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## Case History of an Unusual Foundation in Steep Sloping Ground in São Paulo

Un Cas de Projet et Construction de la Fondation d'un Grand Édifice sur des Terrains assez inclinés à São Paulo

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### Summary

A case history of design and construction of the sub-structure of a big building on steeply sloping ground in São Paulo is presented.

It concerns a 16-storey building with six basements requiring excavations up to 20 m below ground level and 10 m below ground water: interesting problems were created by the fact that along one property line a 10-storey building was founded on shallow footings and a part of the lot comprised a roughly 1:1 slope of 10 m creating difficult working conditions for the equipment. In this case the whole design of the structure was conditioned by the subsoil problems: the foundation design finally included every type of foundation, viz. pneumatic caissons, piles, footings and an inverted dome shaped raft.

Among the problems that are faced in the development of some of the sites in the densely built down-town area of the city of São Paulo is one that poses questions of some interest, for the foundation design results from the steepness of the natural slopes frequently encountered, which, together with the desire of maximum land utilization, leads to delicate problems of temporary support of vertical cuts. A case is described here which led to solutions considered quite original among us, and they are believed to be of considerable interest as a demonstra-

### Sommaire

Le projet concerne un bâtiment de 16 étages comptant six étages souterrains, exigeant des excavations jusqu'à 20 m de profondeur dont 10 m sous le niveau de la nappe, à côté d'un bâtiment de 10 étages appuyé sur des semelles superficielles: en outre le problème d'exécution de la fondation devint délicat à cause d'une inclinaison à 1:1 de 10 m d'une partie du terrain naturel. Le projet entier dans ce cas fut envisagé du point de vue des problèmes de fondation, et le bâtiment incorpore tous les types de fondations: pieux, semelles, caissons pneumatiques, et un radier en forme de cuve.

tion of the flexibility of practical applications of foundation engineering.

### Garage 'America'

The case presented subsoil problems of such a nature as to affect the entire structure on the basis of recommendations designed to facilitate the foundations and temporary support of the cuts. Fig. 1 shows the plan and topography of the site for which a 16-storey garage building had been designed. On

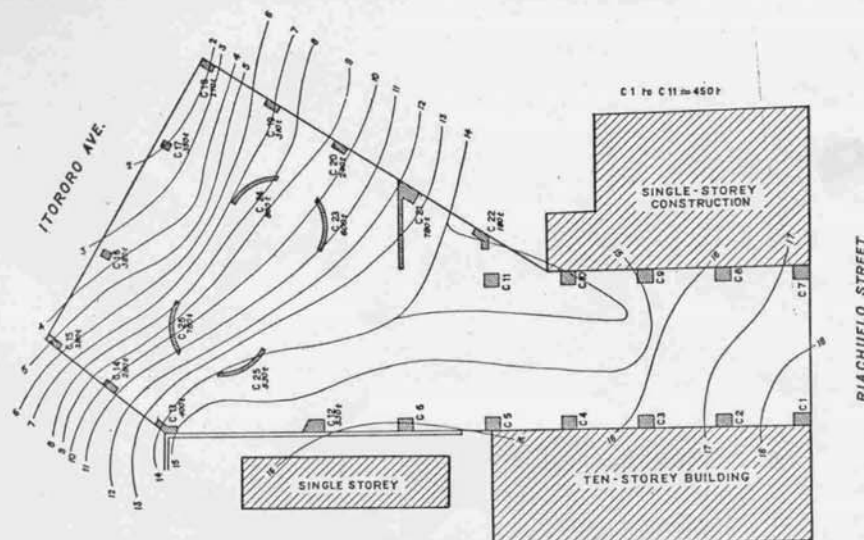
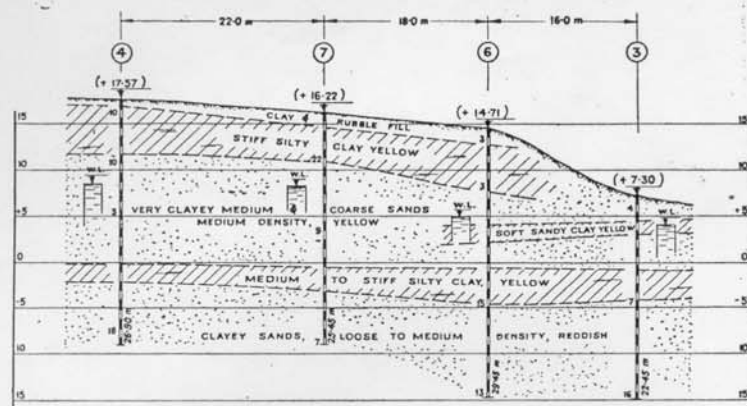


Fig. 1 Garage 'America'. Topography and initial conception of distribution and loads of concrete columns  
Garage 'America'. Topographie et conception préliminaire des positions et charges des colonnes en béton armé



Numbers at left of boring profiles represent standard penetration test

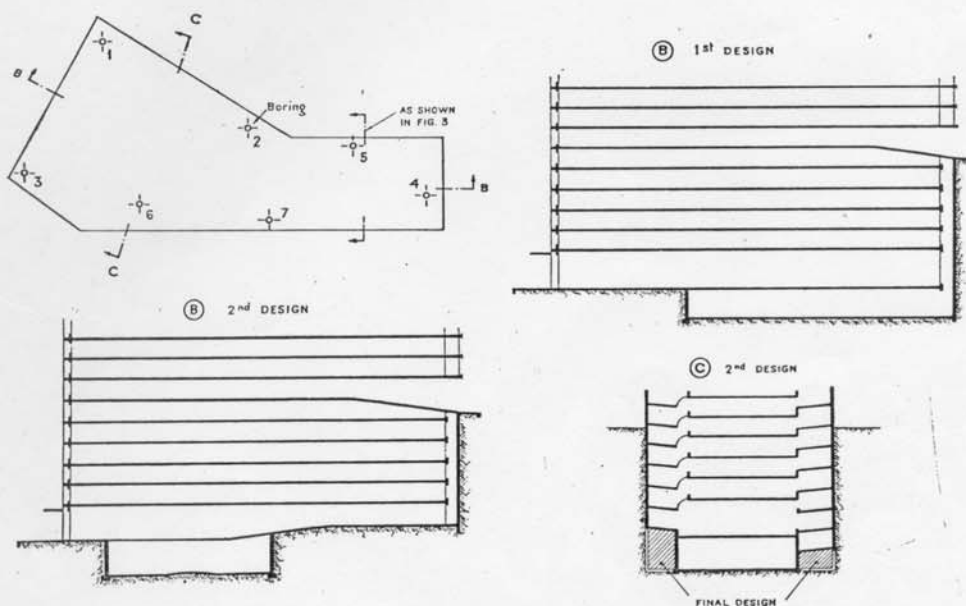


Fig. 2 Subsoil section and cross-sections of sub-structure as modified in successive steps  
Coupe du sous-sol et coupes des fondations selon les modifications successives

the same plan we have shown the position and load of various columns as initially conceived. In Fig. 2 we summarize the information obtained from dry-sample borings with penetration resistance measurements: beside this subsoil profile is indicated the architect's initial concept of the position to be occupied by the building with its several floors excavated below the level of the higher street. The building had naturally been put forward as a reinforced concrete structure.

Early conferences between the engineers and consultants and the owner centred around the rectangular area facing Riachuelo St. (Fig. 3), where the problem of temporary support was

accepted as most acute because of the adjoining 10-storey building founded on footings. It was immediately seen that the standard approach based on a system of temporary support by means of driven steel I sections and intermediate horizontal wooden boards together with horizontal bracing across the trench-like excavation would require unusually heavy elements because of the high pressures expected and the appreciable distance (12 m) between opposite faces of the excavations; further it would lead to some loss of extremely important width and frontage of the already narrow lot; finally it would result in a very slow construction because after placement of temporary



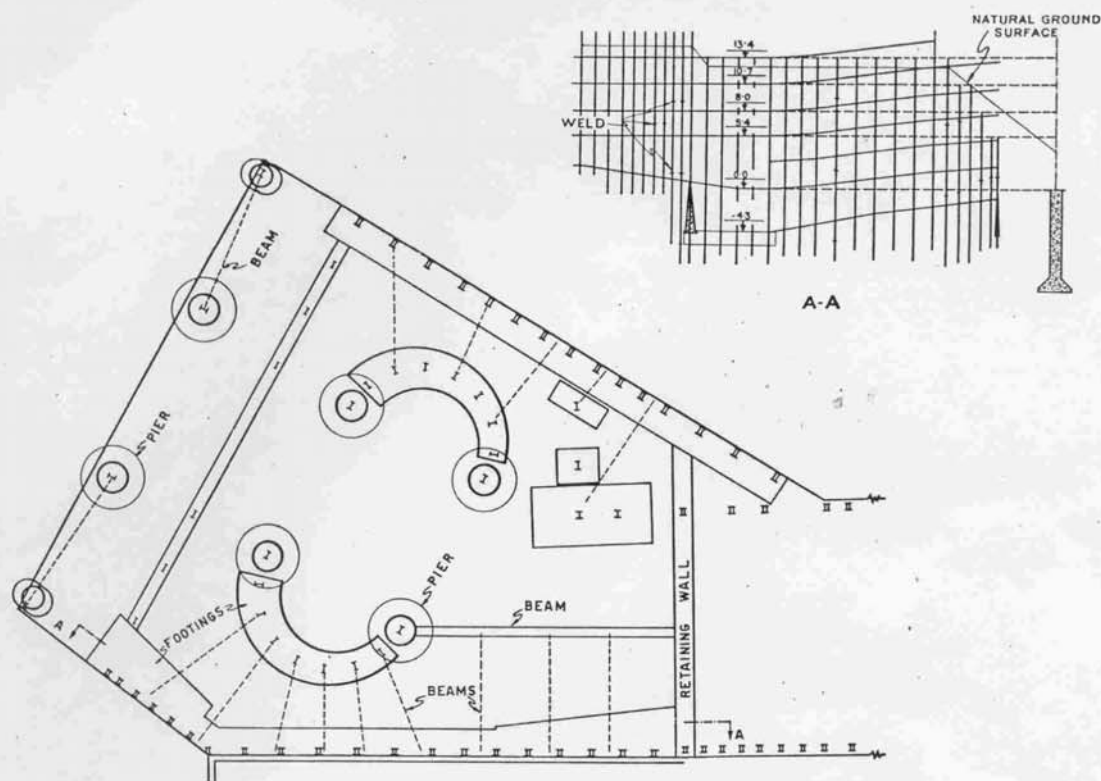


Fig. 4 Foundation plan of remaining area, and explanatory cross-sections  
Projet des fondations de l'autre partie, et coupes explicatives

be of steel and that its construction follow the pattern of the standard temporary support above described but be simultaneously designed to remain and serve as the definite structure. In short, since temporary steel piles could be driven and braced across the excavation by steel sections (it had already been conceded that the cross-bracing would have to be of steel because of the distance across and the magnitude of the pressures), it was merely decided to drive permanent steel piles which, as the excavation progressed, would be exposed in part and would start working also as columns. As each floor level was reached, the floor itself would be built to provide cross-bracing and the piles would be driven deep enough to possess the necessary load-carrying capacity for the weight of all of the basement floors plus some of the superstructure (so as to permit greater speed of construction).

When thoughts reached this stage, the next step was to accept the suggestion of making the entire structure of steel, a suggestion put forward by engineers of the Volta Redonda steel mills (Companhia Siderurgica Nacional) which were at the time beginning a new line of production of structural steel sections.

We have narrated this sequence of thoughts in some detail because of the interesting fact that the foundation problems of this rather extraordinary building were responsible for the adoption of the steel structure—the first building so erected in São Paulo (among the first in Brazil). Furthermore some alterations were introduced in the substructure's architecture on account of soil problems. Thus the decision to reduce the depth of excavation in the area of the rectangle, and to transfer the lowest basement to the other area was intended to avoid unnecessary risks to the adjacent existing buildings (Fig. 2).

Similarly the decision to add the cross-hatched areas of basement for which little utility could be foreseen was bound to the construction method envisaged, based on the row of pile-columns driven along the property line. Finally, if it is true that foundation problems to some extent controlled the substructure's architecture, it is also a fact that the foundation design was closely conditioned by some of the peculiarities of the architectural design.

As a general principle it was established that: (a) a steel structure would be used; (b) the columns along the property lines would be driven from ground level down in the form of piles that would serve the double function of transferring vertical loads to the foundation level and of resisting lateral earth pressure; (c) the substructure would be built from ground level down so that the floors themselves would serve as cross-bracing for the lateral pressures; (d) the pile-columns would be driven a few m further than the lowest excavation level so that they could furnish temporary support for the basement floors plus a part of the superstructure that would have been built, with a view to reducing construction time, before permanent foundations were ready; (e) since the deep excavations reached highly satisfactory bearing strata and conditions, footings would be used as the permanent foundation elements.

However, a few special considerations interfered with the simplicity of this scheme, adding points of interest to the overall design. We shall enumerate them as follows:

(1) Within the rectangle the pile driver's dimensions required that the row of piles be drawn away from the property line (face of the building) a minimum of 25 cm. As a result, on top of the heavy girders capping groups of three piles (Fig. 4)

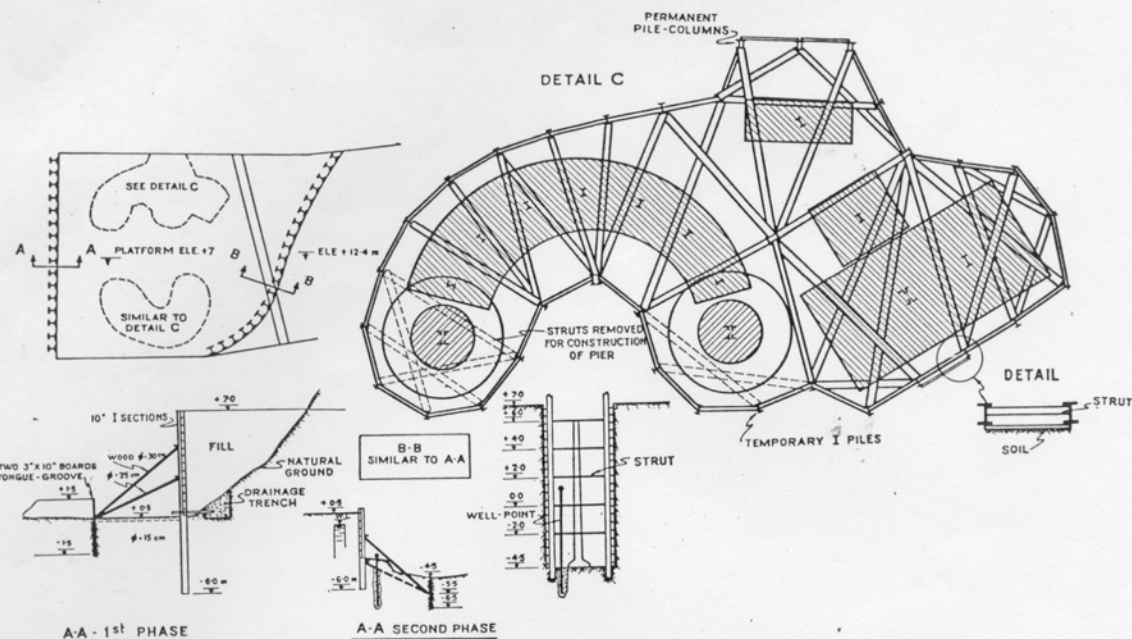


Fig. 5 Temporary supports necessary for construction as planned in Fig. 6  
Ouvrages de soutènement temporaire nécessaires à la construction selon le projet de la Fig. 6

special beams were introduced, perpendicular to the rows of piles and extending beyond them, to offer support for the superstructure's columns that had to regain the lost width.

(2) In order to avoid the heavy foundation girders that would be necessary to absorb the eccentric line load on footings along the opposite property lines, the foundation in the rectangle was designed as an inverted cylindrical dome raft. The additional space that resulted was used to fulfil fire-insurance requirements of reserve water storage.

(3) At the extremities of the rectangular area, positions of piles were determined so as to maintain a uniform line load (90 metric tons per m) along the edges of the inverted dome.

(4) The four front columns (Fig. 4) were to fall in the area in which no basement was permitted (Fig. 2). As a result, bearing in mind the loads to be supported and the difficulties and costs involved in seeking excavations down to elevation  $-5$  m for footing foundations, it was concluded that it was preferable to employ pneumatic pier foundations designed for bearing pressures of  $8 \text{ kg/cm}^2$  at an elevation approximately  $-10$  m.

(5) In order to employ the technique described above of building the various basements from the top down, it was necessary to prepare the interior columns to receive progressively the loads of the floors. It was suggested that these interior columns be driven in the form of piles, as was established for the columns along the periphery, but the idea was rejected because it would not permit shop finishing the structural steel elements. The only alternative was to prepare the concrete footing foundations at the bottom of temporary trenches, and to raise the steel columns (temporarily braced to avoid buckling) to ground level: finally the total excavation would proceed routinely without further necessity of temporary bracing.

Since these temporary trenches would be very deep (footings would rest at elevation  $-4$  m roughly) it was necessary to maintain them as narrow as possible to permit simple cross-bracing through which the columns would be lowered. The maximum allowable bearing pressure at elevation  $-4$  m was

taken as  $40 \text{ t/m}^2$ . Thus, since the four heavy interior columns (Fig. 4) would require very wide and awkward footing areas for this bearing pressure, it was decided to support them on pneumatic piers designed for bearing a pressure of  $8 \text{ kg/cm}^2$  at elevation  $-10$  m. These piers were constructed within the trench and employed a temporary shaft down to elevation  $-4$  m; the full concrete pier rose to this elevation and from there up the steel column was raised.

(6) The steep inclination of the site in the wider portion made it necessary to develop a temporary intermediate working platform at elevation  $+7$  m. The front row of I-section piles was driven from  $+7$  m down to  $-5$  m so as to serve also for the temporary support of the final excavation for the basement (Fig. 5).

From this platform were driven the temporary piles for excavation of the trenches for the foundations of the interior columns. With respect to the temporary support of these trenches the only point of some interest that may be brought to the reader's attention lies in the fact that it became necessary to dispense with the cross-bracing temporarily at the points where the piers were to be put in; the trench was therefore made tightly curved in plane at these points and the horizontal wood sheeting between vertical steel sections was roughly planned to carry load by arch action.

In conclusion we may further bring to the reader's attention that the special circumstances that obtained in this job led to the simultaneous adoption of all four types of foundation commonly recognized. The finished structure employed only spread footings, cylindrical piers, and the raft (inverted-dome). With respect to the first two the experience we possess is vast and permitted our planning the bearing pressures without risk of differential settlements. The inverted-dome raft was, to our knowledge, used for the first time; it was estimated to behave approximately as a spread footing of equal dimensions. Temporarily the structure was supported on a row of steel piles with little friction along one face throughout the depth of



excavation, and friction and point resistance along the lowest portion (1 to 2 m) embedded below lowest excavation level: although the piles were driven with open end, a plug of soil was formed after a few m of driving and remained constant thereafter. The behaviour of such piles was altogether unknown, but was expected to be satisfactory. The load which they actually received before permanent foundations were incorporated could have reached an estimated maximum of about 50 metric tons if no allowance is made for the rather indeterminate friction components along the walls. The overall be-

haviour of all the foundation elements and of the lateral support of the earth pressures has been entirely satisfactory.

The complex nature of the engineering problems involved called for close team work. Principal contributions to the items herein described came from: (1) Engenharia de Fundações S.A. who put forward many of the initial suggestions until the steel structure was adopted, and later drove the piling and the piers; (2) Eng. Paulo Fragoso, designer of the steel structure; (3) Cavalcanti-Junqueira S.A., general design and construction engineers in charge of the whole project.