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The deep foundation design of the first 40-story tower in the Atlantic coast of Guatemala, verified with bi-directional barrette load tests

La conception des fondations de la première tour de 40 étages sur la côte atlantique du Guatemala, vérifiée par essais de charge de barrette bidirectionnelle

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ABSTRACT: Located in Puerto Barrios, Izabal, Manati Tower will be the most ambitious real estate project to date in the region. The local stratigraphy is dominated by materials from continental sedimentary origin. The site under study is located between the larger traces of the Polochic fault and the Motagua fault systems, because of this and the slenderness of the building structure, the seismic behavior governs the design. The foundation was defined with high stiffness elements, reinforced concrete barrettes with specific characteristics for each area of the project. The foundation elements for the shear walls are barrettes. The initial design of the foundation was based on a major campaign that included SPT, CPTu and laboratory shear-strain test with undisturbed soil samples. Load capacity and load-settlement behavior were validated with bi-directional barrette load tests. The foundation slab was analyzed with 3D FEM in which the axial stiffness of the barrette-soil unit was incorporated. The approximate load values for the foundation will be of the order of 10,300t in compression and 8,300t in tension. The paper describes all the hypotheses and validations of the geotechnical-structural design, as well as the construction recommendations for deep foundation elements, referring to the recommendations and international codes used.

RÉSUMÉ : Située à Izabal, sur la côte de la mer des Caraïbes au Guatemala, la tour Manati sera le projet immobilier le plus ambitieux dans la région. La stratigraphie locale est dominée par des matériaux d'origine sédimentaire continentale. Le lieu de l'étude est situé entre les plus grandes traces de la faille Polochic et les systèmes des failles de Motagua. À cause de cela et de l'élancement du bâtiment, le comportement sismique régit la conception. La fondation a été définie avec des éléments de grande rigidité, des barrettes en béton, et une dalle de fondation. Cela a été analysée avec 3D FEM. La conception initiale de la fondation était basée sur une campagne de SPT, CPTu, des tests de déformation de cisaillement et par des tests de charge bidirectionnels en barrette. Les valeurs de charge sont environ 10 300 t en compression et 8 300 t en tension. L'article décrit toutes les hypothèses et validations de la conception géotechnique-structurelle, ainsi que les recommandations constructives en se référant aux recommandations et codes internationaux utilisés.

KEYWORDS: deep foundation, foundation seismic behavior, barrettes, load tests, bi-directional load test.

1 INTRODUCTION.

The project consists of the construction of the first 40 story apartment tower located in Puerto Barrios, Izabal, Guatemala. The project will have 135 private apartments and over 36,000 m2 of construction. This will be the most ambitious project in the Caribbean Coast and the first outside of the perimeter of Guatemala City.

Because of its location, it has several technical challenges including the foundation construction process and its implications to access the site with the clam shell equipment. Several site soil investigations were performed to obtain soil parameters for the analysis and design of the tower foundation.

Besides the strength design, vertical and horizontal displacements were verified using finite element analysis. Before the project starts, the settlements will be validated with bi-directional barrette load tests

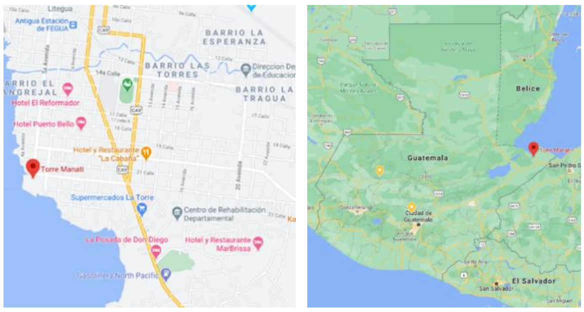

Figure 1. Specific and general location of the project.

2 GEOTECHNICAL DESIGN

CPT results were used to estimate the barrette geotechnical resistance. The average reduced skin friction for the barrettes was 8.8 t/m^2, using qc values from the CPT results. To compare these values with the ultimate loads obtained from load combinations, a reduction factor of the order of 0.45-0.56 was applied. The factored loads were obtained from combinations recommended by ASCE SEI 7-16 which for compression the governing combination is 1.2D+L+Ev and for tension, the governing combination is 0.9D-Ev. As a result, a series of 60.0m deep and 1.0m wide barrettes were analyzed and designed. All the following calculations are based on these dimensions. Rather than focusing on the geotechnical design, this article focuses on the bi-directional load tests simulated to obtain vertical and horizontal displacements.

3 LATERAL DISPLACEMENTS

Two models were used to determine the behavior of the barrettes under lateral seismic loads. The service lateral load given by the structural engineer has a magnitude of 8179 t. The first model involves the soil limit pressure and the use of the software Picasso. The second model involves the soil reaction modulus and the use of FEM software SAP 2000.

3.1 *Model based on soil limit pressure*

Picasso is a Soletanche Bachy Group software which allows to analyze the behavior of a group of piles or barrettes connected to a rigid slab, under point or distributed loads. The foundations modelled can cross through several elastic or elastoplastic soil layers.

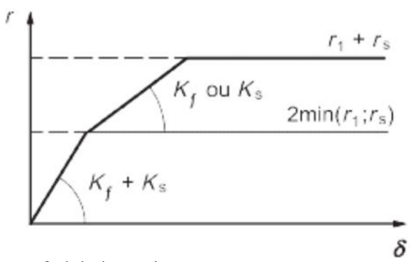

Figure 2. Law of global reaction

The software estimates the stresses and deformations along the depth of the barrettes connected to a rigid slab, under lateral and vertical loads. Table 1 shows the Nspt values considered for the analysis. Tables 2 and 3 show the soil reaction modulus for the X and Y axis.

Table 1. Soil stratigraphy based on SPT values

UNIT	Depth (m)	Depth (m)	Description
U1	0.00	-0.50	NSPT 18
U2	-0.50	-8.00	NSPT 8
U3	-8.00	-10.00	NSPT 20
U4	-10.00	-23.00	NSPT 6
U5	-23.00	-27.00	NSPT 30
U6	-27.00	-32.00	NSPT 17
U8	-32.00	-60.00	NSPT 40

Table 2. Soil reaction modulus X axis

Soil	Kf (t/m^2)	Ks (t/m^2)	Rf (t/m)	Rs (t/m)	Rp (t/m)	point Dy1 (cm)	A1 rp1 (t/m^2)	point Dy2 (cm)	A2 rp2 (t/m^2)
SPT_3	825	825	15	0	15	0	0	0.61	15
SPT_6	1,650	1,650	30	0	30	0	0	0.61	30
SPT_17	4,676	4,676	85	32	117	0.23	64	0.61	117
SPT_18	4,951	4,951	90	12	102	0.08	24	0.61	102
SPT_20	5,501	5,501	100	40	140	0.24	80	0.61	140
SPT_30	8,252	8,252	150	40	190	0.16	80	0.61	190
SPT_40	11,003	11,003	200	40	240	0.12	80	0.61	240
SPT_50	13,753	13,753	250	40	290	0.1	80	0.61	290

Table 3. Soil reaction modulus Y axis

Soil	Kf (t/m^2)	Ks (t/m^2)	Rf (t/m)	Rs (t/m)	Rp (t/m)	point Dy1 (cm)	A1 rp1 (t/m^2)	point Dy2 (cm)	A2 rp2 (t/m^2)
SPT_3	825	825	15	0	15	0	0	0.61	15
SPT_6	1,650	1,650	30	0	30	0	0	0.61	30
SPT_17	4,676	4,676	85	32	117	0.23	64	0.61	117
SPT_18	4,951	4,951	90	12	102	0.08	24	0.61	102
SPT_20	5,501	5,501	100	40	140	0.24	80	0.61	140
SPT_30	8,252	8,252	150	40	190	0.16	80	0.61	190
SPT_40	11,003	11,003	200	40	240	0.12	80	0.61	240
SPT_50	13,753	13,753	250	40	290	0.1	80	0.61	290

Even though they are designed to work as a monolithic piece, the barrettes were modeled as different pieces depending on the steel reinforcement configuration, as follows:

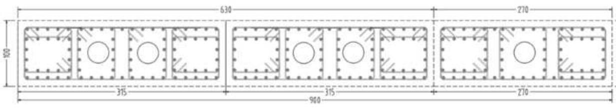

Figure 3. Barrette and steel reinforcement configuration

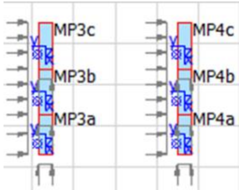

Figure 4. Barrette and steel reinforcement configuration

Table 4. Stiffness values

Barrette	L (m)	EIx	EIy
Section c	3.15	7.45E+05	7.40E+06
Section b	3.15	7.45E+05	7.40E+06
Section a	2.7	6.39E+05	4.66E+06

The next figures show the location of every barrette and moment, shear force, and displacements envelopes through the 60.0m deep barrettes, subject to the lateral load previously specified.

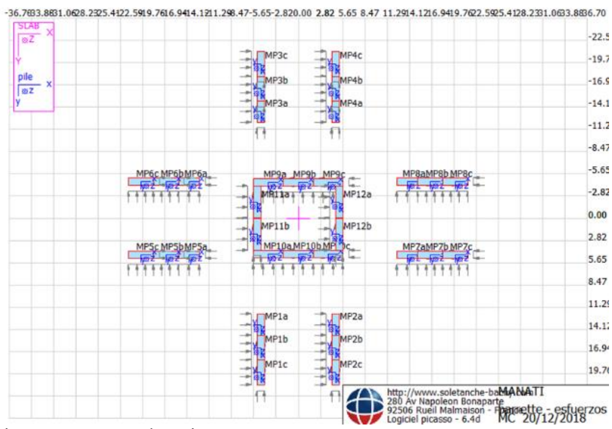

Figure 5. Barrette location

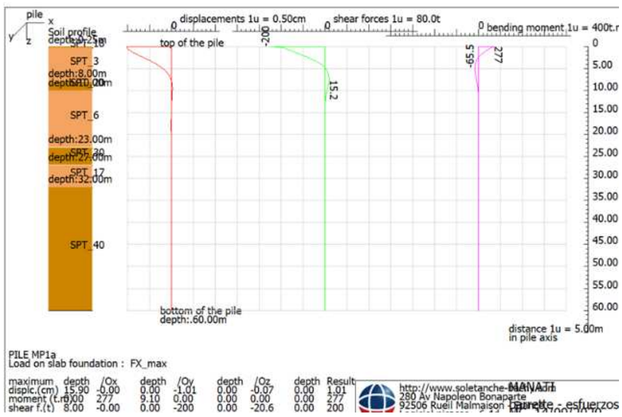

Figure 6. Barrette MP1a envelopes

Due to construction procedure: crane capacity, steel reinforcement weight, on site areas and spaces, the steel reinforcement cages were modeled and will be placed as independent bodies corresponding from 2 to 4 pieces in each barrette, as shown in the next figure.

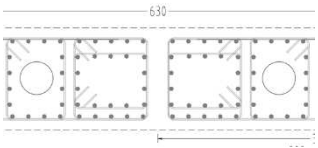

Figure 7. Steel reinforcement independent pieces

The analysis performed in the Picasso software is modeled considering the independent bodies formed by separate steel cages. MP1 barrette is modeled as an example:

- MP1a: 2.70m long, 1.0m wide
- MP1b: 3.15m long, 1.0m wide
- MP1c: 3.15m long, 1.0m wide

Considering that the barrettes will be joined in the upper part by a rigid slab, the following displacement are obtained:

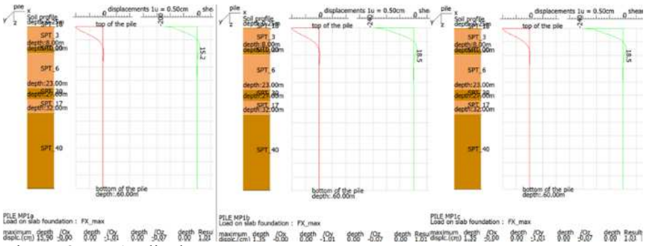
Figure 8. MP1a displacements

The maximum displacements are described as follows:

- MP1a: 1.01cm
- MP1b: 1.01cm
- MP1c: 1.01cm

As seen before, even though the barrette is modeled using three independent bodies, the displacement in each body is the same magnitude due to the soil reaction and the connection with the rigid slab.

3.2 *Model based on soil reaction modulus (Kh) and SAP2000 software*

SAP 2000 is a finite element analysis and design program with 3D graphic interface oriented to objects, prepared to perform the modeling, analysis and dimensioning of several problems in structural engineering.

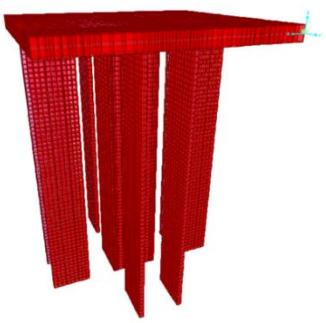
Figure 9. SAP2000 tridimensional barrette model

The soil information provided by the project's client is shown in the next table.

Table 5. Reaction modulus (Kh)

	Soil Description	Depth (m) from	Depth (m) to	Thickness (m)	Unit Weight (t/m^3)	Friction angle deg	Cohesion (t/m^2)	Factor	Kh (t/m^3)
1	Fill	0.0	2.0	2.0	2.0	30	0.50	2.02	3,332
2	Sandy clay and silt	2.0	4.0	2.0	1.8	20	1.70	1.24	2,001
3	Clayey sand	4.0	6.0	2.0	1.9	26	1.00	1.69	2,704
4	Clayey sand	6.0	8.0	2.0	1.8	30	1.00	1.95	3,508
5	Clayey sand	8.0	10.0	2.0	1.3	20	2.00	1.22	2,072
6	Sandy clay	10.0	15.0	5.0	1.6	15	3.00	0.87	1,724
7	Sandy clay	15.0	20.0	5.0	1.9	2	3.00	0.12	812
8	Sandy clay	20.0	23.0	3.0	1.9	14	6.00	0.74	2,234
9	Clayey sand	23.0	27.0	4.0	1.9	20	2.00	1.22	2,072
10	Silty clay	27.0	29.0	2.0	1.6	2	4.00	0.11	935
11	Sandy clay	29.0	32.0	3.0	1.6	14	1.30	0.89	1,299
12	Silt with a trace of sand	32.0	35.0	3.0	2.0	5	8.00	0.27	1,686
13	Silty clay	35.0	40.0	5.0	2.0	10	6.00	0.53	1,806
14	Clayey sand	40.0	47.0	7.0	2.3	15	6.00	0.80	2,356
15	Sandy silt	47.0	49.0	2.0	2.2	25	5.00	1.35	3,653
16	Clayey silt	49.0	57.0	8.0	2.1	14	6.00	0.74	2,234
17	Clayey silt	57.0	60.0	3.0	2.1	15	4.50	0.82	2,025

The 3D analysis was performed for a single load case applying 8,179t as a lateral load, the critical condition for the barrettes' displacement. As mentioned in the previous section, each barrette will be equipped with 2 to 4 independent pieces of steel reinforcement. This discontinuity is modeled in SAP 2000 by making the horizontal flexure m11 and m22 equal to zero, achieving an almost near to reality situation in the finite element model. The blue stripes in the following figure simulate the null values for horizontal flexure.

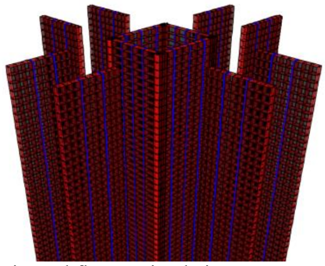
Figure 10. Null horizontal flexure simulation

The 3D FEM model has 6 degrees of freedom (X, Y, X, Rx, Ry and Rz), through all its height. To be able to simulate real conditions of reaction modulus values of the soil, a series of compression and tension springs were assigned to the model, as shown in table 5. According to the project structural engineer, 8,179t was assigned as a lateral seismic load to obtain horizontal displacements.

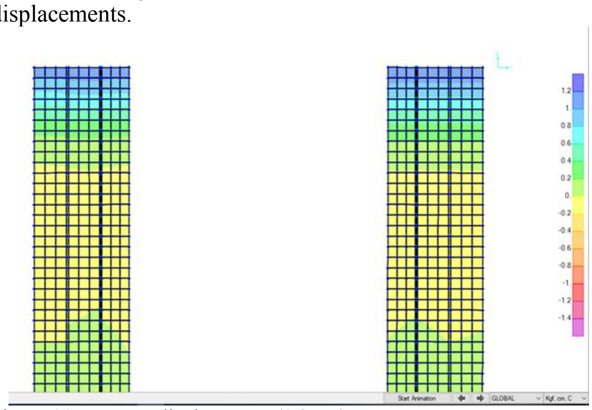
Figure 11. Barrette displacement (1.2 cm)

There is a small variation in the horizontal displacements in different locations in the barrette, before and after the horizontal flexure discontinuities. As shown in the figure below, at the left of the discontinuity there is a 1.087cm displacement, while at the right side there is a 1.12 cm displacement.

Both models gave similar results, giving displacement values of less than 1.2cm.

4 VERTICAL DISPLACEMENTS

The stratigraphy used for this model was obtained using the results from the CPTs performed on site, described as follows:

Estrato	φ (°)	C (t/m^2)	E (kPa)	ν
Sand (soft)	40	2.5	15000	0.25
Silt / clay with sand (soft)	35	2.5	9000	0.30
Silt / clay (soft)	29	2.5	7000	0.35
Silt / clay	29	4.5	13000	0.35
Silt / clay	29	7.5	20000	0.40
Sand	40	7.5	35000	0.30
Silt / clay	30	7.5	50000	0.35
Sand (hard)	30	7.5	22000	0.40
Silt / clay (hard)	30	12	80000	0.35

Figure 12. Stratigraphy and soil properties

For the analysis of the vertical displacements of the barrettes, an axisymmetric model was performed using Plaxis 2D software. The axisymmetric model is based, as its name indicates, on the symmetry along a specific axis, ideal for modeling circular shaped figures (like a circle shaped excavation or a foundation pile). Despite the barrette being a rectangular shaped foundation, it can be modeled using an equivalence for a circular pile. The primary resistance along the barrette will be the skin friction, so the equivalence must be made using the perimeter of the barrette to the perimeter of the equivalent circle. If the barrette is 9.0m long and 1.0m wide, its perimeter will be 20.0m. So, using the perimeter equation of a circle and solving for the value of the diameter given the known perimeter, an equivalent diameter of 6.37m is obtained. Having the value of the pile's diameter and knowing that the axisymmetric analysis models half the geometry, a 3.20m radius pile is modeled, as shown in the following figure.

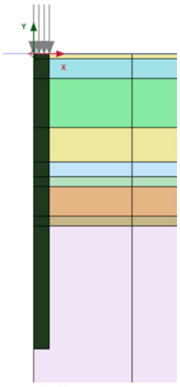

Figure 13. Equivalent pile modeling

The application of the load was performed in increments of 10%, simulating a real-life situation. Simultaneously, the vertical displacements were recorded for each load increment.

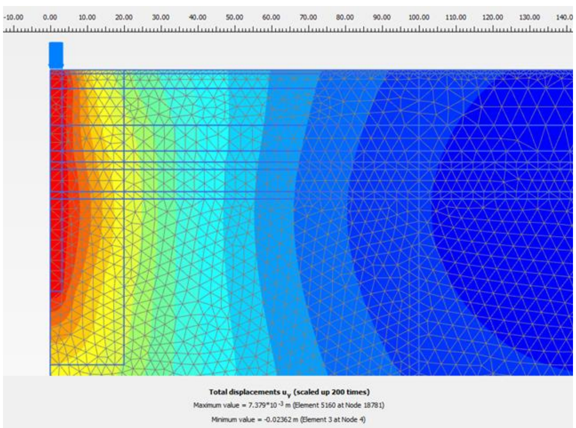

Figure 14. Software output

A load deformation curve was obtained using the values from each load increment, in this way predicting the real behavior of the barrette in service.

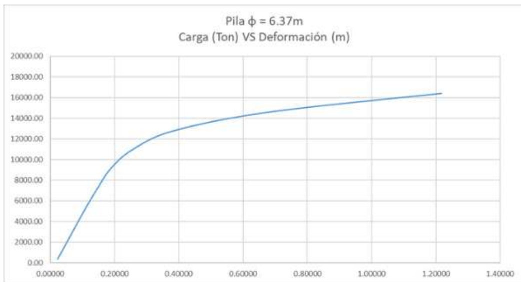

Figure 15. Load-deformation curve

Based on the previous curve, and taking the displacement value near the elastic limit of the element, the value of stiffness is approximately K=5,300 t/m3, using the following expression:

$$K = \frac{\sigma}{\delta} \quad (1)$$

5 CONCLUSIONS

In addition to the geotechnical and structural capacity calculation, every foundation project should include vertical and lateral displacement analyses.

In this article, both lateral displacement calculations resulted in similar values and the vertical displacements were low, considering the load magnitudes.

This investigation hasn't been able to be tested in site, but before the project starts bilateral load tests should be performed on at least one barrette.

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