Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0618

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Challenges of design and construction of passenger terminal building foundation, New International Airport of Mexico, Mexico City

Défis de la conception et de la construction des fondations de l'aérogare, nouvel aéroport international de Mexico, Mexico City

M. C. J. Clark, CEng MIStructE PE
Arup, New York

S. Kumar, CEng MICE, H. Cheng, PE
Arup

ABSTRACT: The foundation of the main terminal structures of the New International Airport of Mexico (Nuevo Aeropuerto Internacional de México, NAIM) is a single compensated raft over 1.6km long, 600m wide and 500,000m^2 in plan area. The monolithic jointless foundation supports more than 25 distinct large structures, including elevated highway bridges, car parks, a train station and the terminal superstructures along with its distinctive roof. The campus foundation sits on Texcoco lakebed, an area renowned for its soft lacustrine clays. The paper discusses the practical solutions derived to manage the challenges of regional settlement, soft soils, corrosive soil chemistry, volcanic activity, strong seismic shaking and foundation settlement management during and after construction. Construction methods are discussed to illustrate their influence on the final solutions, as well as the specific demands of the jointless funicular roof in shaping the foundation works. These challenges are all considered in the context of a critical airport facility to be built on a fast schedule. Performance of the as-built raft is discussed and compared against predictions, including tolerances, settlements during construction and practical considerations of the follow-on superstructure construction.

RÉSUMÉ: La fondation des structures principales du nouvel aéroport international du Mexique (Nuevo Aero-puer-to Internacional de México, NAIM) est un seul radeau compensé de plus de 1,6 km de long, 600 m de large et 500 000 m2 de surface plane. La fondation monolithique sans joint supporte plus de 25 grandes structures distinctes, y compris des ponts autoroutiers, des garages de stationnement, une gare et les superstructures de l'aérogare ainsi que son toit distinctif. La fondation de l'aéroport est située sur le lit du lac Texcoco, une région réputée pour ses argiles lacustres douces. L'article examine les solutions pratiques dérivées pour gérer les défis de l'affaisement régionale, les sols mous, la chimie corrosive du sol, l'activité volcanique, la sismicité élevé et la gestion de l'affaisement des fondations pendant et après la construction. Les méthodes de construction sont discutées afin d'illustrer leur influence sur les solutions finales, ainsi que les exigences spécifiques de la toiture en funiculaire sans joint dans la mise en forme des travaux de fondation. Ces défis sont tous considérés dans le contexte d'une installation aéroportuaire critique qui doit être construite selon un calendrier rapide. La performance du radeau tel que construit est discutée et comparée aux prédictions, y compris les tolérances, les tassements pendant la construction et les considérations pratiques de la construction ultérieure de la superstructure.

Keywords: Texcoco, NAIM, Raft, Differential Settlement

1 INTRODUCTION

If reviewing a map of Mexico City, one comes across a seemingly ideal place for a new airport hub: a large tract of undeveloped flat land, measuring over 10km across and near the city urban center. However, the appeal of the site for an airport is countered by the negative reputation of its very soft lacustrine soil and ongoing regional subsidence.

The geological and social histories of the site are uniquely connected via human interaction with the landscape's water. The next chapter of this history is still unfolding as the authors record their experience in this paper. Society needed a new airport and the selected site was Texcoco lake, but nervousness about politics, water and ecology fed doubt on the selection of this site. Construction had started and has again changed the social and geophysical nature of the site permanently. However, politics has recently intervened and the very subject of this paper – will the airport sink? – became part of a larger anecdotal social argument that has suspended construction.

While the future of politics and the site is unknown, the raft has largely been completed and is not sinking. The raft is now a permanent asset to the City and country and hopefully can be made useful once more in the future. This paper intends to record the design and construction challenges, solutions and future capabilities of this remarkable foundation slab.

1.1 Challenges

The lakebed surface at the airport site is continuously sinking at an approximate rate of 0.2m per year but varying across the site. The ground contains up to 6 parts water for one part soil, and the chloride concentration is up to 2 ½ that of sea water. The site's fundamental period is around 1 second, creating a spectral response in parts of our building up to 1g sideways.

In practical terms, one cannot walk easily on a virgin cut surface of the clay without getting one's boot stuck or sliding on its slick surface. While the cut clay quickly crusts over with salt as the water evaporates, a thick layer of crushed Tezontle (local pumice-like material), is needed to form a surface that a vehicle can operate on without sinking in.

2 STARTING POINT

The airport's buildings are designed to subside with the surface geography rather than fight against it, so deep foundations contacting a hard seam (the CD layer) at about 20m below ground level were not an option, since the building would slowly emerge as the soft ground consolidated. The design was required to enable construction to start quickly, so pre-consolidation was unfavorable. Construction was to be on a vast scale, so simplicity was key.

The chosen solution was a compensated system, where simple management of applied stress to the soil resolves settlement issues rather than any artificial enhancement of the soil itself. However, construction of compensated systems in poor soil is not simple as it involves open excavation then pouring heavy concrete elements that must not immediately sink into the mud.

Figure 1 - Trial Excavation after completion of the reinforced concrete blinding slab sat on the red Tezontle subgrade. Note the shiny black recently cut virgin clay to the left and the 5m open depth, at the time unprecedented on the site

The reinforced raft slab was to be poured in one thick layer rather than multiple thin ones, so a stiff sub-base had to be created quickly and simply. A system of a geo-grid under a Tezontle layer was selected. This created a foundation for the second layer: a 150mm reinforced concrete sacrificial blinding layer. It is sacrificial due to the corrosive nature of the ground that it is permanently exposed to. The blinding layer also formed the substrate for the third layer: a self-adhering water and chemical proof membrane. Although not specifically designed for the purpose, this blinding layer proved strong enough to support mobile crane outriggers and loaded concrete trucks without damage. It became a great benefit to site logistics.

On top of the sub-base, the raft reinforcement was set, and concrete poured in approximately 400m^2 cells to the full 1.3m to 1.5m thickness in a single pour. Both predictions and measurement showed that the blinding layer settled approximately 50mm under the weight of the wet concrete raft at the free edges. Only surface water was pumped away, there was no ground water lowering efforts thanks to the low permeability of the clay.

Prior to construction, the entire excavation and construction system was successfully means-tested in a trial where two 400m^2 cells were excavated and built while being monitored.

3 FOUNDATION AS A CAMPUS SOLUTION

An airport is a collection of buildings and infrastructure, many of which cluster about the Passenger Terminal Building (PTB). The foundation of NAIM supports many of these structures on a single continuous raft.

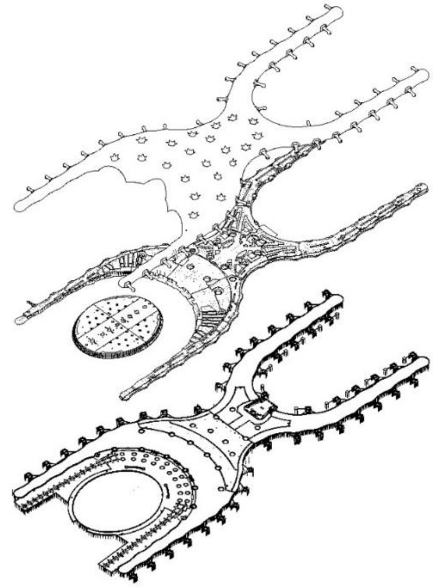

Figure 2 - Exploded view of the terminal roof, over multiple building and civil structures, all on the continuous raft campus foundation

The 3 main superstructures are a ground transportation center (GTC), including carparks, bus stations and a train terminal; an elevated highway bridge; and finally, the PTB itself, which is comprised of 18 separate structures under a single independent roof.

The decision to put all three main structures on one foundation minimizes the interfaces where abrupt differential settlements can occur. These interfaces are specifically designed exterior vehicular access points which can accommodate the movement using transition slabs and adjustable interfaces.

3.1 One roof, one foundation

The architectural vision for the big roof was 'one system': a seamless skin enveloping the whole PTB and housing all functions. This has been achieved with a structural design allowing the whole roof to be built a mile long with no movement joints. The singular roof had to sit on a single foundation to be viable. The idea of 'one foundation' was also set as a philosophy at the project's start and was returned to as the project developed.

The One Foundation decision was also based on practical experience. When travelling via T2 at Aeropuerto Internacional Benito Juárez, travelers cross a noticeable ramp between the concourse structure and the main body of the building. As of 2018, the ramp manages an elevation change of over 1m. Two different foundation systems under the two buildings have settled differently over time.

Figure 3 - Ramp between two separate foundation systems at the current airport

4 SCHEMATIC DESIGN

The raft works quite simply. Point loads from columns push down from above and soft soil pushes back in equilibrium. The raft acts as a device that turns the point loads into an even bearing stress. The relative stiffness between the soil and the raft structure determines how evenly the soil can push back. The upper bound condition with the worst bending moment is when the soil is soft and reaction pressure from the soil is even, not concentrated under columns. This allowed an upper bound strength limit state to be simply derived with confidence and a minimum raft thickness to be selected early on in design.

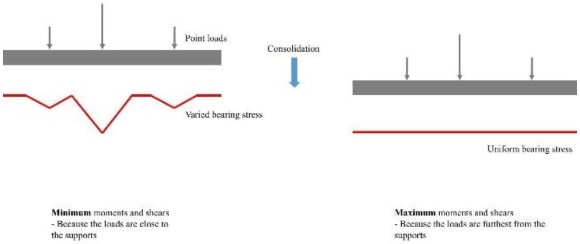

Figure 4 - The upper bound calculation for raft bending

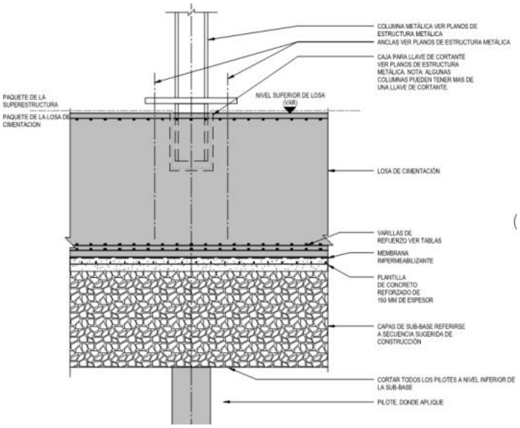

Figure 5 - The structural section of the raft, from top down: reinforced raft slab, water-proofing and corrosion membrane, reinforced blinding slab, tezontle, geo-grid, settlement reducing pile..

The compensated foundation approach aims to reduce the changes in the soils' effective stress regime due to the construction to a practical minimum. Careful matching of excavation depth with spatial variations in total structural load, including blinding, was required. The net change in effective stress due to construction was generally no closer than 10 kPa less to the Yield Stress, typically found at an Overconsolidation Ratio of about 1.8. Fortunately the Tezontle imported fills have a similar unit weight as the native soils.

Therefore, by bounding the worst-case assumptions about the soil stiffness, the engineer set an elevation and thickness of the raft based only on the weight of the building, the column spacing and the density of the soils. The solution was then analyzed using linear and non-linear methods to verify the design. Using these guiding principles, an early foundation construction package was delivered over a year before the superstructure design was finalized.

The PTB is not uniformly tall, nor evenly dense with an even column grid. Therefore, compensation can never be perfect. It was the structural engineer's role to apply their skills of design and persuasion to take a complex airport and try to make all the loads touching the raft even. However, the usage of the basement's programmed spaces and head height constraints took priority over calculations. In the case of the PTB, it is the baggage handling system that governs the top of raft level in much of the building footprint.

The mass of the building is only an estimate as adjustments to elements such as floor finishes can have a significant effect on the compensation calculation. On the other hand, the raft itself is an effective de-sensitizer due to its large mass. The raft's mass is over half of the whole building mass and is a controlled by the structural engineer. The building must be as lightweight as possible to minimize seismic loads as well as excavation depths.

Table 1. Mass distribution of the passenger terminal building segment of the raft and superstructures

Component	Mass (T)	% of total
Raft	1,152,000	62
Superstructure	347,000	19
Finishes	270,000	15
Roof Structure	27,550	1
Roof Finishes	51,250	3

4.1 Big roof point loads

The roof funnels function to bring light and air into the wide building from above. The compensated basement functions as a giant air plenum under the entire building footprint, except for the areas occupied by baggage handling. Air handlers draw fresh air supply direct from the basement and exhaust via ducts to the perimeter wall.

The base and foundations of the funnels therefore function foremost as air entraining devices. They must allow a large free area for air to pass. They also must manage storm water, hail and ash ingress. In fact, the funnels are designed to withstand pressure from being filled will hail ice, like an ice cream cone. The roof spans are over 100m. The structural challenge was to re-distribute the roof funnel point load into a uniform bearing pressure that the raft could manage, while minimizing the thickness of the concrete and keeping the weight of the raft on the soil as even as possible.

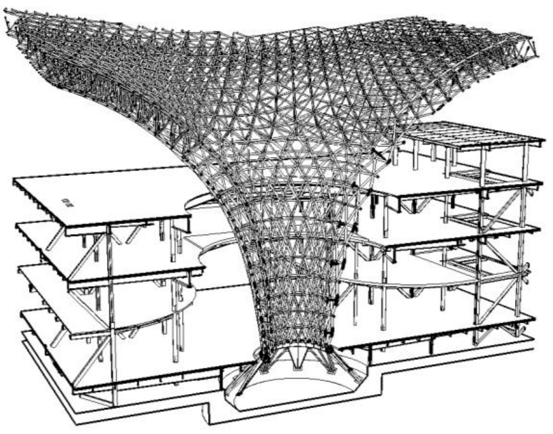

Figure 6 - Cross section of a roof funnel

At ground level, the circular funnel is at its minimum diameter, set by air entrainment requirements. The funnel above and below this point flare out to larger diameters, collecting the load from the roof area and redistributing the load back to the raft area. Below the publicly visible area and the ring beam, the structure is a conic section of triangular struts, flaring out to connect to the raft via inclined baseplates.

The raft is locally formed into a circular depression to receive the steel cone. The circular wall generates high structural stiffness with minimal added weight of concrete. The added depth aids compensation directly under the roof point load, bearing on deeper soil and receiving greater pore pressure opposing gravity. The depression is also a practical storm water retention tank with emergency backup pumps should the gravity driven gutter system fail. Lastly, the circular shape allowed the contractor to utilize a sheet-piled cofferdam as temporary works to achieve some of the deepest excavations on the site.

Because of careful design, the roof funnels do not impose significant point loads on the soil where compared to the surrounding raft. This is achieved by the shape of the system, the lightweight roof but mainly the void in the main superstructure floors through which the funnel passes.

5 DIFFERENTIAL SETTLEMENTS

5.1 Causes

There are four main causes of differential settlement across the building: Ongoing regional subsidence, Imbalance of imposed load vs. compensation depths and initial topography, variability of soil properties across the site and finally post-construction groundwork activities near the edge of the built foundation.

Attempts were made to quantify each of these four causes by investigation, desktop study and analysis in the short term during construction and the long-term life of the building. Regional subsidence history was available. Linear elastic structural models on soil springs (Oasys GSA) were used for sensitivity studies and non-linear soil-structure interaction models (Plaxis) were used to validation and consolidation affects.

Table 2. Estimated maximum curvatures of the raft

	Estimated max. raft curvature	
	Construction	**75 years**
Subsidence	L/64,000	L/1,000
Compensation	L/1,000	L/150
Soil properties	L/1,000	L/300

The apron earthworks were being engineered by others and the interface analysis an on-going project at the time of writing, so values are not mentioned here.

5.2 Solutions

The Kansai Airport project, engineered by Arup in the 1990's, provided a precedence for a mile-long building on settling ground with elevation adjustable baseplates under columns to provide adjustable superstructure elevation. (Dilley, 1994).

A similar concept was adopted at the external aircraft boarding structures, which can be independently elevated and trimmed upon their separate compensated pad foundations which float in the unpredictable apron area. However, the main bulk of the building differed. Kansai utilized a flexible moment frame lateral system. NAIM, however, has an intentionally stiff structural system with extensive braced frames. These frames could not accommodate individual raising of columns to any useful curvature unless the whole braced frame could be lifted together at once. Some braced frames are over 50m long. Their additional stiffness works compositely with the raft to resist differentials in addition to minimizing seismic loads. (superstructure seismic forces are reduced by a stiffer response when below the 1 second period of this site) Given that there are over 5000 columns in the building and many are essentially rigidly connected to each other, post-construction adjustment was considered impractical.

When considering the actual predicted curvatures, adjustment of structure on the raft was also deemed un-necessary past the setting of the columns at construction. At Kansai the design required adjustment should curvatures reach 1:100 in the main building or 1:200 in the concourses. At NAIM the predicted curvatures were only approaching this level after the 75-year design life.

For all these reasons and our confidence in the smoothing effect of soil-structure interaction between a stiff raft and soft soil, we decided a subtler approach to differentials was appropriate.

5.3 Elevation tolerances

Normal building tolerances should be considered in detail before assuming that tolerances will be a problem on a raft subject to differential settlement. Will the expected differential settlement be within normal building tolerances?

The AISC Code of Standard Practice for Steel Buildings and Bridges does not address long buildings, but instead presents local tolerances for beams and columns. Concrete floor tolerances refer to Ff and Fl indicators to ASTM E1155, but these again are limited in scope to local areas. It is therefore up to the engineer and architect to set alternate limits if they are justified. If the functions of the building are met and all the machinery (baggage, vertical transportation, etc.) function properly, there is no need to require the building to achieve a lower slope in a long building as we would require for a short building. Following this logic, the solution to potential differential settlement is to set reasonable tolerances and check they are practically achievable given the expected differential settlements.

In the case of NAIM, all expected settlements were estimated to be within normal building tolerances, except those created by airside earthworks on the boarding gatehouses for which the jacked column solution was utilized. It is worth noting that the curvature of the earth across the 1.5km long building is approximately 200mm, and that the total regional settlements in the order of 6-12m are expected over the lifetime of the building.

6 HOW TO BUILD ON A MOVING FOUNDATION

When the first cell of the foundation raft was cast, in the approximate center of the building complex, its absolute elevation was chosen at an estimated position relative to the current lakebed surface and a metal surveyor's marker was cast into the slab (known to the project as the "Bullet Tip"). All other segments of the raft were then cast to match that single marker elevation on the day that they were cast. This approach caused the construction datum to float down with the topography and raft response. Surveying to absolute elevations became unnecessary. The airfield would have then followed the same elevation datum as the building.

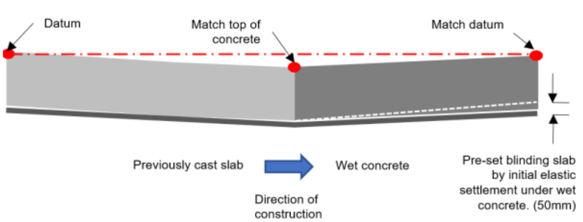

Figure 7 - Raft elevation control

All column baseplates were provided with additional height tolerance within the grout depth but were levelled to the datum and set permanently with grout soon after they were installed. The steelwork then was built as per a normal building, each column height measured from its own baseplate.

This practical system mitigated several issues, most importantly it avoided reliance on complex analysis of unpredictable soil behavior and unpredictable construction schedules. The system is based on the understanding that differential settlements that may occur after a baseplate is set are locked into the building and are not recoverable. This works if there is confidence the differentials will not create slopes beyond those that a normal building can accommodate. Structurally, all elements were designed to accommodate an imposed differential displacement. The roof was to be fabricated flat and bent into position if the funnels move differentially during construction, the induced forces factored in the design of the roof.

7 PERFORMANCE SO FAR

The main PTB area of the raft took approximately 18 months to build. Construction was achieved generally within the 200mm vertical tolerance allowed. Differential movements are shown in figure 8. The overall settlement of the raft has reasonably matched the expected regional settlement of about 15mm per month. The shape of the observed differential displacements resembles the initial topography, where initial higher elevation areas have seen lower total settlement. Measurements of water pressure changes, during excavation and placement of structural loads including the raft, showed that the soils behaved in direct response to changes in volumetric stresses with very low generation of excess pore pressures due to shear. This comparatively benign behaviour undoubtedly assisted in the close agreement between measured and calculated settlements during construction. One of the effects of the suspension of the project will be that, due to the incompleteness of the structural load, the foundation is overcompensated: this has required attention as to how to mothball the project such that it can be potentially adapted for use in the future.

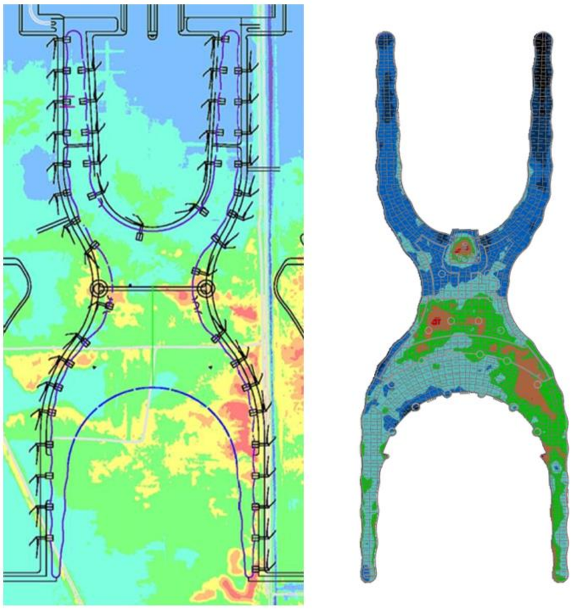

Figure 8 – Left, Initial surface topography before excavation (range of about 2m from high point in red to low in blue) and right, observed differential settlement of the completed raft between September and November 2018 (range of 50mm from least in red to most in blue)

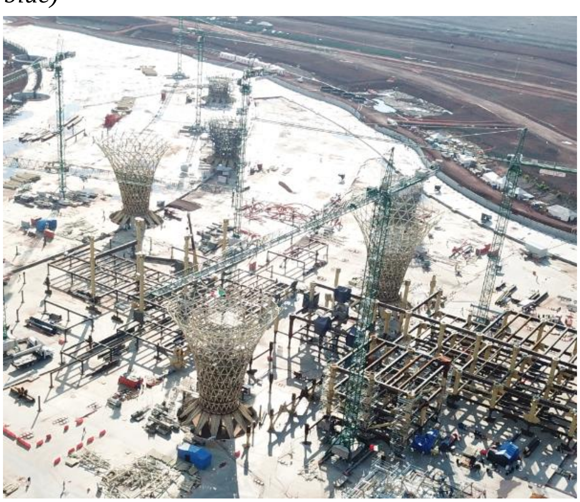

Figure 9 – Under construction, November 2018 (FP-Free)

8 CONCLUSIONS

The Texcoco lakebed (and sites like it), can be built on by practical means without soil improvement or intensive analysis. Differential settlement on such sites is a real phenomenon but can be managed by using contiguous foundations, minimizing interfaces between different foundations and developing lightweight and well distributed structural loads. Moreover, it is possible to derive basic raft design dimensions for these sites before knowing details of soil parameters. Practical engineering decisions at an early design stage are key to success.

9 ACKNOWLEDGEMENTS

Everyone at Ingenieros Civiles Asociados S.A. de C.V. (ICA) who built the raft.

10 REFERENCES

Dilley, Philip. 1994. Kansai International Airport Terminal Building – the Design, The Structural Engineer, 72 (18)

G. Auvinet. Excavations, Foundations and Geotechnical Hazards: The case of Mexico City (Publication TBC)

Kostura, Clark, Olson, 2018, Design of a 500,000m^2 Iconic Roof for the New International Airport for Mexico City, IASS Symposium

O' Riordan, Kumar, Ciruela-Ochoa & Canavate-Grimal. 2017a. Estimation and Calibration of Input Parameters for Lake Texcoco Clays, Mexico City. NUMGE

O' Riordan, Kumar, Ciruela-Ochoa & Canavate-Grimal. 2017, The stiffness and strength of saltwater Lake Texcoco clays, Mexico City, 2017 ICSMGE Seoul

Resendiz D, Auvinet G & Silva C (1968) Conception des fondations du Palais des Sports de la Ville de Mexico en presence de frottement negatif. Specialty session at 7th ICSMFE Mexico City, 20 pp.