RIGID INCLUSIONS FOR SOIL IMPROVEMENT IN A 76 BUILDING COMPLEX

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Abstract: A 76 building complex is being constructed in Morelia City, in Central-West Mexico; buildings are 5 levels high, and are founded with a shallow slab. Soil conditions include a very soft clay stratum, going up to 8 m depth, and a seismic area. Pile foundations and micropiles were considered, but discarded, due to economic factors. The alternative of soil improvement with rigid inclusions was used. A FEM analysis was conducted to determine the diameter, spacing, length and arrangement of the inclusions. Construction was implemented with traditional methods: soil boring, and mortar tremied with the aid of a sock for material containment (no steel reinforcement was used). So far, 46 buildings have been built, and level measurements since 2006 are recorded for 18 buildings, with a good behavior in both total and differential settlements.

1 Introduction

The project is located in Morelia City, in the mexican state of Michoacan, in mid-west Mexico.

The 76 building complex is 5 levels high, with a plan area for each building of 230 m^2, arranged around parking and green areas.

Site stratigraphy incluyes a soft clay unit of variable width, up to 9 m thick, overlaying a hard stratum; this clay presents very low shear resistance, and high compressibilty; therefore, a deep foundation solution was needed. Pile foundations were considered, including micropiles, but a soil improvement using rigid inclusions proved to be a better alternative.

2 Geotechnical information

Geologically speaking, the site is formed with alluvial-lacustrine deposits from ancient lakes, extended several miles around, with thickness from few meters, and up to 50 m.

Morelia City is located in a highly seismic area, which includes several active or potecially active faults.

Site exploration included CPT, SPT and selective sampling borings, and open pits. CPT were carried up to the hard stratum, with a maximum depth of 9.0 m. Up to this depth, site stratigraphy consists of five basic units:

1. Controlled fill: In the surface, a compacted fill was placed, formed with coarse gravel with an average width of 0.9 m. This fill consitutes part of the distribution layer.

2. Dark brown clay: From the surface, a dark brown clay was founded, dry hardened.

3. Dark gray soft clay: Under the fill, there is a dark gray soft clay, with water content around 110%

4. Clayey sand lens: Beneath the clay, a sand lens was founded, with a width varying from 0.7 to 1 m.

5. Dark gray medium clay: This unit was found under the sand lens, up to the maximum boring depth (9.0 m).

Soil borings were interrupted after bottom rock was reached. Water table was not founded in the explored depth.

Table 1 shows the mechanical properties asigned to each layer, after field and lab tests, and were used in the geotechnical analysis.

Table 1 Mechanical properties of the soils

Unit	Lower level [m]	Bulk weight [t/m³]	Undrained shear strength [t/m²]	ϕ [°]	Young modulus [t/m²]	Poisson ratio	m_v [cm²/kg]	m_r [cm²/kg]
Fill	0.9	-	-	-	-	-	-	-
Dark brown clay	1.2	1.36 - 1.55	4.2 - 5.1	-	403 – 505	0.35	0.07	0.04
Dark gray soft clay	5.4 - 6.1	1.33 - 1.37	2.7 - 3.1	-	268 - 378	0.45	0.14	0.06
Clayey sand lens	6.5 - 7.0	1.63	7.8	15	679	0.35	0.04	0.01
Dark gray medium clay	8.5 - 9.0	1.40	6.2	-	530	0.45	0.10	0.05

Where:

Undrained shear strength and Young´s modulus were determined from UU triaxial tests
ϕ Angle of internal friction, estimated from SPT
Poisson ratio was estimated
m_v Compressibility modulus, from oedometric tests, virgin and recompression branches

3 Foundation solution

Building´s foundation is a concrete slab, of 16.65 by 15.90 m and 20 cm thick, rigidized with beams in both directions (Fig.1). The slab was placed on the distribution layer with an average thicknes of 0.5 m.

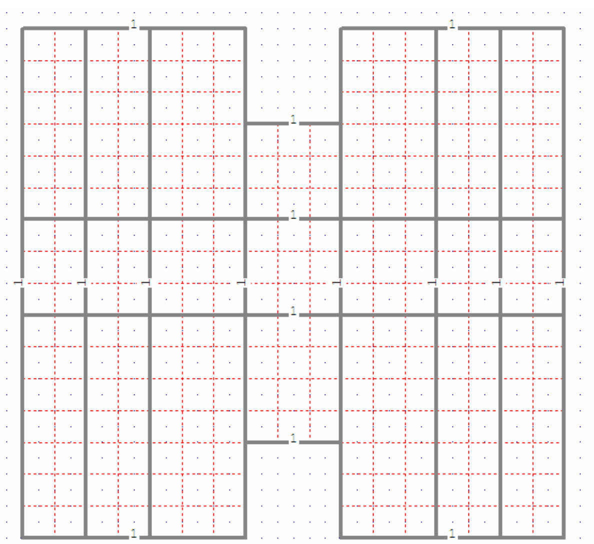

Figure 1 Slab foundation

Slab construction was started after soil improvement with inclusions was made.

3.1 Settlement of a building with flexible slab and without inclusions

As a starting point, total settlement (elastic plus consolidation) was calculated, assuming a building with slab foundation without inclusions. Analitycal calculation was made using traditional methods: Boussinesq stress distribution and Young and compressibility modulus, from UU triaxial and consolidation tests.

For a flexible slab, a total settlement at the center of the slab would be of 57 cm, and in the corners of 16 cm. Modulus of subgrade reaction were calculated. Clearly, settlements in this conditions are excesive, as slab distortions, acknowledging the use of inclusions as a soil improvement, for settlement reduction.

Results from above calculation, were calibrated with a numeric analysis, using an axisymetric finite element mesh, with an equivalent circular slab, and same soil properties. Results are shown in Fig. 2, with the same total settlement for the center of the slab, 57 cm, as in the analytical procedure.

With this calibrated mesh, inclusions behavior is studied, for both total and consolidation settlement.

3.2 Analysis for settlement reduction using inclusions

The settlement due to applied loads by the buildings was studied (5.2 t/m^2 for operation conditions, plus compacted fill weight with a thickness of 0.5 m adding 0.85 t/m^2), and the reduction with rigid inclusions.

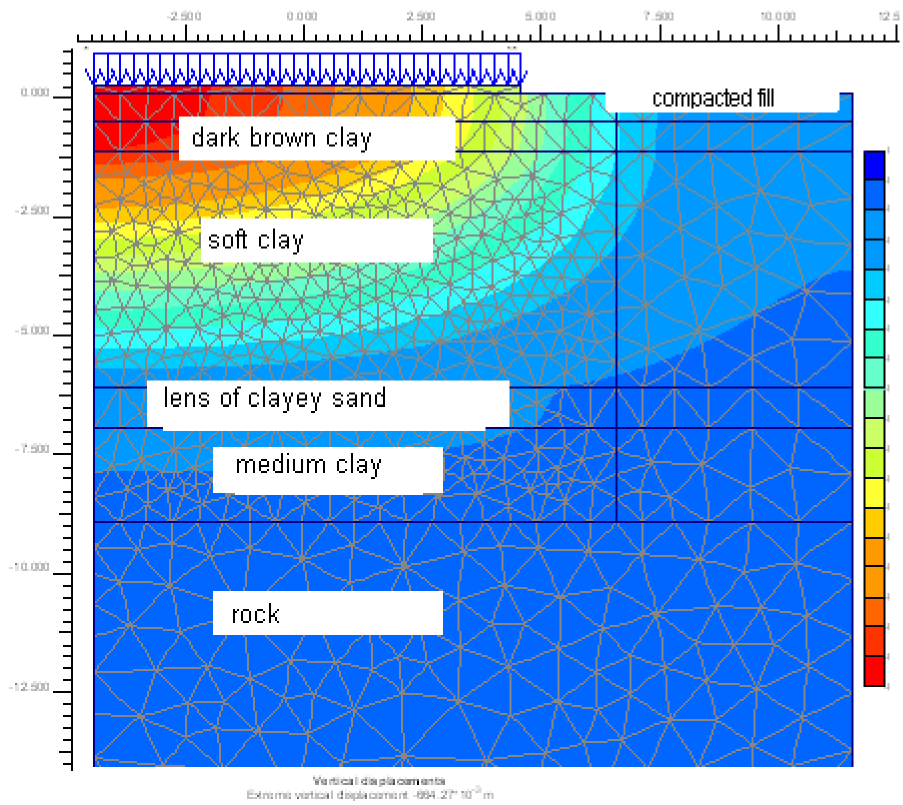

Figure 2 Total settlement in slab foundation

The analysis philosophy consists in founding the optimal separation between inclusions, for a determined diameter (40 cm) and supported in the clayey sand lens, with 7 m depth.

The model used takes into account the axisymmetric character of the problem, after Rodríguez and Auvinet (2002) and using the Finite Element Method (FEM). A group of inclusions is considered, within 1 m beneath the distribution layer, in a triangular distribution, as is showed in Fig. 3; afterwards, the problem turns axisymmetric. Radius R from the figure is the influence radius of the inclusion, and corresponds to the radius of the axisymmetric mesh of FEM (aproximately half of separation S between inclusions, S = 2R).

Cylindrical concrete inclusions were analyzed with 40 cm of diameter, and 5.40 m length, with heads in the lower boundary of the distribution layer, and point embedded 40 cm in a clayey-sand lens, between 6.1 and 6.9 m depth, as is shown in Fig. 4.

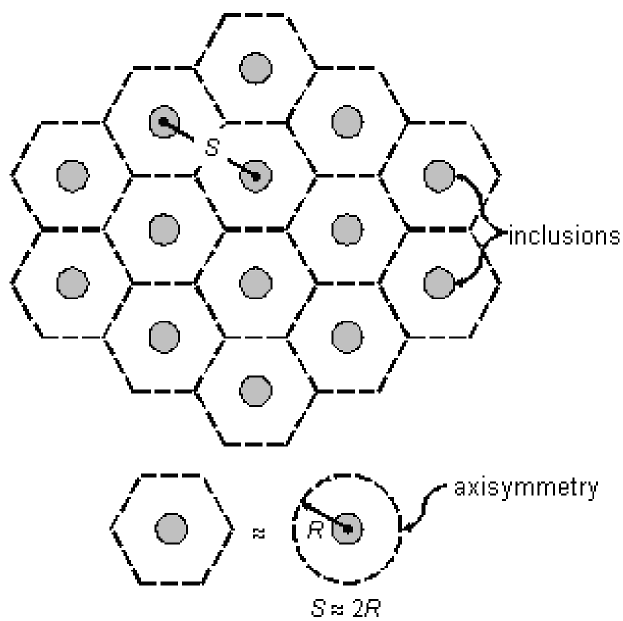

Figure 3 Triangular arrangement of inclusions (Rodríguez and Auvinet, 2002)

Thus, inclusions reduce the increment in effective stress in the soft clay layer, transferring it to deeper and more competent soils.

With this model, working conditions of the inclusion are studied, stresses in the distribution layer, and deformabiltiy of the system inclusion-distribution layer-slab. Afterwards, this results among load tests results in the inclusion are used in 3D numerical models for a complete behavior.

In Fig. 5 results for a typical building are presented, in the most unfavorable zone; short and long term settlemens are shown, according to several inclusion separations.

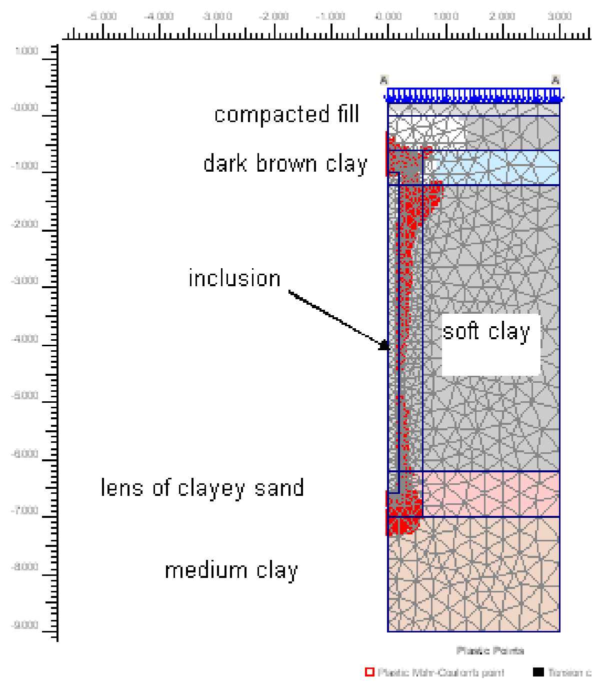

Figure 4 Mesh for rigid inclusions analysis

Total settlements vary from 25 to 56 cm for inclusion separation between 2 and10 m. However, elastic settlements will occur during construction, therefore long term consolidation settlements were analized also, founding values between 20 and 45 cm, for separations between inclusions of 2 and 10 m. That is, a 2 m separation, center to center will be used.

3.3 Analysis for foundation system with inclusions

A 3D FEM was used. It was possible to know the settlement distribution in the foundation plan, due to the applied loads, according to the following hypothesis:

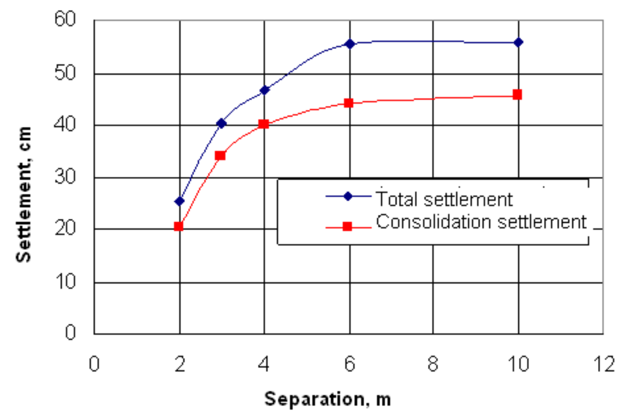

Figure 5 Settlement vs. Inclusions separation

1. The soil is represented as a continuum media, with different stratigraphic properties, after the before mentioned model. The distribution layer stiffness is acknowledge.
2. The slab foundation is modelled with its real stiffness, given geometry, thickness and beam location. Structure wall stiffness is neglected.
3. Load applied includes both service loads and compacted fill.
4. Beneath 9 m, soil and rock deposits are incompressible.
5. Settlement reduction due to inclusions is modelled by lineal vertical springs with the actual inclusions location. The lineal stiffness of an inclusion was determined after two load tests, for a typical inclusion, resulting in 300 t/m.

Settlements layout for a slab with rigid inclusions is shown in Fig. 6; a cross section of settlemens is included. An extra row of inclusions was included, in the perimeter of each building, to optimize the stress distribution.

Settlements in the center of the slab reach a maximum value of 17 cm, and of 8 cm in the corners, which are within limit values allowed by local building codes; however, maximum slab distortion is of 1%. Structural design was enhanced to increase the slab stiffness. For this purpose, modulus of subgrade reaction was calculated, and presented in Fig. 7.

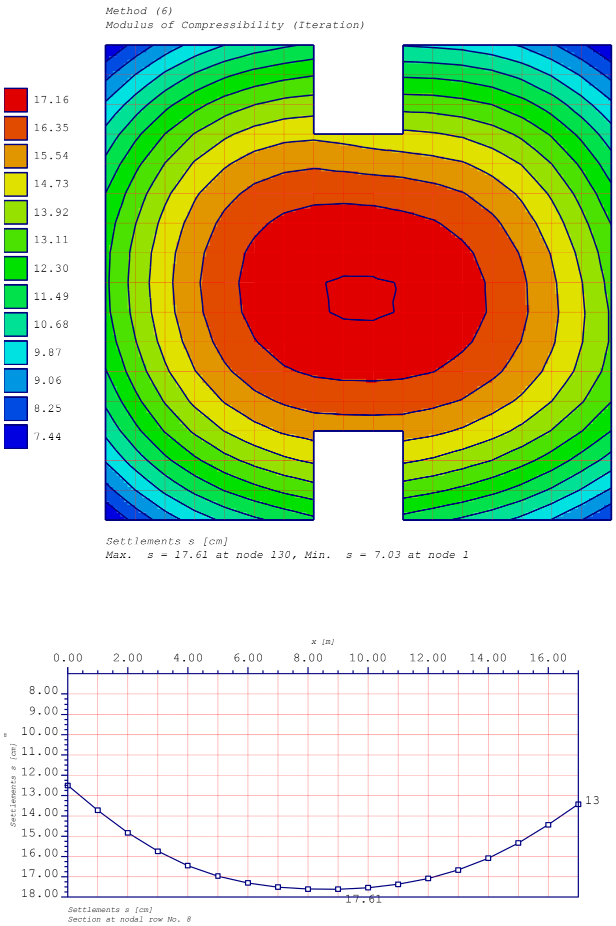

Figure 6 Configuration of settlements

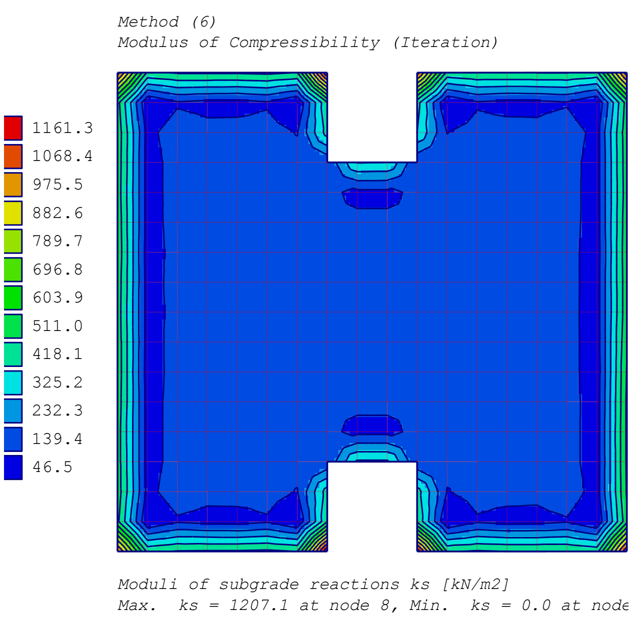

Figure 7 Configuration of modulus of subgrade reaction

4 Construction of inclusions

Before inclusions construction, unit 2 was cut; afterwards, the compacted fill was placed, using uniform coarse gravel and boulders, wich was used as a working platform, hydraulic filter and distribution layer for the inclusions.

Inclusions were built using conventional deep foundation equipment: Watson-5000 rig, mounted in a crawler crane, using augers and buckets; water was used as drilling fluid.

Once the desired depth was reached, tremie pipe was introduced, using a sock in all the length of the inclusion, to diminish the additional mix consumption. The body of the inclusion was made with a soil-cement mix, with f´c of 100 kg/cm^2, and 20 cm slump, Fig 8.

No steel reinforcement of any kind was used. Soil-cement mix was placed up to the lower boundary of the compacted fill; the space between the inclusion head and the surface was filled with the same coarse gravel.

Figure 8 Inclusions construction

5 Buildings behavior

Periodical vertical settlement measurements were made, for 18 buildings, to monitor the foundation behavior. Figure 9 shows levelings for almost two years. It is appreciated that settlement is less than the one predicted, with a stabilizing trend.

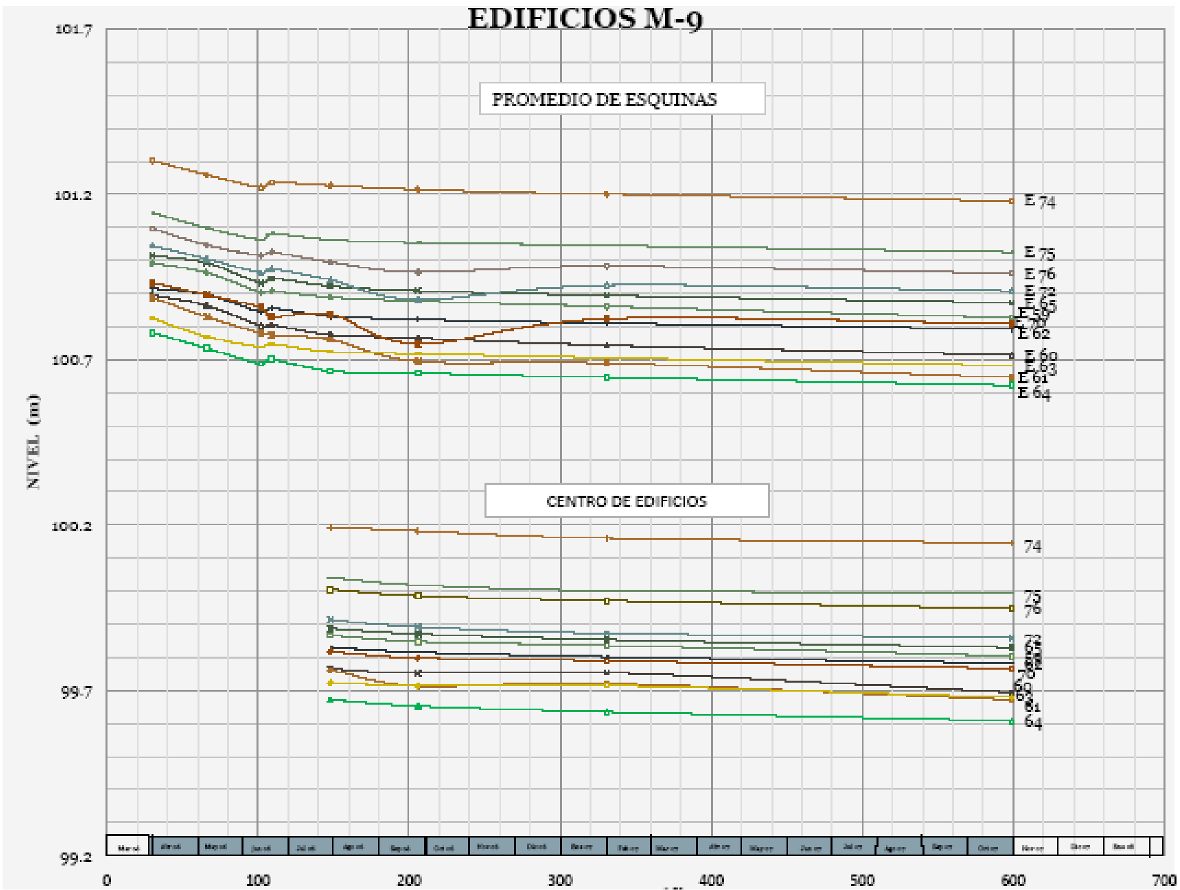

Fig 9, Settlement measures in 18 buildings

6 Conclusions

By the end of 2007, soil improvement with rigid incusions was finished for 46 buildings, for a total of 76 buildings that will be built.

The buildings were founded witha concrete slab, above a soil improvement of rigid inclusions; for each building, 100 inclusions were used, of 40 cm diameter and 7 m depth, filled with a soil-cement mix.
To evaluate the settlement, measurements were made in 18 buildings, from 2006 to 2007.

In general, all the buildings show a good behavior, with a stabilizing trend, without relevant differential or total settlements.

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Rodríguez, J. F., and Auvinet, G. (2002), “Manual of geotechnical construction”, Chap. 9, Inclusions, Mexican Society for Soil Mechanics, Vol. II, pp. 403-446. México, D.F. (in spanish).