Hojas de cálculo para el análisis de losas combinadas con pilotes

Spreadsheets for the analysis of piled raft foundations

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Resumen

En el diseño de cimentaciones en balsas combinadas con pilotes, se determina un gran número de incógnitas de forma tal que se obtenga una cimentación racional y que a su vez cumpla con los requerimientos de proyecto. El empleo de hojas de cálculo, facilita el trabajo del proyectista, al poder predimensionar la cimentación, evaluando la influencia de los diferentes parámetros que intervienen en el diseño, para finalmente utilizar programas de cómputos para el cálculo definitivo. En este trabajo se muestran los resultados obtenidos con hojas de cálculo programadas en MathCad y se comparan los valores de la curva estimada carga vs deformación de las hojas de cálculo con resultados de modelos a escala real y otros de la literatura sobre el tema.

Palabras Clave: Pilotes, balsas, modelación numérica, diseño

Abstract

In the design of foundations in piled rafts, a great number of unknown facts are determined in order to obtain a rational foundation, which in turn meets the requirements of the project. The use of spreadsheets facilitates the work for the designer, to estimate the dimensions of foundation, thus evaluating the influence of various parameters involved in the design, so as to finally use computer programs for the final calculation. This paper shows the results obtained from spreadsheets programmed by MathCad and, it compares the values of the estimated curve load v/s deformation of spreadsheets with the results of full scale models and others from literature on the subject.

Keywords: Piled raft, settlement, numerical modeling, design

1. Introduction

Piled raft foundation is a constructive system characterized by the joint action of the following elements: rafts and piles, which purpose is to transfer loads from the superstructure onto the ground where the foundation is to be laid. Over the past decades several investigations and concept developments have been carried out, in order to better understand the joint behavior of rafts and piles (Poulos 2001; Cunha et al., 2000a; Cunha et al., 2000b, O'Neill et al., 2001; Van Impe W.F. y De Clercq 1994), which turns this constructive system into a foundation alternative generally associated to high buildings laid on granular soils and, particularly on clay-strengthened or over-strengthened soils.

Regardless of the type of soil, the application of the raft-piles system could become an advantage, when a foundation is only laid on piles, the number of piles increases and the distance between them decreases. In a deep conventional foundation, the piles' supporting capacity shall be reduced when the distance between piles decreases to values lower than three or four times its diameter approximately. It leads to an increase of piles length and, therefore, it raises the foundation costs.

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The interaction analysis of the three elements: raft, piles and soil is of major importance for the evaluation of the settlements unit, no matter if they are uniform or differential ones. At the same time, an accurate settlement forecast is essential in order to verify that serviceability requirements are duly met.

Besides leading to a settlements reduction, additional positive effects can be mentioned about piled rafts (CPRF) compared to a single foundation raft:

- *Increased supporting capacity of foundation*
- *Reduction of loading strengths transferred into the soil from the foundation raft, by means of a proper selection of piles amount and layout.*
- *Improved service behavior due to the reduction of individual or differential settlements. In other words the CPRF acts by putting the brake on the settlement.*
- *Reduction of failure and cracking risks on the superstructure elements, particularly on buildings front walls.*
- *The stability for the whole foundation unit is secured, as the raft itself does not guarantee the stability in regards to live loads.*

In accordance with regulation DIN 1054 (1994), a CPRF project is based on the idea of absorbing the total load by means of a piles system, by disregarding the supporting capacity from the foundation raft. It is quite evident that taking this proposal into consideration will lead to cost-effective projects, thus reducing the amount of piles and, at the same time, ensuring settlements within allowed limits.

Although the CRPF behavior has been surveyed and researched since decades, the exterior loads distribution mechanisms, as well as the behavior under load settlement, have not been fully distinguished, because of the complex interaction of its elements.

The most important factors affecting the load-settlement behavior in a CRPF are the following:

- *Interaction between a set of piles*
- *The reciprocal effect between piles and rafts*

The Figure 1 depicts the layout for the relationship load-settlement for a single pile, for a set of piles and for a raft. On one hand, the interactions between the set of piles and the piled raft, lead to a reduction of piles stiffness, in regards to their load-settlement behavior. On the other hand, they increase their supporting capacity to its limit.

Figura 1. Curvas esquemáticas carga asentamiento (Poulos 2001)

Figure 1. Layout curves for load-settlement (Poulos 2011)

2. Development

2.1 Analysis Methods

Several analysis methods for combined piled raft foundations have been developed (Poulos et. al., 1997), some of them are mentioned as follows:

- Streamlined calculation methods
- Approximate computer methods
- Accurate computer methods

Among streamlined methods, we are able to mention the ones proposed by Poulos and Davis (1980); Randolph y Wroth (1983); Randolph (1994); Van Impe and De Clerq (1994) and Burland (1995). All of them develop a streamlined soil modeling and a loading application streamline.

The method by Poulos and David (PDR) employed for the development of this study is further described. The hypothesis is based on the consideration that the ultimate foundation loading capacity, under vertical loading, absorbed one of the following values:

- The addition of the raft's loading capacity plus the total piles' loading capacity, or
- The addition of loading capacity of the unit formed by piles and the raft plus the raft remaining portion.

It is worth mentioning that the isolated pile's loading capacity will be affected by the adjacent piles, which is known as unit efficiency, varying from $\xi = 0.7$ to 1.

So as to estimate the load deformation curve behavior on the combined piled raft foundation, the expressions proposed by Randolph (1994) are applied and, the stiffness of the CPR foundation is determined as follows:

$$K_{pg} = \frac{K_p + K_r(1 - \alpha_{cp})}{1 - \alpha_{cp}^2 \left(\frac{K_r}{K_p} \right)} \quad (1)$$

Where:

K_{pg} Stiffness of piled raft foundation

K_p Pile stiffness

K_r Raft stiffness

α_{cp} Piled raft interaction factor

The share of total load transferred to the slab is expressed as follows:

$$X = \frac{K_r(1 - \alpha_{cp})}{K_p + K_r(1 - \alpha_{cp})} \quad (2)$$

By obtaining such coefficients, the estimated foundation load deformation curve can be developed. Poulos (2001) proposed the use of MathCad spreadsheets in order to facilitate calculation processes and to rapidly evaluate the effect of piles amount to be used for laying the foundation.

2.2 Use of Spreadsheets

So as to solve this problem, not needing to employ powerful calculation programs, MathCad spreadsheets were selected for the abovementioned procedure, by taking advantage of their abilities for engineering design.

MathCad is the solution for engineering calculations, which simultaneously solves and stores calculations, also considerably reducing the risk of high cost errors. This program allows engineers to design, solve and store their work under an easy-to-understand format, which is shareable and reusable, thus improving cross checking and validation, broadcasting and collaboration during the whole execution process.

MathCad is an ideal tool used to solve engineering problems under a didactic approach. A special advantage of this software is its ability to represent algebraic equations involved in the solution of a problem, together with the corresponding numeric evaluation. This feature turns this software into an ideal tool for engineering problems, which presentation is required as a report or a calculation worksheet, thus helping to understand the problem (MathCad 2011; Galambos 2001). Besides, this tool offers a "board design" environment allowing engineers to capture, apply and easily manage requirements, critical data, methods and products assumptions in order to quickly develop calculations. By using MathCad, original concepts, underlying assumptions, math formulas, explanatory graphs, information texts, remarks, outlines and results are clearly seen on the worksheet.

For this case that draws our attention, several spreadsheets were programmed interacting among themselves, so as to allow a friendly interface between the user and the computer, thus offering the possibility of changing entry data and design parameters.

Among the several advantages provided by the use of spreadsheets, we mention that:

- They facilitate the analysis of several variables, saving time and computer resources.
- Stratum soils can be analyzed.
- The variation of the general deformation module and its depth can be analyzed.
- It is possible to interact with the spreadsheet and to modify expressions, parameters, etc.

2.3 Applications

2.3.1 Spreadsheet Validation

So as to validate spreadsheets, they are compared with the results obtained by Sales (2001). This author analyzed cases quoted by international literature about combined piled raft foundations supported by 4 and 16 piles.

Figura 2. Ejemplos analizados

Figure 2. Analyzed examples

For the case of piled raft foundations supported by 4 piles (Table 1), the soundness of obtained results is proven, thus showing a greater difference for loads higher than 500 kN, where the foundation begins to work under a combined way.

Tabla 1. Comparación entre los métodos para estimar los asentamientos en una balsa sobre 4 pilotes

Table 1. Comparison between methods used to estimate the settlements of a raft supported by 4 piles.

Carga (kN)/ Load (kN)	Asentamientos (mm)/ Settlements (mm)		
	Método Poulos (1980)/ Poulos Method (1980)	Método Poulos (1998)/ Poulos Method (1998)	Hojas de Cálculo/ Spreadsheets
0	0	0	0
100	1.16	1.41	1.34
200	2.34	2.83	2.26
300	3.48	4.24	3.40
400	4.64	5.66	5.61
500	5.81	7.09	6.68
550	7.68	7.78	8.57
600	9.55	9.51	11.56
700	13.29	13.25	14.56
800	17.03	16.99	17.55

In the case of rafts supported by 9 and 16 piles (Tables 2 and 3) proposed by the Technical Committee TC-18 of ISSMGE (Poulos (2001)), the results are similar to the ones obtained by the calculation software, GARP6, which proves the soundness of elaborated spreadsheets and their potential.

The use of spreadsheets quickly allows to count with a computer tool developed by applying the Poulos method (1998), disregarding the use of complicated hand-made calculations originally demanded by such method. However, we should not forget that spreadsheets can never replace the engineers' experience and that obtained results shall be compared with some other methods and full scale results.

Tabla 2. Valores de rigidez obtenidos aplicando diferentes métodos. Balsa sobre 9 pilotes

Table 2. Stiffness values obtained by applying different methods. Raft supported by 9 piles

Parámetro/ Parameter	Método Poulos (1998)/ Poulos Method (1998)	Software GARP6/ GARP6 Software	MathCad
Kr (kN/m)	26739	27719	26742
Kp (kN/m)	37152	39824	37252
Kpr (kN/m)	70630	79702	70531

Tabla 3. Valores de rigidez obtenidos aplicando diferentes métodos. Balsa sobre 16 pilotes

Table 3. Stiffness values obtained by applying different methods. Raft supported by 16 piles

Parámetro/ Parameter	Método Poulos (1998)/ Poulos Method (1998)	Software GARP6/ GARP6 Software	MathCad
Kr (MN/m)	240	310	240
Kp (MN/m)	2190	1901	2174
Kpr (MN/m)	157	157	156

Figura 3. Curva Carga vs asentamiento utilizando varios métodos

Figure 3. Load v/s settlement curve employing several methods

2.3.2 Actual Load Tests

Once results obtained from spreadsheets were compared to international literature examples, they were applied to actual problems, which are documented by full scale load tests. To do so, the results obtained by Koizumi and Ito (196) were applied to a 2m x 2m footing foundation, supported by 9 piles of 0.3 m diameter each, which lay across two soil layers. Such authors determined the individual and collective contribution of the foundation, piles and combined piled raft foundation.

Tabla 4. Parámetros de los suelos, balsa y pilotes del ejemplo analizado
Table 4. Parameters for soils, raft and piles of the analyzed example

Suelo/ Soil	Módulo Gral de Deformación/ Overall Deformation Module (MPa)	Coefficiente de Poisson/ Poisson Coefficient	Espesor/ Diámetro/ Thickness/ Diameter (m)
Suelo 1/ Soil 1	12.8	0.4	1.7
Suelo 2/ Soil 2	15.6	0.4	3.8
Balsa/ Raft	30000	0.2	0.7
Pilote/ Pile	200000	0.2	0.3

Figure 4 shows the comparison of results between the actual test (Koizumi and Ito (1967)) and the spreadsheets, which prove once again their soundness and their application to estimate the load deformation behavior of piled raft foundations.

Figura 4. Curva carga asentamiento en el ensayo real Koizumi y Ito (1967) y las hojas de cálculo
Figure 4. Load v/s settlement curve developed by Koizumi and Ito's (1967) actual test and by spreadsheets

Design Safety Evaluation

Once spreadsheets were validated, different factors involved in the foundation design for combined piled raft foundations were evaluated, by employing the abilities provided by card files elaborated by MathCad.

The first analysis is related to the effect of the piles number to be used and the safety of the obtained settlement, which in turn is related to the settlements expected to take place.

Therefore, a piled raft is analyzed, where the number of piles has been increased and the safety factor is determined for the whole foundation (SF) and the estimated settlements. A pre-designed raft of 10m x 8m (without piles), $SF = 1.5$ and settlements of 90 mm are considered; then the effect of adding piles for the settlement decrease and the increase of safety factor are taken into account.

$$FS = \frac{P_{ultimate}}{P_{admissible}} \quad (3)$$

Where:

$P_{ultimate}$: Ultimate foundation load

$P_{allowable}$: Allowable foundation load

Figura 5. Cantidad de pilotes vs factor de seguridad

Figure 5.

Figura 6. Cantidad de pilotes vs. asentamientos

Figure 6. Number of piles v/s settlements

As shown on Figures 5 and 6, there is an increase of security factor as long as the number of piles rises (results correspond to a 4D spacing). However, when using more than 16 piles, the estimated settlements are kept almost equal. Therefore, the increased number of piles does not decrease settlements, thus making this design even less reasonable.

For values obtained from 4 and 16 piles (Safety Factor, $SF = 2$ to 3), the effect of piles as settlement reducer agents is noticeable in the foundation, thus justifying the use of piles in a CPRF, in order to make the foundation safer and to achieve the project deformations.

Such results are similar to the ones proposed by Poulos (2001) in "A Report Prepared on Behalf of Technical Committee TC18 on Piled Foundations, ICGSMM-2001".

2.3.4 Evaluation of Piles Number

The effect of piles number on the behavior of the estimated load deformation curve is evaluated below. For this numerical example a raft of 8m x 8m and 0.7 meters high was considered. Piles are fabricated from reinforced concrete with diameter of 0.5 meters and length of 15 meters. Concrete with compression resistance of $f'_c = 30$ MPa was considered for both raft and piles. For the foundation soil, two layers of 5 and 10 meters were considered $E_o = 12.5$ MPa and $E_o = 30$ MPa, respectively. The estimated loading capacity of piles is 1.93 MN.

Figura 7. Curva carga asentamiento para diferente número de pilotes

Figure 7. Load v/s Settlement curve for different number of piles

Figure 7 shows the results of load deformation curve for different number of piles. It is observed that for small loading values lower than 8 MN, the settlements are quite similar, so the effect of piles number is insignificant. In this case a safety factor $SF = 2$ was considered for the CPR foundation. It is observed that although under 12 MN axial load, the foundation supported by 9 piles stands up against live loads ($SF = 1.33$) and deformations exceed 150 mm. However, CPR foundation supported by 16 and 25 piles maintains safety values higher than 2 ($SF > 2$) and deformations of 40mm approximately.

This example highlights the use of piles, which is justified in cases where raft settlements are intended to be reduced. It is possible that: (1) they reach safety values under external loads higher than 1.5 ($SF > 1.5$) not meeting the ultimate deformation limit (9 piles); (2) safety values under external loads higher than 1.5 ($SF > 1.5$) are achieved and the ultimate deformation limit is fulfilled (16 piles $SF = 2$) and; (3) safety values under external loads quite higher than 1.5 ($SF > 1.5$) are achieved and the ultimate deformation limit is fulfilled (25 piles, $SF = 2.8$)

The obtained results do confirm the ones proposed by Poulos (2001) in "A Report Prepared on Behalf of Technical Committee TC18 on Piled Foundations. ICGSMM-2001"

3. Conclusions

The following conclusions are drawn from this study:

- *The ability of spreadsheets elaborated by MathCad for the analysis of CPR foundations analysis is demonstrated.*
- *The use of spreadsheets facilitates the analysis of CPR foundations, allowing the evaluation of different factors effects, not needing powerful softwares based on numerical methods, thus saving time and computer resources.*
- *The effect of piles used for CPR foundations is evaluated on the whole structure safety as well as the estimated loading deformation curve.*
- *Although the advantages of the spreadsheets use for the analysis and design in civil engineering are evident, special attention shall be focused on the obtained results, which shall be analyzed by experienced and skillful engineers. Such results shall be complemented with some other methods and measurements at full scale.*

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