types of supports as follows:

- Support 2 which resemble the bored piles. The support assumes a spring in the vertical direction (the dots in Figure 2). The spring is defined by the value of the stiffness coefficient (k_p). Typical values of k_p ranges from 100,000 to 400,000 kN/m. From the pile load test results, the average k_p was obtained to be 141,300 kN/m.
- Support 3 which resemble the soil. The support assumes a spring in the vertical direction. Typical values of (ks) used in this project are range from 1,000 kN/m to 40,000 kN/m. The value of ks used in the STAAD Pro model will be 3,000 kN/m. According to the obtained soil subgrade reaction.

3.2. STAAD Pro Results

The STAAD Pro Computer Package has many facilities among which are the capabilities of giving the results in different forms. Due to the large amount of the results that one can obtain from the computer package, it is decided to limit the results to the load and displacement of each node and subsequently each spring.

Due to the symmetry of loads from the columns the 25 supports (piles) can be categorized into 6 types according to their locations (corner, edge-1, edge-2, center-1, center-2 and center-3) [see Figure 3]. Table 3 shows a summary of the results for both supports (support-2 and 3).

3.3. Evaluation of the STAAD Pro Results

One can deduce the following:

1. The maximum load on the piles did not exceed 1113.2 kN and the maximum displacement did not exceed 7.87 mm.
2. The maximum load on the soil spring did not exceed 26.87 kN and the maximum displacement did not exceed 8.96 mm.
3. The total load transferred through the piles is 27270.28 kN representing 58.58% of the total load on the pile cap of 46547 kN
4. The total load transferred through the soil is 19277 kN representing 41.42% of the total load on the pile cap of 46547 kN.
5. The average load on the pile is 1090.8 kN with a coefficient of variation (COV) of 1.1% which is considered very "good" data. This value should be compared with 1861 kN when the pile cap was designed as supported by piles only.
6. Although the new analysis of adopting the CPRF reduced the loads on the piles from 1861 kN to 1090 kN, however, the allowable capacity of the pile as predicted from pile load test (Qall= 707 kN) is not achieved making the problem "unsafe" from the traditional point of view.

3.4. Analyses Results

Table 4 shows a summary of the ultimate and allowable capacity (Q_{ult} and Q_{all}) of single pile as calculated from four different criteria with their corresponding factor of safety (see Table 3). The accuracy of each pile test is described in statistical terms; "standard deviation" (SD) and "coefficient of variance" (COV). The stiffness of the pile (kp) can be calculated from dividing the ultimate load (Qult) by the mobilized settlement.

In this work, the pile capacity will be used in terms of Q_{ult} and not $Q_{allowable}$ which can differ substantially according to the selection of the factor of safety used in the analysis.

4. Probabilistic Design Approach

From the statistics point of view, the probabilistic approach for the combined piled raft foundation (CPRF) system and/or piled foundation system starts with computing the actual (predicted) load (Q) [as computed from STAAD Pro] and the ultimate (permissible) capacity or resistance (R) [from pile tests] and modeling them as random variables, assuming a range of values in accordance with a probability distribution. The geotechnical properties of soils are mostly modeled as normal distribution curve defined by its mean value (μ) and standard deviation (σ) (Lumb, 1970, Benjamin and Cornel (1970), Ang and Tang, 1984, Duncan, 2000 among many). Figure 4 shows a typical normal distribution curves for actual load (Q) on piles for the piled raft foundation analysis while Figure 5 shows the ultimate pile capacity (R) for criteria No. 4.

The area where the normal distribution curves for (Q) and (R) overlap in Figure 6 indicates the region of failure. The shaded area represents the intersection of the two plots which is defined from the statistical point of view as the "probability of failure (p_f)", as it represents the probability that capacity (R) is less than demand (Q), and can be calculated using basic statistical procedures and tables. Once the "probability of failure (p_f)" is known then one can find the reliability index (β) value from Figure7. The larger this shaded area, the less reliable the system will be.

Figure 7 gives the relationship between reliability index and probability of failure. Most references estimate the probability of failure to be less than 10^{-3} (Smith, 1981, Ang and Tang, 1984, Duncan, 2000 among many), hence a value of less than **3.13** for reliability index (β) is considered "***reliably unsafe***".

There are many methods that can evaluate (β) among which is the First Order Second Moment method (FOSM). This procedure is very time consuming and needs time to calculate the value. Eventually, there is another procedure which defines the reliability index as:

$$b = \frac{m_R - m_Q}{\sqrt{S_R^2 + S_Q^2}} \qquad \ldots\ldots (6)$$

where

m_R = average (mean) value for resistance

m_Q = average (mean) value for the load

σ_R = Standard deviation value for the resistance = COV*m_R

σ_Q = Standard deviation value for the load = COV * m_Q

5. Reference Example for Calculating β

If the reliability index of the piled foundation on piles with (k_p= 203,100 kN/m) is required [criteria No. 2 in Table 4] then one can use the plots similar to Figures 4 and 5 in one plot as shown in Figure 6.

Then from Table 4;

m_R = 2031 kN , m_Q = 1861 kN , S_R = 507.75 kN , S_Q = 62.46 kN

Substituting to get the value

$$b = \frac{2031 - 1861}{\sqrt{507.75^2 + 62.46^2}} = 0.33$$

$b <$ **3.13** **(Not Good)** ..… (7)

It can be seen that the value of β is very low which is obvious since the difference in the values of the resistance (2031kN) and the load (1861 kN) is very low.

One can calculate the traditional factor of safety for the same problem

FS = 2031/1861 = 1.09 < **1.5**

(Not Good) ………. (8)

which is unacceptable from the point of view of engineering (knowing that we are dealing with the ultimate loads and not the allowable loads).

6. Reliability Based Design of Piled Foundation

The reliability index (β) will be calculated similar to the above procedure and compared with the traditional factor of safety (FS) for the four criteria adopted in this study as summarized in Table 5. In the case of piled foundation note that the value for the actual load remains the same for all criteria since the total loads including the self-weight of the raft (46547 kN) is carried by the same number of piles (25) without any additional support from the soil.

Figure 8 shows a linear relation between the factor of safety (FS) for the pile cap with the ultimate pile capacity (Q_{ult}) taken from Table 5 for the 4 criteria. It can be noticed from the figure that the system is considered to be "unsafe" for (Q_{ult}) adopted from (10mm theory, 15mm theory and the average 4 methods) but it is "safe" for (Q_{ult}) equals to 13470 kPa from the theoretical capacity which gives a large FS of (7.23). From this figure, the value of (Q_{ult}) that gives an acceptable safety factor of 1.5 should not be less than 2793 kN. Note that the dotted line in Figure 8, represents the allowable limit of FS, which is 1.5.

For the same problem, the reliability index (β) was calculated for the 4 criteria as illustrated before. The results are plotted in Figure 9 in a similar manner as Figure 8. It can be observed that only the theoretical ultimate capacity is considered to be "safe" since its reliability index is equal to (3.45) which is greater than the acceptable value of (3.13) for geotechnical problems which is shown as the dotted. Also, negative values of the reliability index are not shown in the plot since it is meaningless.

As a final note, one can conclude that the piled foundation system can be considered as "unsafe" for most adopted criteria and for both traditional factor of safety and reliability based design approaches.

7. Reliability Based Design (RBD) of Piled Raft

The reliability of CPRF depends on the reliability of both piles and raft combined. The RBD can be divided into two categories the factor of safety and reliability index and will be calculated for piles and raft separately.

Reliability of Piles

The analyses done before for piled foundation will be adopted to determine the reliability of the system as combined piled raft foundation. The reliability index (β) will be calculated and compared with the traditional factor of safety.

From STAAD results, one can establish Table 6 and both reliability index (β) and factor of safety (FS) can be calculated.

The traditional factor of safety can be calculated from dividing the ultimate pile capacity (1413 kN) by average of the actual load (1090 kN). It can be noticed that the FS is equal to (1.29), which is not acceptable from the traditional point of view assuming piled foundation. However, the concept of the CPRF is to allow full mobilization of the piles and hence the concept of "safe" and "failure" system will be revised.

The statistical data (mean value and SD) from Table 6 can be used to model the actual load and resistance capacity as a normal distribution curves, and Equation 6 can be used to calculate the reliability index of the system. The value obtained is equal to (0.971) which is not acceptable since it is less than (3.13).

It can be noticed that the factor of safety depends on the mean values of the actual loads and resistance capacity only while the reliability index will be affected by accuracy of the results which can be identified by a statistical terms of standard deviation and COV. Figure 10 shows the effect of the change in COV of the adopted (Qult) on the reliability index.

It can be noticed from Figure 10 that the reliability index increases with the decrease of the COV for the same property. This indicates that the more the results are accurate the higher is reliability index. The value of the COV should be as low as 4% (intersection of the curve with β limiting value of 3.13) that the system will be accepted from the point of view of RBD.

Figure 11 shows the relation between the reliability index with the ultimate pile capacity for different COV to visualize the effect of the variance and accuracy in pile test results. Taking the adopted pile capacity (1413 kN), it can be seen that only if the value of the COV is equal to 3% or less can be considered acceptable or “Safe” since it is above the reliability index limit. The COV for the adopted pile capacity is 23.5% (Table 4) which is greater than 3%, so it is considered to be “unacceptable”.

In conclusion, the pile tests can be accepted as “Safe” system under specific conditions depending on the accuracy of the tests (variance of the results) but it will be always “Safe” or “Unsafe” no matter what is the degree of accuracy according to the traditional definition of factor of safety.

Reliability of Raft (Soil)

From STAAD results, the reactions of the soil were taken and demonstrated in Table 7, and both reliability index and factor of safety are calculated.
The traditional factor of safety can be calculated from dividing the ultimate bearing capacity of the soil (100 kPa) by the actual pressure from the super-structure (50.18 kPa), it can be noticed that the FS is equal to (1.99), which is acceptable since it is greater than 1.5.

The value of reliability index can be calculated from Eq. 6 and is equal to 2.81 which is not acceptable since it is less than the limiting value of (3.13).

It can be noticed that the factor of safety depends on the actual and resistance pressure only while the reliability index will be affected by the accuracy of the results of the soil investigation which can be identified by a statistical terms of standard deviation and COV.

Figure 12 shows the effect of the change in COV of the q_{ult} on the reliability index.

It can be noticed from Figure 12 that the reliability index increases with the decrease of the COV for the same property. This indicates that the more the results are accurate the reliability index is higher.

Figure 12 shows that only if the value of the COV is equal to 5% or less for the same bearing capacity of (100 kPa) the raft can be considered acceptable or “Safe” since it is above the reliability index limit.

The adopted COV of the raft is 12.53% (Table 7) which is greater than 5%, so it is considered to be "unacceptable".

In conclusion, the raft is considered as "safe" from the traditional factor of safety (FS= 1.99 >1.5) and it is "unsafe" from the reliability based design approach since the value of β is lower than the limiting value (β=2.81 < 3.13). This is due to the erratic results and non confidence associated with the results.

Reliability of Combined Piled – Raft Foundation

To combine the results of the FS and Reliability Index for the piles and the raft in terms of statistical average this is obtained by combining different variables according to the relative importance of each.

The Factor of Safety of the combined Piled-Raft is calculated from

$$\mathbf{FS_{CPRF} = \%\ Loads\ on\ Piles\ x\ FS_{Piles} + \%\ Loads\ on\ Raft\ x\ FS_{Raft}} \quad \ldots\ldots(9)$$

$FS_{CPRF} = 0.586 \text{ x } 1.29 + 0.414 \text{ x } 1.99$
$= 0.756 + 0.823 = 1.58 > 1.5$ (OK)

$$\mathbf{b_{CPRF} = \%\ Loads\ on\ Piles\ x\ b_{Piles} + \%\ Loads\ on\ Raft\ x\ b_{Raf}} \quad \ldots\ldots(10)$$

$\beta_{CPRF} = 0.586 \text{ x } 0.971 + 0.414 \text{ x } 2.81$
$= 0.57 + 1.16 = 1.73 < 3.13$ (Not Good)

A similar calculation has been done for different values of Q_{ult} for the piles noting that the Q_{ult} of the soil (Ultimate Bearing Capacity) remains constant to study the effect of the pile capacity on the safety of the structure. Table 8 shows a summary of the calculation of Reliability Index and FS for piles, soil and for the combined piled- raft foundation.

From the Table 8 it can be noticed the CPRF is considered "Unsafe" for all (Qult) values except for the theoretical value of the pile capacity, according to the Reliability Index, β <3.13). The CPRF system is considered "Safe" in terms of FS for all (Qult) values, (FS >1.5).

In conclusion, the CPRF can be accepted or "Safe" under specific conditions depending on the accuracy of the results of both piles and soil, but it will be always "Safe" according to the definition of factor of safety.

8. Conclusions

The case study of Basrah elevated water tank was analyzed by STAAD Pro. Computer package to study the effect of input parameters on the results. The safety of the system was investigated in terms of traditional factor of safety (FS) and reliability index (β) for both [original design of the system as a Piled-Foundation] and [proposed Combined Piled-Raft Foundation (CPRF)].

Several conclusions can be summarized as follows:

1. For the piled foundation analysis, the system is considered "Unsafe" in terms of the traditional factor of safety for 3 of the 4 criteria adopted. The same conclusion was obtained from the reliability based design (RBD).
2. For the CPRF analysis, the system is considered "safe" from the point of view of traditional factor of safety (FS > 1.5) while it is considered "unsafe" from the reliability based design approach since the latter takes into account the variation of the problem for 3 out of 4 criteria adopted (β <3.13). If the variation were lower than

the RBD will show acceptable values.

3. The statistical analysis of different pile tests results showed an erratic variation due to the bad piling work in site and non standard tests.
4. Different criteria for defining the ultimate capacity of the piles (Q_{ult}) were proposed and studied. The ultimate pile capacity calculated from the theoretical approach showed a very high value which was not achieved from the pile tests.

Notations

Abbreviations

CPRF	Combined Pile Raft Foundation
FOSM	First Order Second Moment
RBD	Reliability Based Design

Symbols

A_{shaft}	Surface area of the pile shaft
A_{tip}	Base area of the pile tip
b	Pile tip diameter
c.o.v. or COV	Coefficient of variation
σ_Q	Standard deviation of the density functions for the load
σ_R	Standard deviation of resistance
cu	Undrained cohesion
FS	Factor of safety
Fy or P	Sum of all vertical loads
K	Coefficient of lateral earth pressure
k	Modulus of Subgrade Reaction
kp	Pile stiffness spring
ks	Soil stiffness spring
Lp	Length of pile
m or x	Mean value
m_Q	Mean value of load
m_R	Mean value of resistance
Mx, My and Mz	Sum of moments in all directions
N	Number of piles in the group
$N\gamma$, Nc, Nq	Bearing capacity factors
P	Probability
p_f	Probability of failure
p_s	Probability of survival
P_t	Percent of load transmitted to the pile
q	Effective average (or mid-height) vertical stress for each layer
q_{all}	Allowable bearing capacity
q_{ult}	Ultimate (maximum) bearing capacity
Q	Probability density functions for the load
Q_{act}	Actual load
$Q_{allowable}$	Allowable pile capacity
$Q_{friction}$	Ultimate pile friction capacity through different layers
Q_r	Contact load pressures on the raft
Q_{tip}	Ultimate pile tip capacity
Q_{ult}	Ultimate (maximum) pile capacity in compression
R	Resistance
SD_{act}	Standard deviation for actual load
SD_{ult}	Standard deviation for ultimate load

Greek Symbols

α	Adhesion factor
β	Reliability index
δ	Effective friction angle between soil and pile material
γ'	Effective unit weight
σ'	Effective vertical stress at the pile tip
σ or SD	Standard deviation
φ	Angle of internal friction

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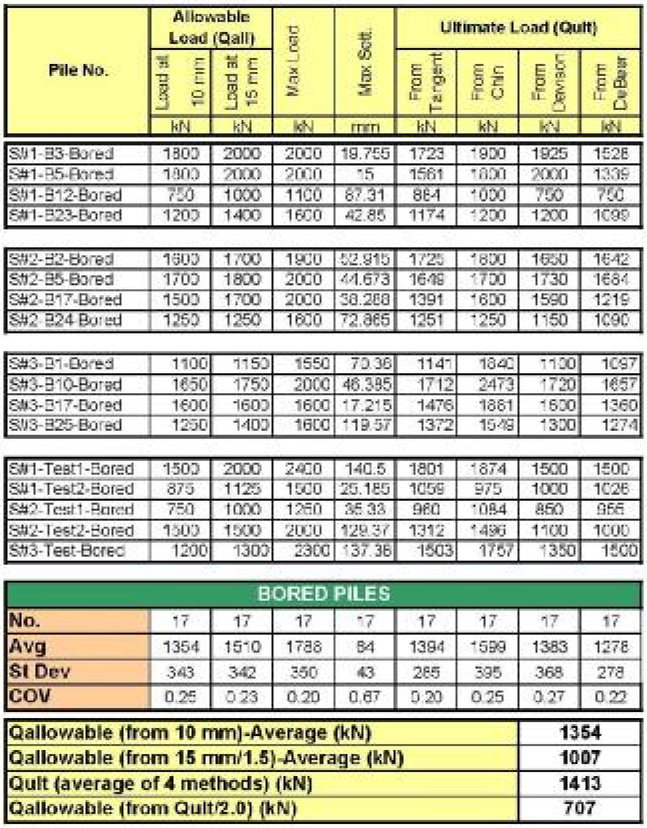
Table (1) Summary of soil report

Layer	Soft Clay Layer					Dense Sand Layer
Site	Thickness (m)	Saturated Unit weight (kN/m^3)	Void ratio, e	Undrained cohesion, c_u (kPa)	Compression index, Cc	Angle of internal friction, j
1	21.5	19.9	0.62	25	0.182	40
2	23	19.8	0.78	36	0.254	40
3	23	19.6	0.755	44	0.135	40

Table (2) Summary of the allowable loads according to the Static Pile Tests results



Pile No.	Allowable Load (Qall)		Max Load	Max Sett.	Ultimate Load (Quit)			
	Load at 10 mm	Load at 15 mm			From Tangent	From Chin	From Davison	From DeBeer
	kN	kN	kN	mm	kN	kN	kN	kN
S#1-B3-Bored	1800	2000	2000	19.755	1723	1900	1925	1528
S#1-B5-Bored	1800	2000	2000	15	1561	1800	2000	1339
S#1-B12-Bored	750	1000	1100	67.31	864	1000	750	750
S#1-B23-Bored	1200	1400	1600	42.85	1174	1200	1200	1099
S#2-B2-Bored	1600	1700	1900	52.915	1725	1800	1650	1642
S#2-B5-Bored	1700	1800	2000	44.673	1649	1700	1730	1684
S#2-B17-Bored	1500	1700	2000	38.288	1391	1600	1590	1219
S#2-B24-Bored	1250	1250	1600	72.865	1251	1250	1150	1090
S#3-B1-Bored	1100	1150	1550	70.36	1141	1840	1130	1097
S#3-B10-Bored	1650	1750	2000	46.385	1712	2473	1720	1657
S#3-B17-Bored	1600	1600	1600	17.215	1476	1861	1600	1360
S#3-B25-Bored	1250	1400	1600	119.57	1372	1549	1300	1274
S#1-Test1-Bored	1500	2000	2400	140.5	1801	1874	1500	1500
S#1-Test2-Bored	875	1125	1500	25.185	1059	975	1000	1026
S#2-Test1-Bored	750	1000	1250	35.33	960	1084	850	956
S#2-Test2-Bored	1500	1500	2000	129.37	1312	1496	1100	1000
S#3-Test-Bored	1200	1300	2300	137.36	1503	1757	1350	1500
BORED PILES								
No.	17	17	17	17	17	17	17	17
Avg	1354	1510	1788	84	1394	1599	1383	1278
St Dev	343	342	350	43	285	395	368	278
COV	0.25	0.23	0.20	0.67	0.20	0.25	0.27	0.22

Qallowable (from 10 mm)-Average (kN)	**1354**
Qallowable (from 15 mm/1.5)-Average (kN)	**1007**
Quit (average of 4 methods) (kN)	**1413**
Qallowable (from Quit/2.0) (kN)	**707**

Table (3) Summary of the results on the pile and soil supports (support-2&3)

Location	Pile support		Soil Support	
	Reaction (kN)	Displacement (mm)	Reaction (kN)	Displacement (mm)
No. of Nodes	25	25	816	816
Sum	27270.28	-----	19277	-----
mean	1090.8	7.78	23.62	7.87
SD	12.53	0.088	1.27	0.42
COV (%)	1.1	1.1	5.3	5.0
Min	1077	7.62	21.45	7.15
Max	1113.2	7.87	26.87	8.96

Table (4) Summary of pile capacity analyses (4 criteria)

Criteria	Mobilized Settlement (mm)*	FS	Q_{ult} (kN)	$Q_{allowable}$ (kN)	C.O.V (%)	Standard Deviation (SD)	k_p (kN/m)
Theoretical	10	6	13470	2245	25	3367.5	1,347,000
10mm Sett.	10	1.5*	2031	1354	25	507.75	203,100
15mm Sett.	15	1.5*	1510	1007	23	347.415	100,700
Avg. 4 Methods	10	2	**1413**	707	23.5	332.055	141,300

***** *assumed values by the researcher***

Table (5) Reliability Index and factor of safety for piled foundation

Criteria	Q_{ult} (kN)	SD (Q_{ult})	Q_{act} (kN)	SD (Q_{act})	FS	b
Theoretical	13470	3367.5	1861.89	85.80	7.23	3.45
10 mm	2031	507.75	1861.89	62.46	1.09	0.33
15 mm	1510	347.415	1861.89	53.16	0.811	-1.00
Avg 4 methods	1413*	332.055*	1861.89*	57.88*	0.758	-1.33

Adopted ultimate pile capacity

Table (6) Reliability index and factor of safety for CPRF – Piles only

Sum (kN)	Sum Loads on Piles (kN)	Percent transferred to piles (%)	Average Value (kN)	SD (act.)	Q_{ult} (kN)	SD (ult.)	b	FS
46547	27267	58.58	1090	12.53	1413.00	332.06	0.971	1.29

Table (7) Reliability index and factor of safety for CPRF– Soil only

Sum (kN)	Sum Loads on soil (kN)	Percent Transferred to soil (%)	Area of Raft (m^2)	Actual Pressure on soil (kN/m^2)	SD (act.)	Q_{ult} Soil (kN/m^2)	SD (ult.)	b	FS
46547	19277	41.42	384.16	50.18	12.53*	100.00	12.53*	2.81	1.99

** assumed values by the author*

Table (8) Results of the reliability index and factor of safety for 4 criteria

Q_{ult} (kN)	b (Piles)	FS (Piles)	b (Soil)	FS (Soil)	b (CPRF)	FS (CPRF)
13470	3.49	7.87	4.09	10.19	3.8	8.83
2031	1.85	1.64	3.28	2.49	2.4	1.99
1510	1.65	1.61	3.12	2.32	2.26	1.63
1413	0.971	1.29	2.81	1.99	1.73	1.58

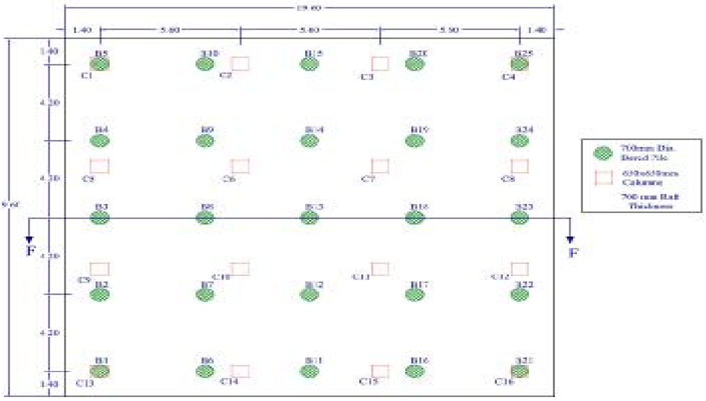


Figure (1) Layout of the pile cap

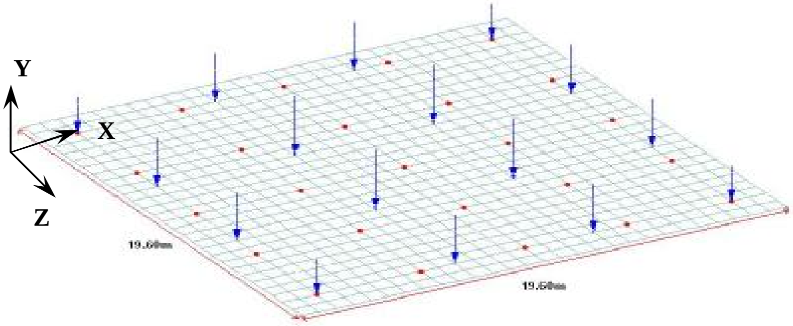
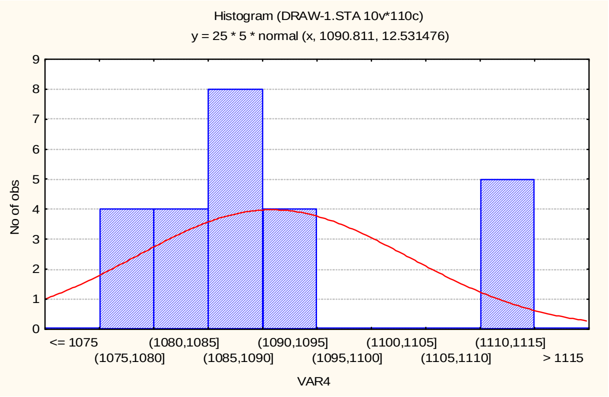


Figure (2) Layout of the STAAD Pro Model

Figure (3): Adopted pile names according to the location



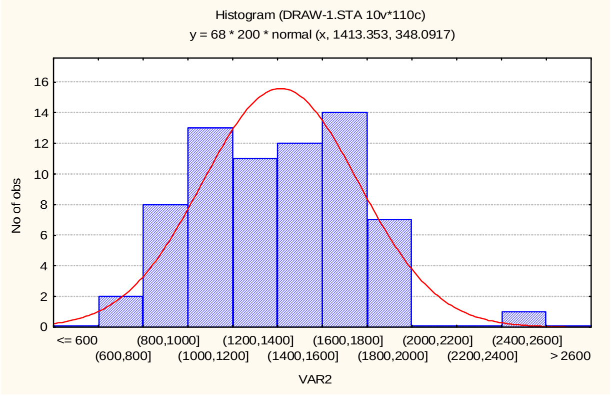


Figure (4) Normal distribution curves of the actual loads for piled raft foundation (Q)

Figure (5) Normal distribution curves for the capacity of the piles (R) for criteria No. 4 (average of 4 methods)

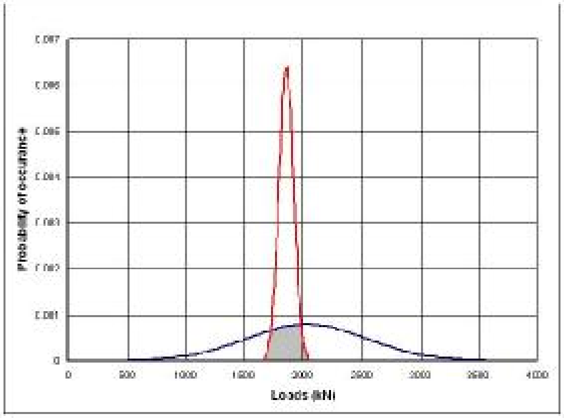


Figure (6) Probability of failure of the piled cap foundation
for piles with k_p=203,100 kN/m

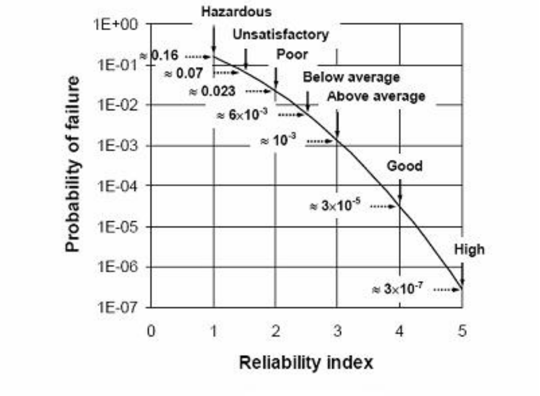


Figure (7): Relationship between reliability index (b) and probability of failure (p_f) [adopted from FHWA, 2001, Table B-1]

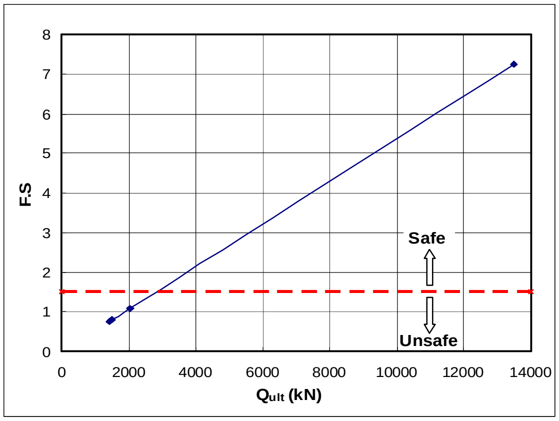


Figure (8): Relation between FS and Q_{ult} for 4criteria

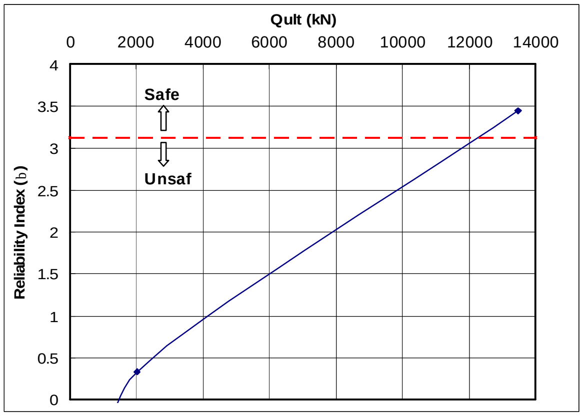


Figure (9): Relation between b and Q_{ul} for 4 criteria

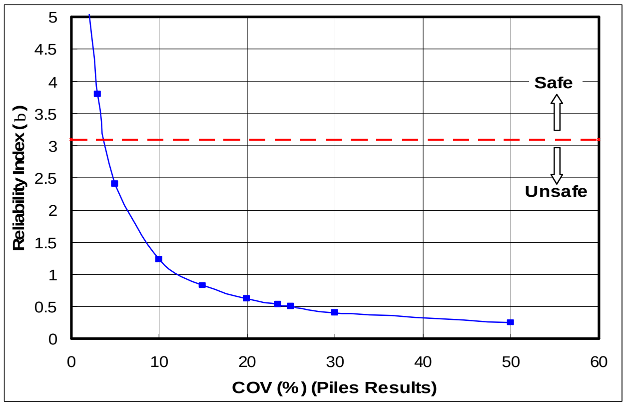


Figure (10) Relation between Reliability Index and COV (for piles only)

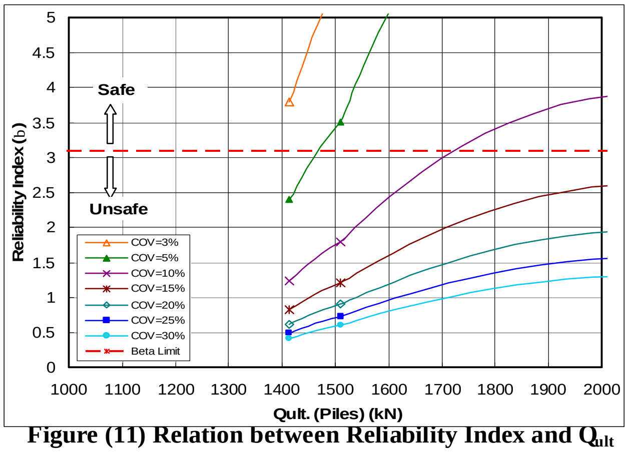


Figure (11) Relation between Reliability Index and Q_{ult} for different COV (for piles only)

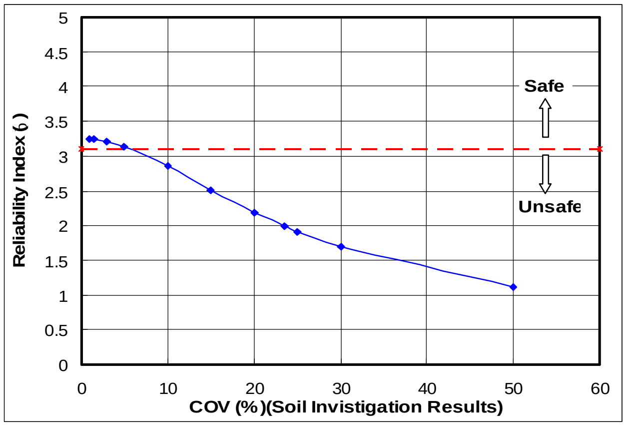


Figure (12) Relation between Reliability Index and COV (for Raft only)