Analysis of concrete masonry structures considering soil-structure interaction

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Abstract. This paper analyses the behavior of a concrete masonry structure with piled raft foundation, where the number of floors and piles are changed, in order to respect the capacity of the soil and it also studies the differences between the rigid and elastic support, when you apply or not wind efforts. During investigation, were collected the stresses in the walls and the bending moments in the raft. The results showed that neither the wind or the support changed the behavior of the structure and the stresses in the walls, but it modified the bending moments in the foundation. Moreover, the experiment presented that the piles had more influence in the maximum stresses and their location than the raft.

Keywords: Structural Concrete Masonry, Soil-structure interaction, Rigid Support, Elastic Support.

1 Introduction

Structural masonry is the method which uses its own walls as part of the structure and the bricks and connections are the ones responsible for resisting the internal efforts and they are also responsible for protecting the building from the weather, as heat, cold, rain, generating a good economy, because combine two systems into one. Furthermore, it works with pre-cast bricks and industrial mortar, which makes the construction similar to an industrial procedure as it doesn't need to produce materials in the field just need to assemble them. With these advantages in mind, many companies in different countries used this technique and studies become more advanced, but researches about the relation between the building and the soil, even with some papers and thesis about the subject, are still insufficient due the complexity of the soil and the interaction. So, this paper studied the behavior of a concrete masonry structure with a piled raft foundation being influenced by wind and accidental loads. The analyses consisted of 2 groups of 9 models each, where we changed the number of floors and piles, this was changed considering that each pile could not transfer more than 600 kN to the soil in order to avoid excessive deformation. The difference between groups is the type of support considered, in one group we insert an elastic spring at the end of the pile and the second we restrained with a pinned support. The idea was to study the behavior of the structure, walls and foundation, while we increase the number of floors and piles, verifying stresses and moments and see the differences in considering the restraint or the spring, comparing to literature results.

2 Concepts

Structural masonry is a technique that had been used for thousands of years and in the last few decades it was studied carefully and some formulations and normalizations were stablished, that helped the academics and constructors to understand its behavior, which generated economy, and created specifications and tests to determine the quality of the bricks, helping to ensure the standardization of the materials, such as the ABNT NBR 16868 part 1 (Design) [1] , part 2 (Execution and site control) [2] and part 3 (Test methods) [3].

A raft or slab foundation, according to ABNT 6120 [4], is a superficial structure that is responsible for transferring the loads from the building to the soil through contact pressure and in order to take this relation into account exist some ways of doing it, as presented by Velloso and Lopes [5], such as Winkler hypothesis and a 3D representation of the soil. In the first, we substitute the soils for a spring (vertical reaction coefficient) under the structure and its value is based on studies and deformations inside the soil layers that can be obtained in a plate test, regulated by ABNT 6489 [6] – Soil – Static load test on shallow foundation. The second we study everything together, soil, structure and foundation and verify their true behavior and this would be the ideal, but it is difficult to create, that's why in this study we used the first consideration.

In his research, Porto [7] apud Gusmão [8], describes that when you consider soil-structure interaction (SSI) instead of a pinned support, you obtain a redistribution of efforts and differential settlement, so, columns that received smaller loads tend to attract more efforts when compared to normal restraint, creating a more uniform distribution.

Poulos [9], during his studies about piled raft foundation, observed that while increasing the number of piles the maximum settlement decreased, but with 20 and more piles the result was almost constant. Besides, the author verified that was not a linear relation between the number of piles and the maximum moment or the differential settlement, he also said that there isn't a good number of piles to be used, showing in his research that the raft with a few piles near the most loaded columns had a better behavior than the model with more piles equally distributed.

3 Methodology

Research was developed with a single building design, presented in Fig. 1, where the number of load levels and piles were increased and the type of support were changed between pinned and spring.

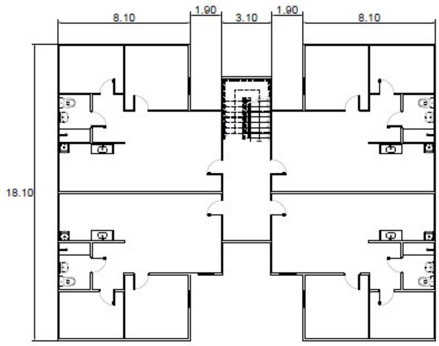


Figure 1. Building Design – Typical floor plan

The 3D typical floor plan was made considering the respective doors and windows openings, in order to include the redistribution of loads, also, every floor have 2,5 meters high, the floors plates are 0,10 meters thick, the slab foundation has a thickness of 0,20 m and a minimum offset of 0,50 m from the outside walls and the piles have a diameter of 0,40 m and a length of 12 m. The walls were stablished with a width of 0,05 m to simulate external parts of the concrete block. The structure was meshed using 0,5 x 0,5 m squares to obtain a good compatibility between nodes. So, the walls were stablished with a width of 0,05 m to simulate the external parts of a concrete block, the foundation was detailed with a 0,20 m thickness while the floor's slabs were described with a 0,10 m thickness. The concrete used in the blocks had a specific weight of 14 kN/m³, poisson ratio of 0,2 and young's modulus of 6720 MPa, and the one used in the slabs and in the piles had the same poisson ratio, but a specific weight of 25 kN/m³, a young's modulus of 22000 MPa and resistance of 20 MPa. The number of floors and piles were increased, the first from 4 to 12 and the second following the indication of Tab. 1 and the position shown in Fig. 2.

Table 1. Number of Piles x Number of Floors

Number of Floors	Number of Piles	Number of Floors	Number of Piles	Number of Floors	Number of Piles
4 Floors	42	7 Floors	64	10 Floors	96
5 Floors	52	8 Floors	80	11 Floors	112
6 Floors	52	9 Floors	96	12 Floors	112

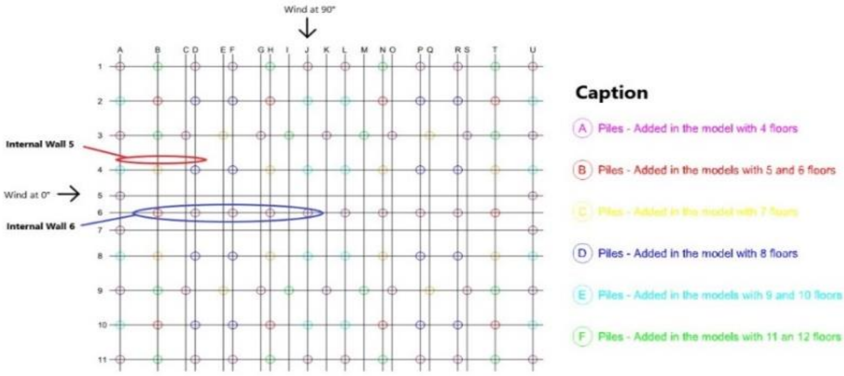


Figure 2. Piles Disposition

The quantity of piles and the value of the vertical coefficient were determined with the analysis of a Load x Settlement curve obtained from a load test done in Brasilia, that is showed in Fig. 3Figure 3.

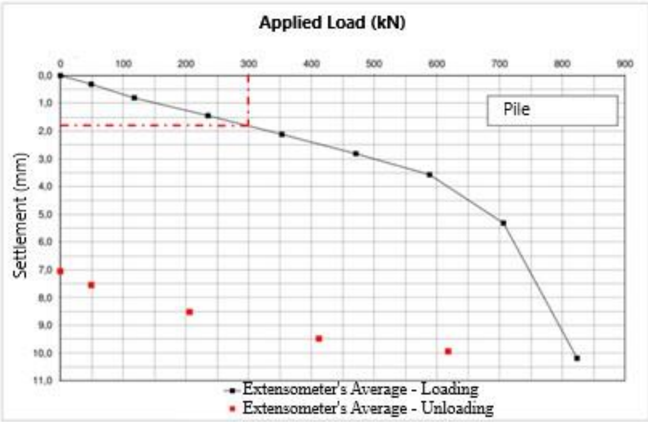


Figure 3. Load x Settlement curve

After the experiment, the force that each pile transfers to the soil was limited to 600 kN to avoid excessive deformation and the spring value was obtained through a relation between the force applied and the corresponding displacement resulting in 167 x 10^3 kN/m that was applied in the end of each pile. The slab wasn't considered in the transference of load from the structure to the soil, because the initial layers of the soil had a small allowable stress.

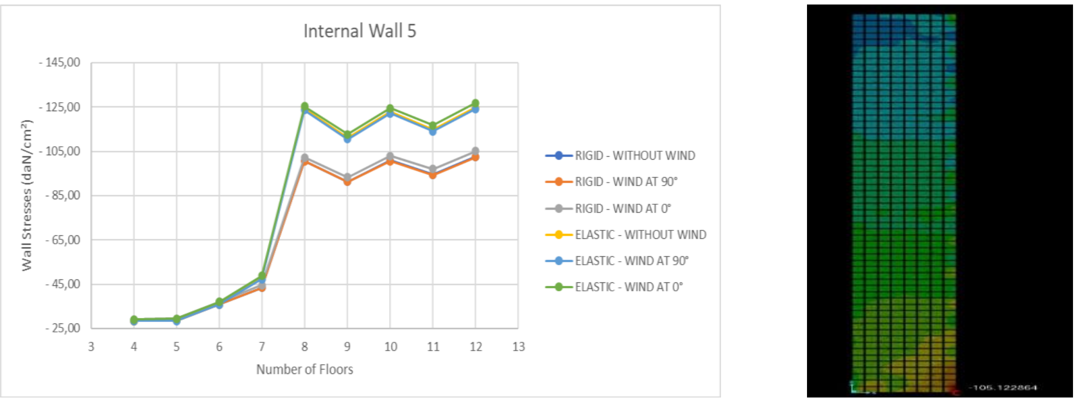
The loads assigned to the structure followed the indications of NBR 6120:2019, that include permanent actions (Dead Loads – D) and accidental actions (Live Loads – L). The wind (Wind Load – W) was considered following the instructions of NBR 6123:1988 and Federal District, Brazil was chosen as base to determine the wind's velocity and terrain coefficients. The direction of the wind and the name of the walls that it occurs are shown in Fig. 2.

4 Results and analysis

The analysis was made using SAP2000 and the combinations adopted were 1,4 D + 1,4 L; 1,4 D + 1,4 L + W (90°); 1,4 D + 1,4 L + W (0°) and D + 0,3 L, for ULS and SLS, respectively.

4.1 Walls

In the study, was observed that the walls presented two different behaviors, exemplified by Internal Wall 5 and Internal Wall 6, located as indicated by Fig. 2. In the first one, was noticed a significant variation in stress between model with 7 and 8 floors, presented in Fig. 4Figure 4 (a), and its location can be seen in Fig. 4 (b).



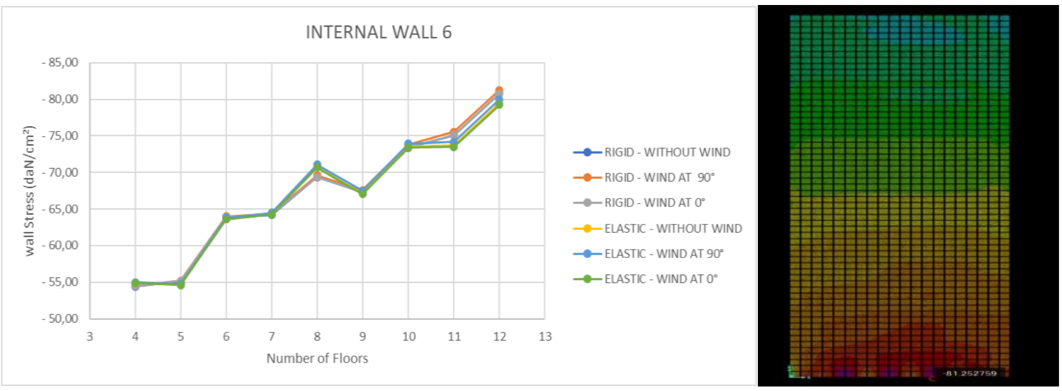
(a) Wall Stresses

(b) Maximum Stress Location

Figure 4. Internal Wall 5 - Data

The stress observed increased 130% and that was caused by the addition of the pile located in D4, that was added in the model with 8 piles, and is located near the maximum stress noted. This behavior was detected in other walls, so, this indicates that adding piles modify the intensity and the place where the great stresses are located, by changing the rigidity of the structure, when they are added near the elements and when the raft contribution isn't considered. Additionally, Fig. 4Figure 4 (a) shows that models with 4 to 7 floors have a difference in the values, comparing elastic and rigid results, of 0% to 9%, while models with 8 to 12 models presented differences of 17% to 19%. Wind loads didn't cause great variations in the product, that can be easily noticed in Fig. 4 (a), where the graphs have the same form and behavior.

Internal Wall 6 displayed an opposite behavior, but this works as a confirmation of the previous explanation, because this element presented a crescent in the stresses, without any great change between two sequential models. This is shown in Fig. 5 (a) and the location of the maximum stress is in Fig. 5 (b).



(a) Wall Stresses

(b) Maximum Stress - Location

Figure 5. Internal Wall 6 – Data

This structure, opposed from the previous one, didn't experience any addition of piles from one model to another, except for model with 5 floors that received two piles in each corner (B6 and T6), so, there was no change in the rigidity of the compound itself. Variations observed in Fig. 5 (a) was due to changes in other places near the wall, but it didn't caused greatly modifications, the increasing tendency remain as was expected for a structure with increased loads. In this case, discrepancies between the models with rigid and elastic joints were around 0,10% to 2%, showing that they were very similar. The same goes for wind efforts, that didn't affect the structure and the values were very close to each other, just 0,13% to 0,61% depending of the model studied.

4.2 Piled raft

In the piled slab were collected the bending moments and the pile reactions from one line in the foundation to consider a point coincident for both (pile and slab), represented by Line 3 (A11 to U11) in Fig. 2. The results will be from models with 4, 7 and 12 floors to show the tendencies for structures with minor, intermediate and major quantity of piles.

Line 3 showed a reduction in the extreme bending moments and an increase in the central moments, when the supports were changed from rigid to elastic, as shown in Fig. 6, considering the symmetry of the values, Tab. 2 display just half of the values. This happened for all the combinations considered with and without wind.

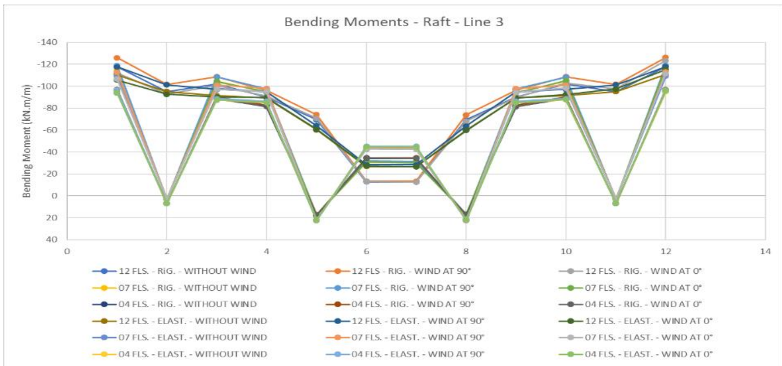


Figure 6. Bending Moments - Line 3

Table 2. Bending Moments (kN.m/m) - Line 3 - Values and Relation

N° Floors	Support	A11	B11	D11	F11	H11	J11
4 – No Wind	R	-95,2	6,8	-88,6	-81,5	17,4	-34,3
No Wind	E	-95,0	6,8	-87,5	-85,0	21,9	-44,6
	R to E	-0,2%	-0,1%	-1,3%	4,1%	20,6%	23,0%
4 – Wind at 90°	R	-97,1	6,9	-90,0	-82,7	17,6	-34,7
Wind at 90°	E	-96,6	6,8	-88,8	-86,2	22,2	-45,1
	R to E	-0,4%	-0,2%	-1,4%	4,1%	20,6%	23,0%
4 – Wind at 0°	R	-94,0	6,7	-88,5	-81,9	17,6	-34,5
Wind at 0°	E	-94,0	6,7	-87,3	-85,2	22,1	-44,7
	R to E	0,0%	-0,1%	-1,3%	3,9%	20,4%	22,8%
7 – No Wind	R	-114,2	2,9	-104,7	-94,6	17,0	-30,8
No Wind	E	-109,0	2,6	-97,8	-94,8	21,8	-42,6
	R to E	-4,8%	-11,0%	-7,0%	0,3%	21,9%	27,8%
7 – Wind at 90°	R	-118,7	3,1	-108,3	-97,8	17,6	-31,7
Wind at 90°	E	-112,9	2,7	-101,0	-97,9	22,6	-43,9

	R to E	-5,2%	-11,9%	-7,2%	0,1%	21,7%	27,8%
7 – Wind at 0°	R	-111,2	2,9	-104,1	-95,2	17,4	-31,2
Wind at 0°	E	-106,5	2,7	-97,2	-95,0	22,2	-42,9
	R to E	-4,5%	-10,2%	-7,1%	-0,1%	21,6%	27,4%
12 – No Wind	R	-117,7	-95,1	-101,8	-90,3	-69,4	-12,8
No Wind	E	-110,4	-95,1	-91,3	-89,4	-60,2	-26,8
	R to E	-6,6%	0,0%	-11,5%	-1,1%	-15,4%	52,2%
12 – Wind at 90°	R	-126,0	-101,5	-108,5	-96,4	-74,0	-13,4
Wind at 90°	E	-117,6	-101,1	-97,0	-94,9	-63,9	-28,3
	R to E	-7,1%	-0,4%	-11,9%	-1,5%	-15,8%	52,6%
12 – Wind at 0°	R	-112,1	-92,7	-100,7	-91,1	-70,7	-13,1
Wind at 0°	E	-105,7	-92,6	-90,1	-89,6	-60,8	-27,2
	R to E	-6,1%	-0,1%	-11,7%	-1,7%	-16,4%	51,8%

Bending moments increased 50% in the middle of Line 3 and reduced 0,1% to 16% in the extreme parts, proving that the moments were absorbed by less loaded areas, when considering elastic supports.

Line 3 had an increase in the moments when submitted to wind at 90°, that accordingly to Fig. 2, is applied in the negative y direction, this can be seen in Tab. 3.

Table 3. Relation of Moments - Wind at 90° and Without Wind - Line 3

Place	04 Floors		07 Floors		12 Floors	
	Relation Wind at 90° / No Wind		Relation Wind at 90° / No Wind		Relation Wind at 90° / No Wind	
	R	E	R	E	R	E
A11	1,88%	1,65%	3,80%	3,46%	6,59%	6,13%
B11	1,31%	1,19%	4,28%	3,47%	6,36%	5,99%
D11	1,54%	1,43%	3,33%	3,16%	6,20%	5,89%
F11	1,44%	1,37%	3,26%	3,11%	6,28%	5,86%
H11	1,42%	1,37%	3,55%	3,33%	6,14%	5,82%
J11	1,15%	1,17%	2,84%	2,80%	4,58%	5,25%
L11	1,15%	1,17%	2,85%	2,81%	4,58%	5,26%
N11	1,42%	1,37%	3,57%	3,35%	6,15%	5,83%
P11	1,44%	1,37%	3,27%	3,12%	6,28%	5,87%
R11	1,54%	1,43%	3,33%	3,16%	6,20%	5,89%
T11	1,31%	1,19%	4,28%	3,48%	6,36%	5,99%
U11	1,88%	1,65%	3,79%	3,45%	6,58%	6,12%

The value increased around 1,4%; 3,0% and 5,0% for models with 4, 7 and 12 floors, respectively.

Now, comparing wind at 0° with the model without wind occurred, in the center of all Lines, a reduction in one side and an enlargement in the other side, as seen in Tab. 4 for Line 3, that can be explained by the gap, caused by the lack of wall's continuity (Line 3). So, for both compounds separated by the gap, there are increments and reductions for each part.

Table 4. Relation of Moments - Wind at 0° and Without Wind - Line 3

Place	04 Floors		07 Floors		12 Floors	
	Relation Wind at 0° / No Wind		Relation Wind at 0° / No Wind		Relation Wind at 0° / No Wind	
	R	E	R	E	R	E
A11	-1,35%	-1,14%	-2,71%	-2,35%	-5,01%	-4,47%

B11	-0,32%	-0,28%	-0,70%	0,04%	-2,55%	-2,64%
D11	-0,18%	-0,25%	-0,57%	-0,66%	-1,09%	-1,27%
F11	0,50%	0,23%	0,62%	0,21%	0,82%	0,23%
H11	1,15%	0,90%	2,03%	1,62%	1,81%	0,93%
J11	0,68%	0,38%	1,20%	0,65%	2,00%	1,20%
L11	-0,56%	-0,29%	-1,14%	-0,58%	-2,01%	-1,17%
N11	-0,95%	-0,75%	-1,94%	-1,56%	-1,80%	-0,89%
P11	-0,39%	-0,16%	-0,55%	-0,16%	-0,78%	-0,19%
R11	0,20%	0,26%	0,57%	0,66%	1,08%	1,25%
T11	0,33%	0,30%	0,75%	0,08%	2,41%	2,49%
U11	1,17%	1,02%	2,46%	2,17%	4,46%	4,04%

5 Conclusion

So, this paper showed that depending of which type of study is needed rigid supports can be used, if the spring value is similar to the one adopted in this work, for evaluate some behaviors, such as stresses values and locations, because the number of piles and location had a greater influence, the same goes for the wind loads, that almost didn't affect the walls. However, if the data and building design is similar to the one used in this paper, the type of support and the application of wind affect the reactions, moments displacement and for that reason need to be considered.

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