Design and Reanalysis of Pile Cap under Eccentricity

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Abstract. Foundation is the responsible part of any structure to transfer loads from buildings to the soil below. All types of foundation need to be designed properly to avoid any kind of problems that could show up due to poor design. The problems that are encountered during the installation of piles are not taken into account in the early stage of the design. The possibility of exposing to inaccurately driven piles at any construction site is high. Therefore, this study is carried out to design and reanalyze the pile cap due to eccentricity. It focuses on the possibility of the same design to be used under the effect of eccentricity and to reduce the effect of high eccentricity by increasing the number of piles and drive them into the ideal position. The main aim of this research is to figure out how to solve the problem of design and analysis of pile cap due to pile eccentricity that occurs at the site by developing an excel sheet for the pile cap design before and after increasing the number of piles. Beam theory method is used to design and analyze the pile cap due to the flexibility of this method which is not restricted to any number of piles. EUROCODE: MS EN 1992-1-1:2010 is the practice code used for designing and analyzing the pile cap. There are four main parts of this research to explain the outcomes of this study. The first part is the detail drawing of the pile cap which includes the dimension of pile cap, the number of the main reinforcement needed for the pile cap including the bar spacing and spacing between the piles. The second part is testing the design under eccentric load and obtaining the maximum eccentricity to be supported by the pile group without failure. The third part is about designing the pile cap after increasing the number of piles to increase the efficiency of the pile group. The last part is testing the pile cap after increasing the number of piles under the effect of high eccentricity which caused the failure of pile cap before increasing the number of piles. The result of this study shows how the pile cap can sustain the eccentric load until a certain distance which is considered as a safe zone. The same dimension of the pile cap can be used in the third stage of the research by taking into account to locate the additional pile in the most appropriate position which could bring back the centroid of all piles to the original centroid as much as possible.

Introduction

Pile foundation is one of the foundations that usually used when the bearing capacity of the soil is weak for a certain type of structure. A pile cap is a link between the column and the driven piles to transfer the load equally to each pile. However, when the piles are not driven in the accurate location the eccentric load arises which might lead to a big failure of the pile cap. This problem is always not considered in the design stage of the pile cap which can cause either to drive additional piles on the accurate position as shown in the engineering drawing or increase the possibility of pile cap failure if this problem is ignored. The aim of this study is to develop a computer program which is able to analyze the effect of eccentric load on pile cap and decreasing the ability of failure by adding a new pile to increase the capacity of the pile group under eccentricity. This program allows designers to ensure the applicability of the pile cap after designing even under eccentric load.

The number of piles in this study is limited to three piles only and will be increasing to four piles in order to rise up the capacity of the pile group. This research studies the ability to use the same pile cap under eccentricity and checking the optimum limit of the design under high eccentricity prior failure. The failure of pile cap will be considered as a requirement to add a new pile. The created excel sheet will be used by the user to insert all the required data for the new pile and the proposed location by the user then the excel sheet will give the green light for the user to proceed to the design with this location or the red light to propose alternative location.

Literature Review

The pile cap is a concrete block that is cast on the top of a group of piles. The pile cap must have the capability to carry the load that comes from the column and transfer it to the pile group. It must be rigid and capable to distribute the load equally on the piles of a group. There are important parameters need to be checked during the designing process of pile cap which are Punching shear, diagonal shear, Bending and bond in order to avoid any failure of the pile cap and to maintain the rigidity of the pile cap. The driven piles are seldom to be positioned in the exact location as the drawing shown due to the difficulty that might be faced by the workers during the driving of the piles, therefore the tolerance must be taken into account during the design of pile cap.

In [1] the pile caps may be designed by assuming that the load from the column is dispersed at 45º from the top of the cap to the mid-depth of the pile cap from the base of the column or pedestal.

When a pile group is subjected to an eccentric load, it involves the simultaneous mobilization of lateral, torsional and axial resistance of the individual piles. In [2] Based on a previous study that has been conducted for 3x3 pile group subject to eccentricity, it is found from the test results that eccentric load influences the lateral resistance of a pile group subjected to eccentric lateral loading. It also found that a twist center exists in a pile group subjected to eccentric lateral loading. The horizontal displacement of an individual pile in the pile group is proportional to the distance from the pile to the twist center. Moreover, that study indicates that the position of the twist center of a pile group is related to the load eccentricity.

Most of the previous studies were all about the designing of pile cap under an eccentric load without figuring out a good solution for this problem which always cost a lot of money just to replace the failure pile with a new one. In fact, this problem might not have a serious impact on the pile cap if that eccentricity is in the range. Based on the Indian code, the allowable eccentricity is 75 mm in both directions. This limit is actually applicable when all piles move together.

The pile group capacity can be raised up by adding an additional pile. This pile can be one of the solutions to avoid the failure of pile cap under the eccentric load. The position of the additional pile is really critical. The spacing between the pile groups before adding the additional pile might change after increasing the number of the pile. In case the spacing is less than the 3X diameter of the pile, the reduction factor of pile capacity should be taken into account. This reduction is due to the overlapping of stresses.

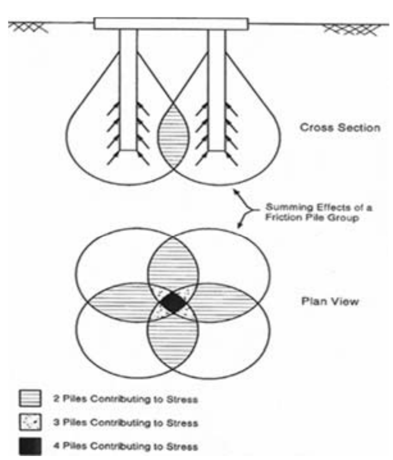


Figure 1: stresses overlapping of 2 piles

In [3] Feld (1943) suggested a method by which the load capacity of the individual piles in a group embedded in the sand could be assigned. According to this method, the capacity of a pile is reduced by 1/16 by each adjacent diagonal or row pile. The embedded is well explained in Figure 2, which shows the layout plan of the group of piles and the distribution of the load. Based on this method, different loads will be assigned to different piles in the group. Table 1 Present the load distribution reduction factor of each pile in a group.

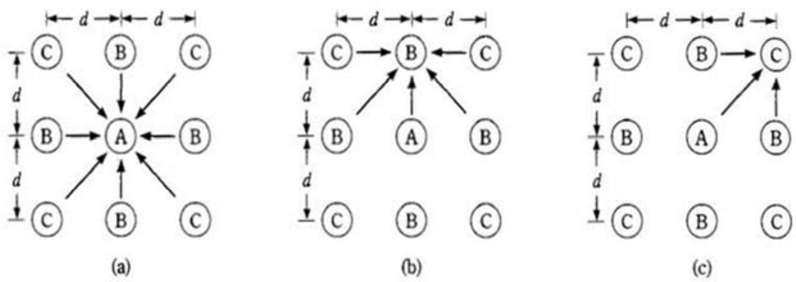


Figure 2: Pile Groups

Table 1: Reduction Factors

Pile type	No. of Piles	No. of adjacent piles/pile	Reduction factor for each pile	Ultimate capacity[a]
A	1	8	$1-\frac{8}{16}$	$0.5Q_u$
B	4	5	$1-\frac{5}{16}$	$2.75Q_u$
C	4	3	$1-\frac{3}{16}$	$3.25Q_u$
				$\Sigma\, 6.5Q_u = Q_{g(u)}$

Methodology

Microsoft Excel is chosen to develop the program because it has various functions and uncomplicated to assist for analyzing, designing and determining the details of pile cap. Microsoft Excel is more flexible, convenient and easier compared to other software.

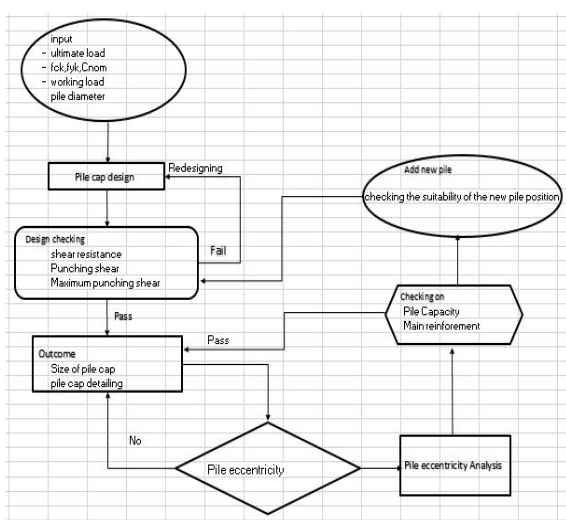


Figure 3: Flow Chart of Analysis and Redesign of Pile Cap

Flow chart in Figure 3 shows the summary of the solution to design and analyze the pile cap. The initial stage of the analysis and designing of pile cap is to insert the information required which are the load and the dimension of pile cap. After that the design checking for pile cap is proceed with shear resistance checking, punching shear checking and maximum punching shear checking. After all the checking have been accomplished, the drawing process and details of pile cap take the second step. During the construction work at the site, when the pile is driven and eccentricity occurs, the pile cap should be reanalyzed again. If the load acting on each pile exceed the pile capacity or the design of the main reinforcement is not sufficient and adequate to support the bending moment due to the eccentricity, redesigning process for pile cap is needed to be repeated. The main objective of this study is to solve the problem of analysis and redesign of pile cap due to the pile failure and develop a program that can ease the engineering work. Therefore, Microsoft Excel is used in this study to do all the calculations whereas AutoCAD is used to draw the detailing of the pile cap.

This section covers the development of data using Microsoft Excel to facilitate the process of analyzing pile cap system:

First stage of pile cap analysis

At the early stage of design, the focus is more on recalculating the load on pile cap and analysis of the load in individual pile and number of pile need to be used.

Second stage of pile cap analysis

The second stage of the design focuses more on the designing of the pile cap based on the data obtained from the recalculating and analyzing of the load at the early stage.

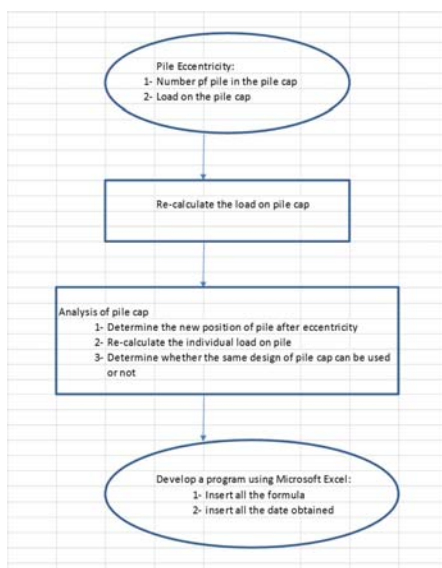


Figure 4: Flow chart of methodology of analysis and redesign of pile cap due to pile eccentricity

Result and Discussion

Pile Cap under Various Cases of Eccentric Load.

In the designing process of pile cap, eccentricity needs to be checked in all cases that might occur in the site. In this spreadsheet, we consider three cases for eccentricity. These cases are:

1. Movement of pile number 1 only from the original position
2. Movement of pile number 1 and pile number 2 only from the original position.
3. Movement of pile number 1 and pile number 3 concurrently from the original position.
4. Movement of all piles concurrently from the original position.

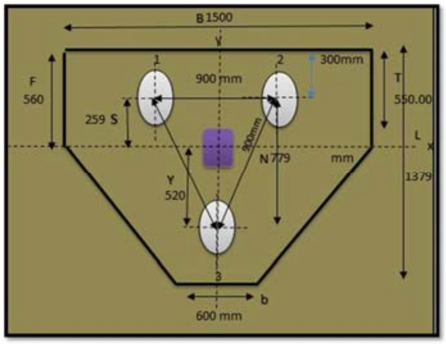


Figure 5: the original positions of all piles

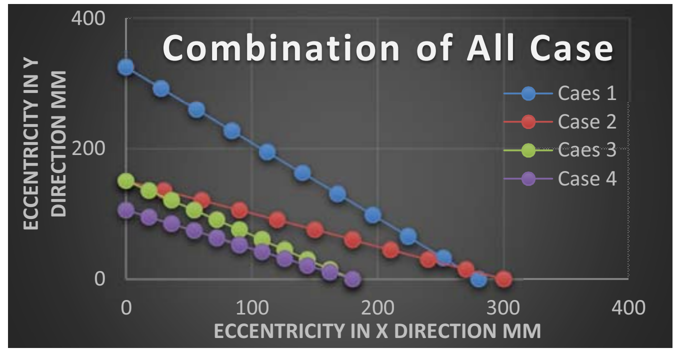


Figure 6: Maximum eccentricity for pile cap in all cases

Figure 6 shows the all the prospective cases that might happen on the site due to eccentricity. The blue line represents the movement of 1 pile only among the three piles. The furthest distance in x-direction can reach up to 280 mm with 0 movements in y-direction and 325 mm in y-direction with 0 movements in x-direction without any failure. Nevertheless, in the movement of the pile in both directions, the furthest safe distance in y-direction is 162.5 mm however in x-direction is 140 mm. This result shows how the movement of one pile could not have a significant impact on the pile cap. The first case is seldom to occur in site. Moving to the second case which is represented by the orange line. It results in the movement of pile 1 and piles 2. From the obtained result, the furthest safe distance in x-direction is 300 mm with 0 movements in y-direction and 150 mm in y-direction with 0 movements in an x direction. In the case of the simultaneous movement of both piles in both directions, the furthest distance in x-direction is dropped to 120 mm as well as a significant drop in the y direction to 90 mm only. The gray line represents the third case which is the movement of pile 1 and piles 3 together. From the obtained data, the maximum distance in x-direction is 180 mm with 0 movements in y-direction and 150 in y-direction with 0 movements in an x direction. The combined movement in both directions is limited to 90 mm in x-direction and 75 mm in y-direction. This result shows how the movement of pile 1 and pile 3 together is more significant than the movement of pile 1 and 2 together. This difference illustrates the effect of the movement of pile 3 which plays an important role in bringing back the centroid of the pile group closer to the original location when pile 1 and 2 are moving. The location of pile 3 has a considerable importance to maintain the centroid of the pile group which is resulting in lowering the possibility of failure due to a certain eccentricity.

The last case which is represented by the yellow line is obtained by the movement of all piles together. All piles can move together in the x direction with a distance of 180 mm conditional upon 0 movements in y-direction. The same concept can be applied to all piles when they move together in y-direction with a maximum distance equal to 105 mm with 0 movements in an x direction. All piles could move together in both directions with limited distances to 72 mm in x-direction and 63 mm in y-direction. The last case is considered as the safest case for any construction of pile cap. This case ensures that all piles can sustain the load without any failure. In comparison with the applied principle in the most designing codes that the maximum distance for each pile is 75 mm from the original location can be taken into account. However, this value cannot be restricted anymore since this study proved that eccentricity depends on the movement of all pile together not on only 1 pile. In a more specific way, the movement of piles produce an eccentric load which can reduce the pile capacity however, this reduction can be controlled if the movement of all piles is still in the limited safe zone. This limited safe zone assures the safety of the pile cap under even eccentric load.

The failure of pile cap under high eccentric load can be overcome by adding a new pile in a new position which can pull back the centroid of pile group to the original centroid.

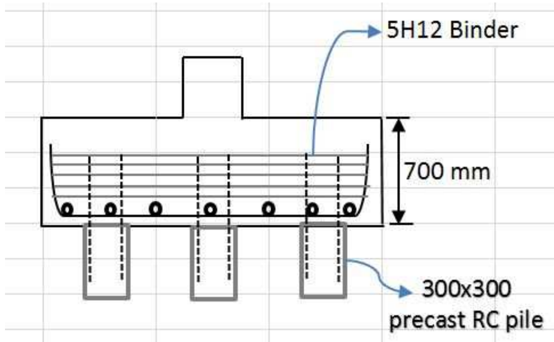


Figure 7: detailing of pile cap (x-x)

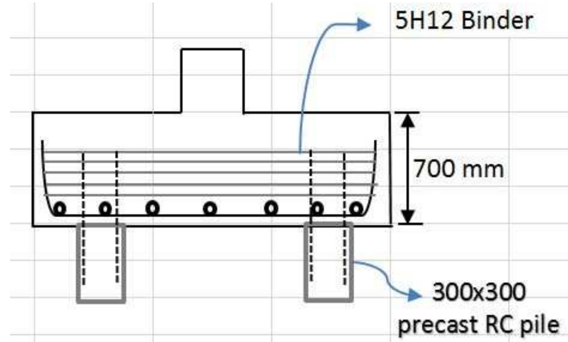


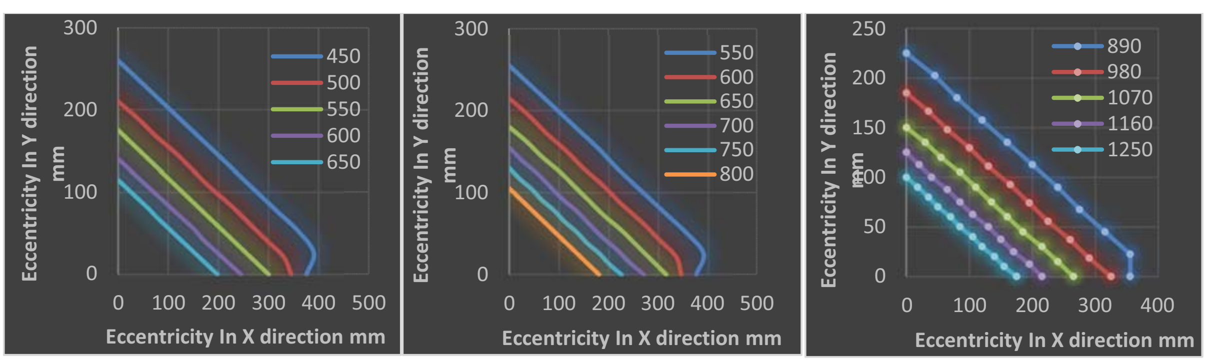
Figure 8: detailing of pile cap (y-y)

Pile Cap Design With Different Working Loads And Various Axial Loads

Figure 9(a) shows the maximum eccentricity for a group of the pile with 250 KN working load. Each line in the graph represents a different axial load. The axial load's range starts from 450 KN up to 650 KN. This range is based on the maximum and minimum load that is required for 3 piles only. The more the axial load the less allowable eccentricity will be obtained from the graph in both directions. The user of this software has the opportunity to refer to this graph to check if the design of pile cap still in the safe zone or not.

Figure 9(b) shows the maximum eccentricity for a group of the pile with 300 KN working load. Each line in the graph represents a different axial load. The axial load range starts from 550 KN up to 800 KN. This range is based on the maximum and minimum load that is required for 3 piles only. The more the axial load the less allowable eccentricity will be obtained from the graph in both directions. The user of this software has the opportunity to refer to this graph to check if the design of pile cap still in the safe zone or not.

Figure 9(c) shows the maximum eccentricity for a group of the pile with 450 KN working load. Each line in the graph represents a different axial load. The axial load range starts from 890 KN up to 1250 KN. This range is based on the maximum and minimum load that is required for 3 piles only. The more the axial load the less allowable eccentricity will be obtained from the graph in both directions. The user of this software has the opportunity to refer to this graph to check if the design of pile cap still in the safe zone or not.



(a) (b) (c)

Figure 9: Maximum eccentricity for pile with (a) 250 KN, (b) 300 KN, and (c) 350 KN working load

Additional Pile

Eccentricity has a really strong effect on the pile capacity. This eccentricity is able to produce a load more than the capability of the pile which leads to a big failure of the pile group. There are many solutions to overcome the problem of high eccentricity such as drive a new pile to resist the high eccentric load.

The most difficult decision to drive a new pile is to locate the most suitable location for this pile which can reduce the effect of eccentricity on the pile group and pull back the centroid of the pile group to the original center.

This spreadsheet is actually created to help the user to find the new location for the additional pile in the condition of failure. Users have the ability to insert the new position of the new pile and the result will come out to show whether the location that is proposed by the user can be applied in the field or not. This spreadsheet is applicable when at least one of the piles is failed to receive higher load than the pile capacity itself due to the high eccentricity.

A new sheet is created for a group of 4 piles to be designed. The new pile has been located at the center of the pile group. This pile has the same characteristics of the other piles. The same cross-sectional area of the pile and the same working load is applied to the new pile which is located just below the column.

The additional pile will reduce the efficiency of the group pile and this reduction is due to the overlapping of stresses between the piles when the spacing is less than 3d. The reduction factor for pile 1 and pile 2 is equal to 0.875. Hence the capacity of these piles will be dropped from 300 KN to 262.5 KN. However, the reduction factor for pile 3 is equal to 0.9375, therefore the capacity of pile 3 will be dropped from 300 KN to 281.25 KN. Last but not least the reduction factor for the additional pile is equal to 0.8125 and the capacity of this pile will be equal to 243.75 KN.

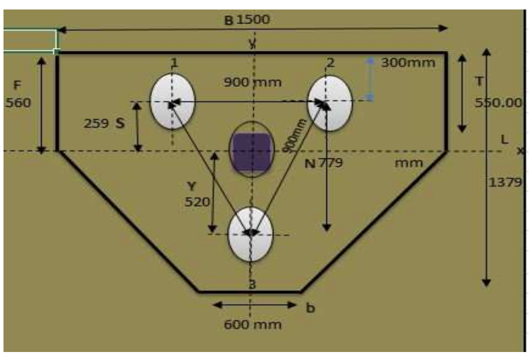


Figure 10: the location of the additional pile

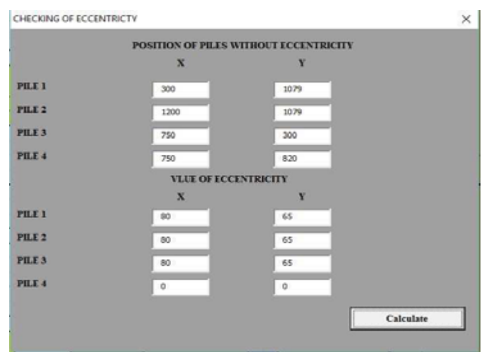


Figure 11: User form of pile eccentricity

Before starting the analysis, the user is required to insert the new value of the eccentricity which must be beyond the safe zone to check whether the additional pile can resist the eccentric load and protect the group of the pile from failure or not.

Figure 12 shows the user form for checking the suitability of the proposed location for the additional pile. The inserted value of eccentricity in both directions are beyond the safe zone that was shown earlier. Based on the obtained data, the pile cap is able to sustain the high eccentricity without failure which can provide a safe pile cap even under high eccentric load.

Checking for pile capacity												
F	=	Service load + selfweight / number of pile	±	Mx(y) / Ix	±	My(x) / Iy						
Fpile 1	=	151.91	+	41.03	+	57.63	=	250.57	KN	<	262.5	OK!
Fpile 2	=	151.91	+	41.03	-	57.63	=	250.57	KN	<	262.5	OK!
Fpile 3	=	151.91	-	8.60	+	10.25	=	153.56	KN	<	281.25	OK!
Fpile 4	=	151.91	-	17.22	+	0.00	=	134.69	KN	<	243.75	OK!

Figure 12: checking for pile capacity

Conclusion

The effect of eccentricity on the behavior of pile group subjected to axial load has been investigated in the paper through computer program assist. Overall, this study has achieved its objective. The program that was created to ease the solving of pile cap system problem has been developed as required. The user is able to use this software to ease the computing and calculation process with the highly accurate result. Moreover, this software is very helpful in designing and analyzing the pile cap with a group of three piles only. The main requirement for increasing the number of the pile is having a high eccentric load which forces the centroid of all piles to be shifted from the original position. Increasing the number of piles might help in most situations especially when the dimension of the pile cap cannot be changed anymore. The additional pile must be driven into a location that can bring back the centroid of the pile group to the original centroid which is right below the column.

From the study, the problem of eccentricity in pile cap cannot be underestimated because of the serious failure that might occur even if the eccentricity of the pile is below 75 mm in accordance with Jabatan Kerja Raya. The movement of all piles in both directions is limited to 72 mm in the x-direction and 63 mm in the y-direction. These two values are less than 75 mm the value that is considered as the safe distance in accordance with Jabatan Kerja Raya.

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