Contiguos Pile Wall in Clayed Silt and Sandy Silt Soils

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ABSTRACT
The construction of structures in urban areas often have significant limitations in the available space for development. These space limitations determine that, in some cases, need to employ particular solutions of retaining walls. Pile retaining walls, contiguous or tangential, are presented as a solution to these problems. In the case of contiguous piles, the separation between piles depends of the characteristics of the soil to contain, the dimensions of the piles and soil structure interaction. One of the first definitions of the theoretical behavior of these systems were carried out by Ito and Matsui (1975), originally developed for the case of slope stabilization systems. The initial resolution of this problem with the use of analytical expressions, allowed the use of more complex tools. Currently, many of the cases treated are resolved with finite element models.
This paper reviews some theoretical background for the application in such works. Solutions in works built on clay loam soil type in the region of Argentine Llanura Pampeana, are presented. Project criteria and stress-strain states, used in projects, is show. Constructive aspects that have been taken into account in the development of some of these works are presented. Finally, the efficiency achieved through the application of these building systems, is analyzed.

RESUMEN
La construcción de obras en áreas urbana, a menudo, presentan importantes limitaciones en los espacios disponibles para su desarrollo. Estas limitaciones de espacio determinan que en algunos casos deban emplearse soluciones particulares de muros de sostenimiento. Los muros de pilotes, contiguos o tangenciales, se presentan como una solución a estos problemas de construcción de elementos de sostenimiento en espacios reducidos. En el caso de los muros con pilotes contiguos la separación entre ejes de pilotes se encuentra regulada por las características propias de los materiales a contener, las dimensiones de los pilotes, y la interacción suelo estructura. Una de las primeras definiciones del comportamiento teórico de estos sistemas es atribuible al trabajo de Ito y Matsui (1975), originalmente desarrollado para el caso de sistemas de estabilización de taludes. Los desarrollos a través de expresiones analíticas han evolucionado hasta la materialización de evaluaciones mediante modelos de elementos finitos.
La presente publicación, revisa algunos antecedentes teóricos de aplicación en obras de este tipo. Se presentan soluciones adoptadas en obras construidas sobre suelos de tipo limo arcillosos, en la región de la Llanura Pampeana de Argentina. Se muestran criterios de proyecto, analizando los estados tensionales y deformacionales valorados para la utilización de este tipo de soluciones. Se muestran aspectos constructivos que han sido tenidos en cuenta en el desarrollo de algunas de estas obras. Finalmente, se efectúan comentarios respecto de la eficiencia lograda con la aplicación de estos sistemas de construcción.

1 INTRODUCTION

The construction of structures in urban areas often has significant limitations in the available space for development. These space limitations determine that, in some cases, need to employ particular solutions of retaining walls. Pile retaining walls, contiguous or tangential, are presented as a solution to these problems. In the case of contiguous piles, the separation between piles depends of the characteristics of the soil to contain, the dimensions of the piles and soil structure interaction. One of the first definitions of the theoretical behavior of these systems were carried out by Ito and Matsui (1975), originally developed for the case of slope stabilization systems. The initial resolution of this problem with the use of analytical expressions, allowed the use of more complex tools. Currently, many of the cases treated are resolved with finite element models.

The authors have participated in the project development and construction of several works which need the use of these solutions. Mostly, these soils are clayed silt and sandy silt. These soils, generated by wind deposition, have a tendency, medium to high, to undergo processes of erosion or collapse, with increasing moisture.

In several cases, the walls of piles have been used as control elements of soil thrust. In some cases, or parts of the project, the piles act simultaneously supporting vertical loads.

The assumptions of the behaviour of structures, used by the authors, are presented. The findings in the modeling of stress-strain states are shown. Constructive aspects have been taken into account in the development of some of these works are presented.

Of the three works presented in this publication, two have been built and shown satisfactory performance. Finally, comments are made regarding the efficiency achieved through the application of these solutions.

2 STATE OF THE ART

Kok and Huat (2008) conducted a review of current knowledge regarding the use of piles in slope stabilization. Some comments of these authors are summarized below.

The successful use of this method has been described by Sommer (1977), Ito and Matsui (1975), Reese et al. (1992) and Rollins and Rollins (1992). Poulos (1995) suggested the design procedure for stabilizing piles. The elastoplastic model proposed by Ito and Matsui is shown in Figure 1.

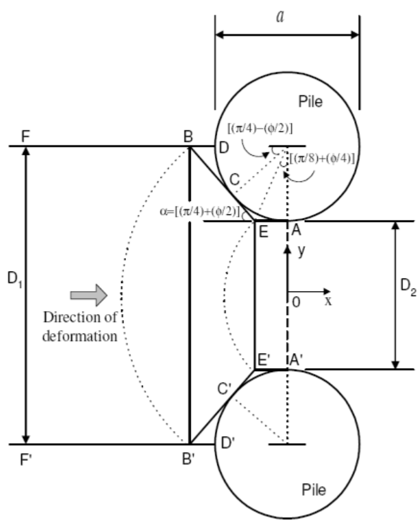


Figure 1. Elastoplastic model from Ito and Matsui.

Carrubba et al. (1989) present a full-scale reinforced concrete instrumental pile to study the response of piles used to stabilize a sliding slope. The concept of equivalent load introduced by Guo (2002, 2003), which allows a correlation between an equivalent load and the magnitude of soil movement. This concept is based on elastic-plastic solutions for either a free-head or fixed head pile.

The impact of excavation on existing adjacent piles has been investigated by Poulos and Chen (1996) and design charts for supported and unsupported excavation are provided. A series of centrifuge model tests have been conducted to investigate the behavior of a single excavation-induced soil movement in dense sand is reported by Leung et al. (2000), piles in clay behind a stable wall by Ong (2006) and piles in clay behind a collapsed wall by Leung et al. (2006) that the pressure distribution is parabolic with a mean pressure and the empirical design charts are developed based on data from centrifugal tests on model piles.

Yamin (2007), provides a detailed analysis of the behavior of contiguous pile walls in relation to its application in slope stabilization.

Firat (2009) analyzed the behaviour of the walls of contiguous piles through the use of elasto plastic flow models. For this problem, a finite element model is used. In these studies, so the problem data, the relationship between the efforts received by the system of piles, and the relationship between the diameter of piles and their separation.

3 HISTORY CASES

3.1 Case 1. Underpass for Railway Tracks. (Glew, Buenos Aires Province, Argentina, 2009)

The most important coditionant was that the construction of the under pass should take place without railway transit interruptions. For these reason it was necessary to use a contiguous pile wall construction system run from the surface, and in later proceeded to the implementation of the floor tunnel in order to stabilize the lateral walls by the action of shotcrete archs between piles that serves as soil retention wall.

The structure consists of four (4) boards girders "U" that rest on two abutments formes by a set of five (5) piles of 1,20 m in diameter with a spandrel beam which supports higher board. The tunnel is complete with a concrete wall that serves as siding and concrete walkway below is part of the structural system. Figure 2 shows a sketch of the structure.

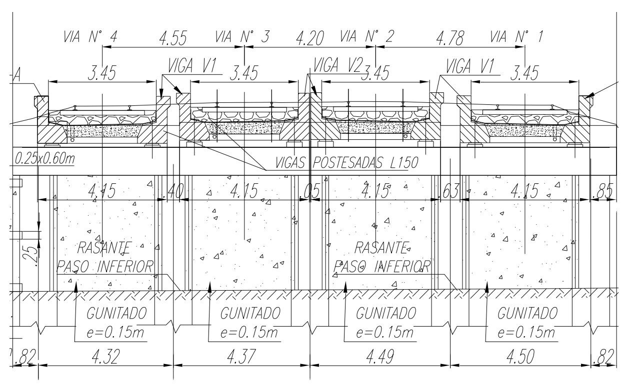


Figure 2. Structure in under pass.

The soil profile consists of the following materials in the following order from the surface:

- High plastcicity clays, medium compacity, from the surface until 1.5 m deep. Mechanical characteristics: γ = 18/19 KN/m3; k = 10^{-6} to 10^{-7} m/s; cu = 50–70 KPa; ϕu = 0°; c'= 0 KPa; ϕ'= 27°-29°.
- Médium plasticity silos and cáliz, slightly compacts preconsolidated. Light brown coloured turning to dark and green, with a slighty cemented matrix. From 1,5 m a 12,0/14,0 m deep. Mechanical characteristics: γ = 18 - 20 KN/m3; k = 10^{-6} – 10^{-7} m/s; cu = 50-125 KPa; ϕu = 0°-5°; c'= 0-15 KPa; ϕ'= 28°-30°.
- Medium plasticity silts and clays hard to very hard, overconsolidated. From 12,0 m a14,0 m deep to the end of the geotechnical borings. Mechanical characteristics: γ = 18-20 KN/m3; k = 10^{-6} – 10^{-7} m/s; cu =120-300 KPa; ϕu = 5°-10°; c'= 15-30 KPa; ϕ'= 28°-30°.

The composition of contiguous pile wall is shown schemat ically in Figure 3.

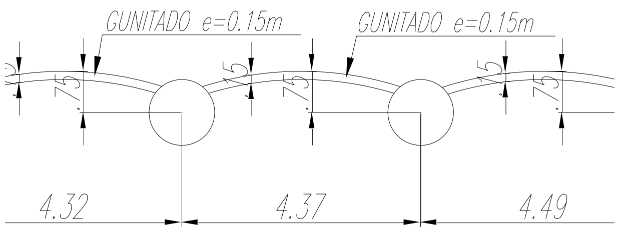


Figure 3. Layout gunning of shotcrete contiguous concrete piles.

The contiguous pile system consist of five (5) piles of 1.20 m in diameter, with an enlargemente of the base with a diameter of 4.50 m, and an arched shotcrete wall reinforced with a steel mesh, placed between the piles in a dome-shaped wall, connected to the piles by armors.
It was used the following construction sequence:

i) excavation of piles from surface.
ii) placed a steel bridge to withstand the tracks in operation.
iii) Under pass excavation with a steel false-work support and lintel beams in both sides.
iv) Trench excavation of acces and tunnel under the railroad tracks until a depth of 4.5 m from the upper level of the future roadway,
v) Shotcrete construction between piles.
vi) Then excavation of the second phase up to 5.0 m deep and proceeded to the construction of the drainage layer, the pavement and the reinforced concrete wall wich support and strengthen the trench walls.
vii) Finally pushed from the side the bridge deck previously constructed to its final position, using to slide their own abutment lintel beam with a top steel plate as a skateboard.

Numerical models were employed in order to establish levels of expected deformations, which were used as control parameters during the construction.

3.2 Case 2. Underpass and Tunnel Crossing. (FFCC Sarmiento, Moreno City, Buenos Aires Province, Argentina, 2010)

The project is a railway-road crossing, through an underpass under the railroad tracks, taking advantage of the difference in levels between the tracks located on an nearby embankment.

Structure is composed by two frame abutments with a top beam supported by two piles of 1.20 m in diameter. The lateral restraint of soil consists of a set of five (5) secondary piles, 0.80 m in diameter with a 0.25 m thick reinforced concrete screen that serves also as tunnel wall.

The main piers are founded 26,0 m depth, anticipating a future buried railway tunnel, secondary piles are 6,0 m long, these ones were designed with a special support sistem in order to transfer only horizontal load to piles, avoiding vertical loads. Figure 4 shows these approach.

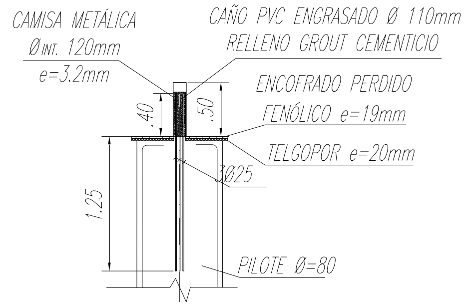


Figure 4. Special aproach employed to avoid transfer vertical loads.

The prestressed concrete top beam that supports the bridge deck, has a square section of 1,50 m side with sides screen walls. These screen is connected with the side walls of the ground support, and also serves to close laterally the spandrel beam. The bridge deck has four post-tensioned concrete slabs, together with two steel side cords, forming a box that contains the ballast and sleepers and the rail system.

Figure 5 shows a cross section of the railway bridge structure and the under pass and future tunnel.

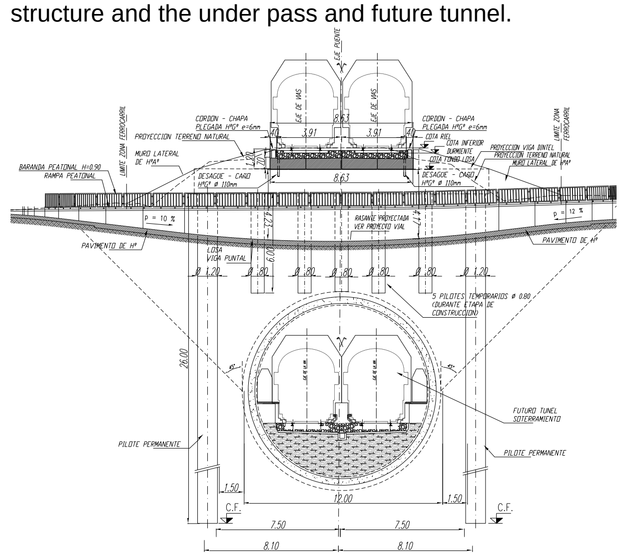


Figure 5. Under pass cross section

The soil profile consists as follows in order from the surface:

- Silty clays, médium compacity, from surface to 6,0/8,0 m deep, γ = 19 KN/m3; cu = 100 KPa; ϕu = 5°.
- Sandy silos firms and hard, with very dense silty sand lenses from a depth of 6,0/8,0 m to 12,0/13,0 m, γ = 19 KN/m3; cu = 110 KPa; ϕu = 15°.
- Silt cemented layer with hard consistency from 12,0/13,0 m to 17,0/18,0 m deep, γ = 18 KN/m3; cu = 130 KPa; ϕu = 14°.
- Silt cemented layers with very hard consistency from 17,0/18,0 m until 32,0 m deep, γ = 19 KN/m3; cu = 150 KPa; ϕu = 10°.

- Silty sands, dense and hard compacity (SPT > 50 blows) from 32,0 m to 34,0 m deep.
- Tertiary Sands (Puelchense formation) with hard compacity (SPT> 50 blows), from 34,0 m a 45,0 m deep.

Contiguous pile wall is schematicatizated in Figure 6.

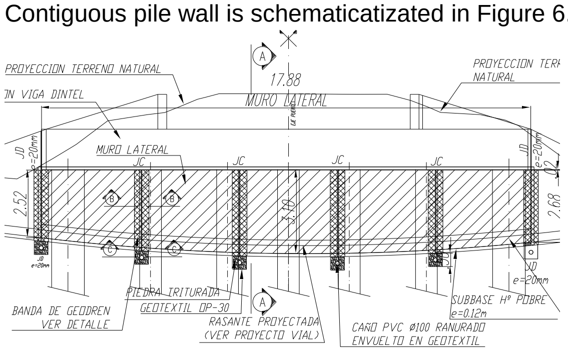


Figure 6. Contiguos pile wall scheme

The contiguous pile system is composed of two extreme piles of 1,20 m in diameter and five intermediate piles of 0.80 m in diameter, with average separation between center lines of 3.0 m, with a reinforced concrete screen of 0.25 m thick that serves like tunnel wall.

The following were the construction steps:

i) Piles were bored from surface.
ii) A steel bridge was placed to support the rails in operation.
iii) The excavation was made with a temporary metal false-work support and lintel beams were constructed on both sides.
iv) The trench and tunnel acces excavation was carried out under the railroad tracks until 5,0 m deep corresponding to the level of future road subgrade.
v) Construction of drainage, road and walls across trench and tunnel.
vi) Finally were retired existing rails and placed the bridge steel decks with a help of a crane.

The deformation established through the employ of numerical models were used as control parameters during the construction.

3.3 Case 3. Basement Building Excavation. (Córdoba City, Argentina, 2006)

These project consist in the excavation for a three levels basement in an urban area with two existing buildings in both sides of the involved area.

The geotechnical investigation of the shows the following profile:

- From the surface to a depth of 2,50 m exist a silt layer with collapsing characteristics. The parameters are φ= 0º, cu=20 Kpa, γ=12 KN/m^3.
- Between 2,50 m and 6,00 m depth, there is a medium coarse sand stratum. The compacity is high (SPT>30 blows) The parameters are φ= 35º, cu=0 Kpa, γ=18 KN/m^3.
- From 6,00 m to 10,00 m exist a layer of sandy silts with low cementation. The parameters are φ= 20º, cu=30 Kpa, γ=14 KN/m^3.
- Finally from a depth of 10,00 until the final of the exploration (20,00 m) exist an horizon of compacted (SPT> 50 blows) coarse sand with gravel lenses. The parameters are φ= 40º, cu=0 Kpa, γ=19 KN/m^3.

In one side of the area exist a 20 storey building wich has not basements, and its foundation are bases resting on the medium coarse sand stratum at a depth of 3,00 m. In the other side there are a 15 storey building fuonded by bored piles resting at a depth of 11,00 m on the depth coarse sands.

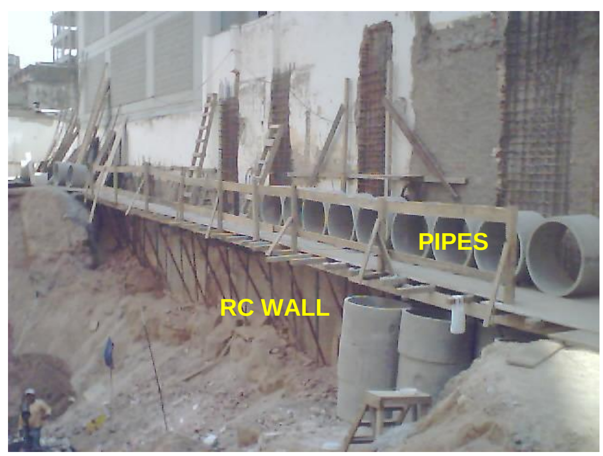
The excavation projected was 9,00 m deep. With these situation could exist the risk of move the soil under the bases of one of the existing buildings, and loose the confinement of the piles in the other side building.

For that reassons it was projected the construction a contiguous pile wall all around the excavation. All piles are hand excavated (shafts), and in order to avoid the excavation through the sand layers it was necessary the employ of concrete pipes introduced as the excavation progress, to support the lateral soil.

In the case of building with spread foundations the piles in the wall were tangent to each other, in the other one the piles were separated 2 diameters between center lines of piles.

The piles has a diameter of 0,9 m and 15,00 m deep and serves like foundation of the perimetral columns of the new building. All the piles are linked by a square section beam 1,2m side. The piles begin at a depth of 2,50 m, under a reinforced concrete wall previous constructed section by section.

Picture 1 shows the initial excavation, the retaining wall and the pipes employed for the piles excavation.



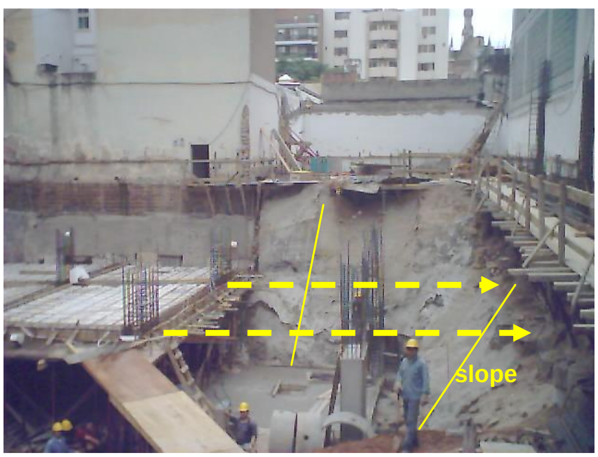
Picture 1. Reinforced Concrete wall and pipes employed to excavate the piles.

The following steps are were executed for excavation and supports construction:

i) Excavation by sectors all around the site in order to execute a RC Wall, 2,5 m deep.

ii) Excavation to the depth of the third basement (9,9 m) of the entire site with a 1:1 slope.
iii) Hand made piles using concrete piles like casings, and fill the piles with concrete until de link beam wich is the base of the RC Wall.
iv) From the bottom of excavation beggin to constyruct the central columns of the building and slabs.
v) When arrive to the second slab from the bottom, complete the beams slab to the base of the RC Wall, where were reinforced bars waiting for further connection.
vi) Excavate the soil in the slope under these slab.
vii) Then make the same with the first slab from the bottom of basement, and excavate the soil in the slopes under these slabs.
viii) While excavation under the slabs the building continuos it construction. The beams and slabs of the basements works like struts supporting the contiguos pile wall.

In picture 2 it can be see the different construction steps.



Picture 2. Different Step of Construction

In the design process horizontal deformation of the wall were estimated by the use of numericals models approach. The measurement of horizontal displacements during construction was the most effective control, in order to make changes in the construction method and minimize the risk of damage to the neighboring buildings.

4 TIPICAL DESIGN EXAMPLE

As an example of tipical design criteria it can be take the following project, is an urban road intersection, with roads at different levels, (Córdoba City, Argentina, 2005).

One of the roads is below surface level. To build it, it becomes necessary to make an excavation, supported by a retaining wall. The work is located in an urban area sector which had important restrictions on the use of space behind the wall. The soil profile consists of the following materials in the following order from the surface:

- Upper sandy silt. These soils are sensitive to increased moisture. This layer has an average thickness of about 4 meters. Laboratory tests show soil moisture between 10% and 15%. These soils are dry unit weight in the order of 13.5 kN/m3. If the moisture is above 20% can be produced phenomena of soil collapse.
- Silty sand with gravel. Is a layer of 4 meters high. The material shows a slight increase in sensitivity to moisture. The possibility of collapse with the increase in moisture is significantly lower compared with that existing in the upper level.
- Compact coarse sand. Is a layer with a resistance, measured in beats SPT test, more than 40. This is a layer with high permeability and low susceptibility to collapse.

The composition of contiguous pile wall is shown sche matically in Figure 7. The pile system, which makes up the screen, is composed of elements of 0.80 meters in diameter, with a separation between axes of 2.00 meters.

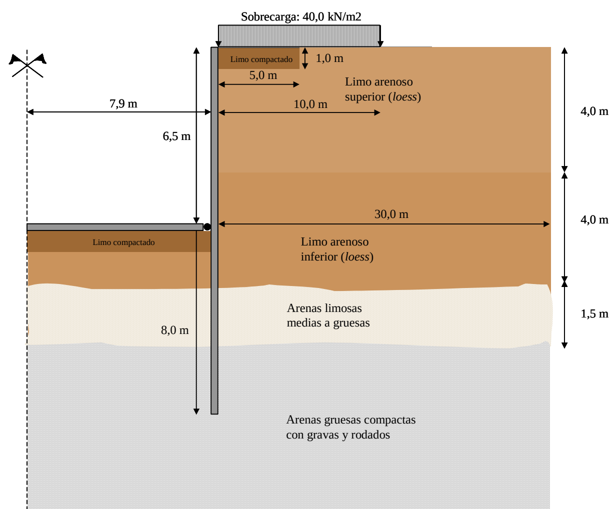


Figure 7. Structure profile

For the evaluation of soil – structure interaction of piles adjacent screen, there were two models. First, a check of the voltages induced in the ground located between the piers, has been made. With this model, the arch effect is analyzed, as shown in Figure 8.

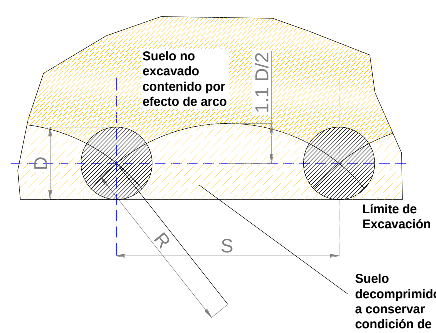


Figure 8. Simplified model of arch effect between piles.

With the proposed calculation model, it has been the state of stress generated in the wall of the excavated soil arch. This stress state has been compared with soil resistance to failure. The result of this comparison is the safety factor of soil, in the area that is not supported by the pile.

Second, there has been a numerical analysis of soil - structure interaction. The analysis evaluated two forms of soil behaviour: short term (undrained strength of cohesive soils above is used), and long term (drained condition is u sed.). Table 1 shows the main parameters of calculation.

Parameter	**Unit**	**Upper Sandy Silt**	**Silty Sand**	**Compact coarse sand**
Dry Unit Weight	kN/m3	14.8	17.5	19.6
Wet Unit Weight	kN/m3	16.2	18	20
Young Module	kN/m2	8570	25000	45000
Poisson Relation	---	0.2	0.3	0.3
Cohesion	kN/m2	20	1	1
Friction angle	º	23	27	35

Table 1.a. Parameters used to model of short term.

Parameter	**Unit**	**Upper Sandy Silt**	**Silty Sand**	**Compact coarse sand**
Dry Unit Weight	kN/m3	14.8	17.5	20
Wet Unit Weight	kN/m3	18	18	19.6
Young Module	kN/m2	19500	25000	45000
Poisson Relation	---	0.2	0.3	0.3
Cohesion	kN/m2	25	27	35
Friction angle	º	14.8	17.5	20

Table 1.b. Parameters used to model of long term.

The contiguous pile wall has been represented in two-dimensional finite element model, through a relative stiffness, set for the simulated unit depth. The results of the models developed, allowed to make the following conclusions:

- Horizontal displacements of the wall. Simulations, results in horizontal displacement, with values less than 0.04 meters. These values are located in the crown of an excavation of 8.0 meters in height. The displacement increases with the development of the excavation. Most of the displacement occurs during the development of the work.
- Settlements of the road and sidewalks, located behind the wall. During the construction process are expected settlement between 0.01 and 0.04 meters.
- Moments in the wall. The expected times at various stages of construction, have been evaluated. These values have been used for structural verification of pile system.

To ensure drainage behind the wall and the front shield drainage systems, using geosynthetics, have been designed.

During construction it was be applied a sequence, comprising the following steps:

a) construction of piles, b) construction of the beam above link, which link the piles.

c) excavation of the central sector of the space between walls, with a approach to screen up to 0.50 meters of the pile.

d) local soil excavation to reach the edge of the pile, closer to the excavation.

e) positioning of the pile reinforcement to allow its ties with the front screen.

f) local concrete pile and the space between the lower surface of the front wall.

g) location of geosynthetic drainage between piles.

h) concreting of the screen, in the space between two piles.

Picture 3 shows an image of the construction process.

Picture 8. Step of construction process.

The model made possible to establish points of control, especially for the measurement of displacement in several parts of the work. During the course of construction there have been movements of about half of those predicted in the corresponding models.

5 CONCLUSIONS

- Based on the results obtained from numerical models and actual experience it can be concluded that, inter-axis separation of adjacent piles comprised of 3 to 4 times for cohesive soils and from 2 to 3 times the diameter granular soils works satisfactorily.
- For each particular the appropriate separation must take account the geometric characteristics of the wall screen and soil strength parameters.
- The methods used in the design stages, allows a preliminary estimate of displacement. In general, the proposition allows two-dimensional analytical, a problem which is obviously three dimensional.
- The calculated values are a reference for control during construction, and allows make adjustments to the design or cosnstruction stages, if that does not meet the original hypothesis

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