Numerical modelling of a box-type foundation with control piles, pile number effect

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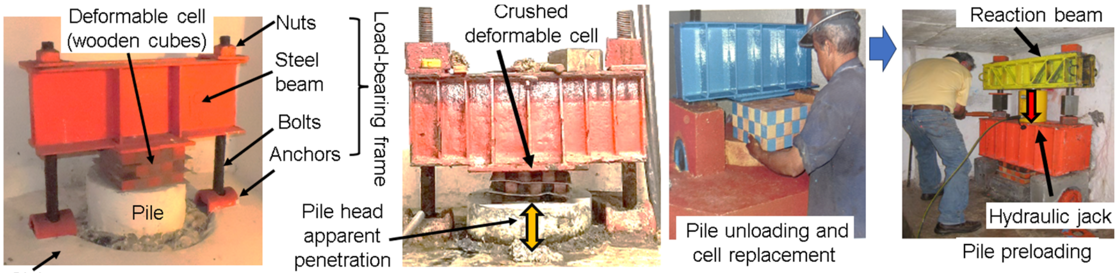
1 Introduction

Control piles (Figure 1a) are a special type of foundation used in the area affected by regional subsidence in Mexico City. This area is characterized by thick layers of lacustrine soft clay submitted to pore water pressure drawdown due to deep pumping. In this area, many deep foundations tend to present an apparent protruding that affects the surrounding buildings. Control piles were proposed (González, 1948) to control the load on each pile and mitigate the magnitude of the apparent protruding.

The control pile is a pile whose head is structurally disconnected from the bottom slab of a box-type foundation. Slab-pile load transmission is carried out through a control device that consists of a deformable cell and a load-bearing frame. Plastic flow of the cell ensures that each pile receive an approximately constant load. Periodically, the apparent penetration of the pile causes the deformable cell to crush (Figure 1b), and maintenance is required (Figure 1c). Control piles have been implemented in over 600 buildings and have exhibited adequate behaviour. Most of these designs were developed using empirical criteria.



a) Initial condition **b) Long-term condition** **c) Maintenance (main activities)**

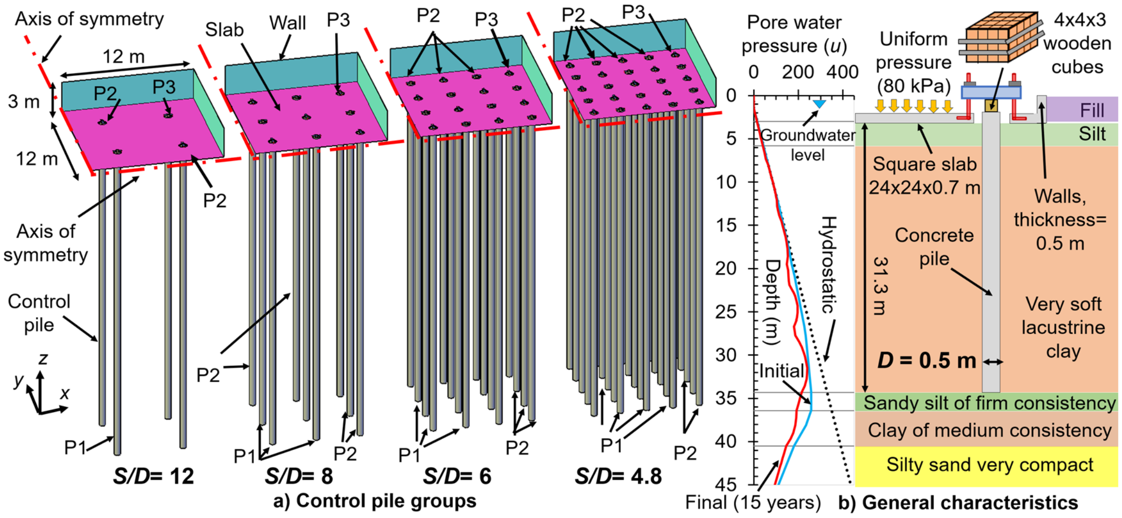
Fig. 1: Basic arrangement of the control pile and maintenance sequence.

This paper aims to numerically assess the static long-term behaviour of a control pile foundation depending on the number of control piles. This paper presents the first known numerical analysis of control piles (Domínguez-Alfaro, 2024).

2 Methodology

Four groups of uniformly distributed control piles were selected (Figure 2a) with *S*/*D*= 12, *S*/*D*=8, *S*/*D*=6 and *S*/*D*=4.8, where *D* is the pile diameter, and *S* is the centre-to-centre separation. Four three-dimensional finite element models were implemented using *Plaxis* 3D software®. The common characteristics of the four numerical models are mentioned below (Figure 2b):

- The stratigraphic profile is characterized by thick clay layers. It is considered that pore water pressure drawdown induced a free-field settlement of 128 cm that occurred during a period of 15 years (Domínguez-Alfaro, 2024).
- Only one type of square slab (24x24x0.7 m), uniform pressure (80 kPa), walls, concrete pile, deformable cell and load-bearing frame are considered.
- P1 are interior piles, P2 are piles at the slab edges, and P3 are corner piles.
- The deformable cell is represented by volume elements. Piles are represented by volume elements and interfaces on the shafts. Steel beams are represented by plates while bolts are represented as rods. Box-type foundation slab and walls are represented by plates.



a) Control pile groups **b) General characteristics**

Fig. 2: Characteristics of the numerical models.

Each numerical model is developed according to the following sequence:

1) Initial state, free field.
2) Control pile foundation construction (short-term).
3) Interaction of the control pile foundation with the free-field regional subsidence. Analysis is performed until one of the deformable cells reaches a 25% vertical strain (criteria established to execute maintenance).
4) Maintenance of the control pile group. Maintenance is performed on a single control pile at a time.
5) Steps 3 and 4 are repeated one after another.

3 Results

Table 1 summarizes the maintenance sequence (*M*), the number of control piles intervened in each of them (N_P) and the apparent protruding calculated at the two control references points A and B indicated in figure 3. *S/D*=12 and 8 groups tend to require all control piles to be intervened in the same year. *S/D*=4.8 group requires its first maintenance after 15 years, but only for P3 pile. The lowest apparent protruding magnitude is clearly observed in the case of the *S/D*=12 group.

Tab. 1: Summary of the maintenance sequence and calculated apparent protruding.

Time (years)	***S/D* = 12**		***S/D* = 8**		***S/D* = 6**		***S/D* = 4.8**		***S/D* = 12**		***S/D* = 8**		***S/D* = 6**		***S/D* = 4.8**	
	Maintenance								**Apparent protruding (cm)**							
	M	N_P	***M***	N_P	***M***	N_P	***M***	N_P	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
3	1st	4	-	-	-	-	-	-	0.5	0.0	2.1	0.7	3.1	1.4	3.7	1.9
6	-	-	1st	9	-	-	-	-	2.6	0.5	6.9	3.6	9.0	5.0	9.9	5.7
8	2nd	4	-	-	-	-	-	-	5.0	1.6	8.9	4.3	13	7.8	14	8.7
12	3th	4	2nd	9	1st	3	-	-	9.5	4.0	17	9.6	22	15	24	17
15	4th	4	-	-	1st	5	1st	1	16	8.4	25	16	32	23	37	28

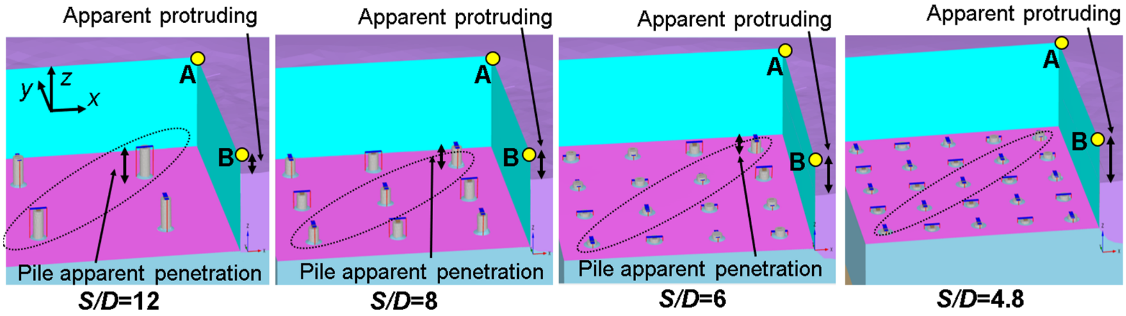


Fig. 3: Deformed mesh (amplified five times) after 15 years.

Figure 4 shows close-ups (piles highlighted in Figure 3) of the deformed meshes displayed at the year of the first maintenance of each pile group. S/D=12 and 8 groups tend to have uniform crushing and allow the maintenance of each pile in the group to be performed in the same year.

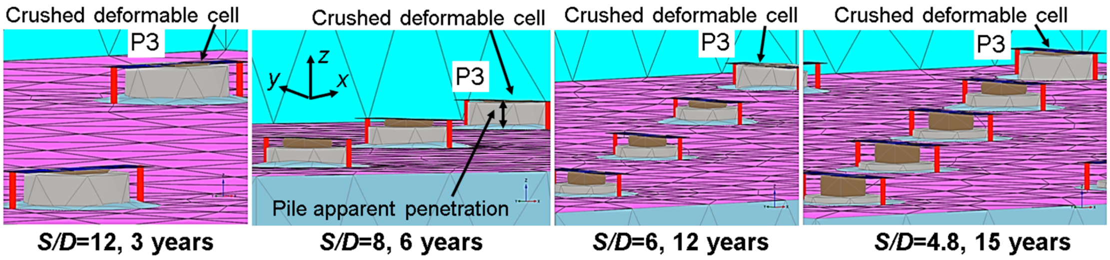
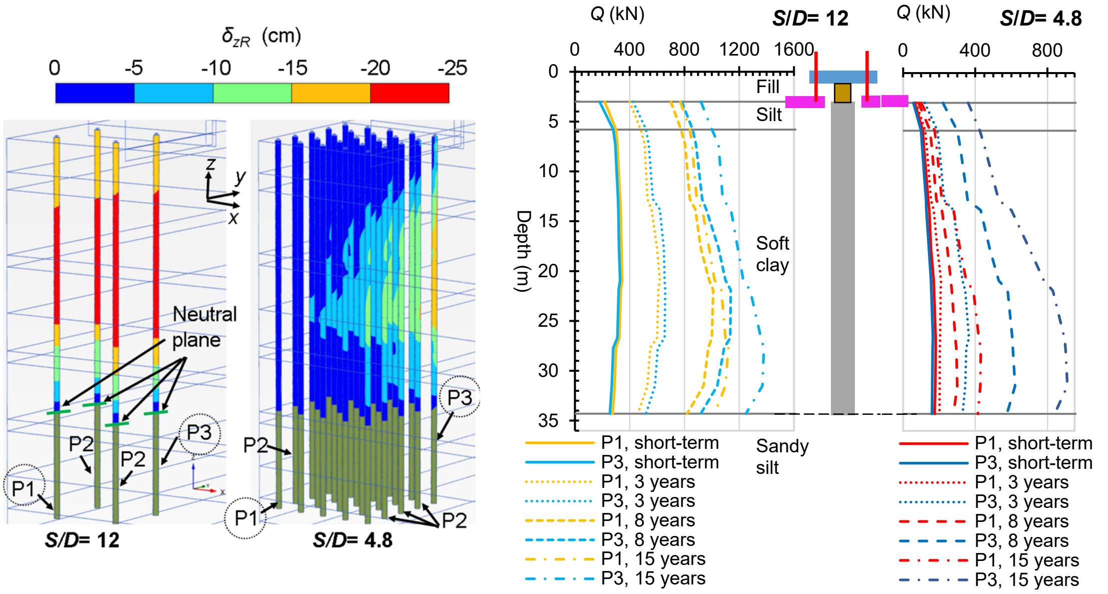


Fig. 4: Deformed mesh (amplified 3.3 times) for different years.

The results of the extreme groups: *S/D*=12 and 4.8 can be compared. Figure 5a shows the vertical relative displacements fields (δ_{zR}) in the piles after 15 years. The scale has been set to show only the displacements of the soil relative to the pile. *S/D*=12 group presents a uniform distribution of negative skin friction with a magnitude larger than the *S/D*=4.8 group. An increase in the axial load due to the negative skin friction and the pile apparent penetration is also observed. Figure 5b shows the axial load (*Q*) on P1 and P3 piles, which are highlighted in Figure 5a. The short-term and long-term results (before maintenance is performed) are shown. Axial loads in *S/D*=12 group are higher than those of the *S/D*=4.8 group for both piles. P3 pile presents a higher axial load than the P1 pile for both groups, however, the difference is smaller in *S/D*=12 group than in the *S/D*=4.8 group.



a) Vertical relative displacement fields after 15 years.

b) Axial load P1 (interior) and P3 (corner) piles.

Fig. 5: Comparison between extreme groups: S/D=12 and 4.8.

4 Conclusions

It has been possible to develop numerical models of box-type foundations with control piles, analyse the interaction between this special type of foundation and the regional subsidence and the periodic maintenance required. The number of control piles influences significantly the development of negative skin friction and the static long-term behaviour of the foundation. A large number of piles will improve the safety of foundation but will lead to a larger apparent protruding. Design of control piles foundations thus requires a subtle equilibrium between factors influencing static behaviour and safety.

5 References

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