Foundations of Tall Buildings on Sand in São Paulo (Brazil)

Fondations de grands bâtiments sur sable à São Paulo, Brésil

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Summary

The author describes a method for determining the load bearing capacity and predicting the probable settlement of buildings founded on sand in São Paulo, Brazil.

He reviews the geotechnical properties of sand with particular reference to this material in and around São Paulo, introducing the concept of a "modulus of compressibility" for sand, obtainable from triaxial compression tests, loading tests or observed settlements of structures founded on sands with similar properties. The behaviour of the foundations of seven high buildings on sand is discussed.

Sommaire

Description et commentaires sur une méthode pour la détermination des charges admissibles et pour la prévision des tassements des fondations de bâtiments, utilisés avec succès à São Paulo (Brésil).

Les caractéristiques géotechniques des sables en général, et de ceux de São Paulo en particulier, sont décrites pour introduire la théorie du « module de compressibilité » des sables, ce qui peut être obtenu par des essais de compression triaxiale, des essais de charge ou l'observation des tassements de structures fondées sur sol sableux identiques.

Le comportement des fondations de sept grands bâtiments sur de tels sables est mentionné.

1. Geotechnical characteristics of the São Paulo sands

The soil in the City of Sâo Paulo (Brazil) is a tertiary deposit overlying a stratum of gneiss. In the centre of the city there are hills rising to 760 metres above sea level, and valleys with bottoms at approximately 730 metres above sea level. The hills are formed by eroded layers of mottled stiff clay, silty clay and fine sand with clay, irregularly disposed and with a granulometric composition which varies both vertically and horizontally (1).

There is a deep sand stratum underlying the clay below the 735-metre level. It is angular grained sand, with little clay, varying from coarse to fine sand. Erratic lenses of clay and silt occur within this stratum. The natural ground water sevel coincides approximately with the top surface of this ltratum, with the result that the sand is permanently submerged.

Maximum grain sizes of these sands range from 2 to 0·4 mm. Percentages of grains below 0·1 mm vary from 15 to 60 per cent and their clay content varies from 2 to 20 per cent.

The void ratios of these sands lie between 0·7 and 0·55, averaging 0·65. At their maximum density, the void ratios are about 0·5 and at minimum density about 1·2. Undisturbed samples taken from the bottom of compressed air caissons, when subjected to triaxial compression tests have shown little tendency to compress, which proves that these sands are comparatively dense.

Several tall buildings in Sâo Paulo are founded on such sands, by means of spread footings, mats. caissons or piles.

2. Penetration resistance of the São Paulo Sands

Measurement of the penetration resistance of a split-spoon sampler into the ground during test borings has proved to be the most reliable method for judging the degree of compaction.

The penetration resistance is measured, in Brazil, by counting the number of blows, of a 60 kg hammer, falling from a height of 75 cm necessary to produce the first 30 cm penetration of a split-spoon sampler. This has an external diameter of 46 mm. The casing of the borehole has an internal diameter of 50 mm.

The penetration resistances of Sâo Paulo sands, at the site of several tall buildings, described in a previous paper (2) gave average values of 15 blows for a penetration of 30 cm, ranging from a minimum value of 5 to a maximum of 28.

This penetration test method is not precisely the same as the American "Standard Penetration Test", but it is known that the American method gives results 1·3 to 1·7 times greater than the Brazilian one for certain states of compaction, so the penetration resistance of the Sâo Paulo sands, if measured by the above test, gives a resistance of 22 blows for 30 cm penetration. This average value is derived from values varying from a minimum of 7 to a maximum of 47.

Nevertheless, by observing compression during triaxial tests, these are "dense sands", so that measurement of compaction by penetration resistance alone may give an estimate of compaction which is lower than actually occurs.

3. Estimating allowable loads

Estimation of allowable loads in sands for spread footings, is mainly done by loading tests on plates. A cast iron test plate of 80 cm diameter is placed on the ground at foundation level, and loads are applied to it by an hydraulic jack reacting against a dead load. The loads is applied by increments and the settlement which occurred after each increment is measured. No increase of load is made until the settlement caused by previous loads becomes stabilised. The allowable pressure for a spread footing foundation is admitted to be equal to half the pressure producing a settlement of 25 mm under a test load.

The author established a statistical correlation between resistance to penetration and allowable pressure, as shown in the following table :

Table 1

Correlation between penetration resistance (Brazilian Method) and allowable pressures for São Paulo Sands

Corrélation entre la résistance à la pénétration (Méthode Brésilienne) et les charges admissibles pour les sables à São Paulo (Brésil)

Penetration resistance (blows/30 cm)	*Compactness*	*Allowable pressures (kg/cm²)*	
< 5	loose	fine sands	< 1
		coarse sands	< 1·5
5-10	medium	fine	1 -2·5
		coarse	1·5-3·0
10-25	compact	fine	2·5-5·0
		coarse	3·0-5·0
> 25	very compact	—	> 5·0

An increase of 10 per cent per metre of depth is allowed for deep foundations.

Loading tests are used to determine the bearing capacity of piles, based on a load which produces a settlement of 15 mm, divided by 1·5.

Since penetration resistance of sand increases approximately with depth, piles are driven or cast-in-place to a depth where resistance to penetration exceeds 15 blows for 30 cm. Timber piles have been tested up to a load of 20 tons, whereas precast reinforced concrete piles with a cross section 35 cm square will take a test load of about 50 tons. Cast-in-place concrete piles, mainly of Franki type, will support loads of up to 120 tons or even greater.

Static formulae for theoretical determination of point resistance and skin friction of piles are not commonly used. Dynamic formulae are commonly used to determine the bearing capacity of test piles during driving.

4. Estimating the settlement of buildings on sand

Settlement of tall buildings founded on São Paulo sands have been estimated by calculating the distribution of vertical and radial pressures on the soil. The "modulus of compressibility" vertically is proportional to the final radial pressure at each point (the corresponding coefficient of proportionality α is assumed). The settlement is computed by the integral :

$$W = \int_0^{\infty} \frac{1}{E_z} (\sigma_z - \sigma_r) dz \quad (1)$$

where :

σ_z is the vertical pressure ;

σ_r is the radial pressure (when foundation is not circular, we admit $\sigma_r = \frac{1}{2}(\sigma_x + \sigma_y)$;

E_z is the "modulus of compressibility" which for sands is a function of depth $_r$.

The "modulus of compressibility" could be estimated from triaxial compression test curves. This modulus will include immediate deformation as well as consolidation, if we base its calculation in a completely drained triaxial compression test which would be the most satisfactory way to carry out a triaxial test on a sand sample.

For determining the modulus of compressibility, it would be much easier if we could assume a certain specific strain of the specimen, ε, and compute E_z by the formula :

$$E_z = \frac{\sigma_z - \sigma_r}{\varepsilon} \quad (2)$$

But if we try to estimate the value of ε, we find that the specific strain of a sand foundation soil is very small. In São Paulo, it was found in one case, that it would be about 0·13 per cent in the upper strata, but that it fell rapidly with depth. Being very small the above secant approaches the initial tangent to the curve, so that the determination of E_z from a triaxial compression is too much inaccurate.

However, by means of a triaxial compression test, it is found that the secant modulus is proportional to σ_r, for a certain specific deformation, and this must be true also for the limiting value of $\varepsilon \to 0$, that is the initial tangent modulus.

Then it can be stated that a proportionality between E_z and σ_r, actually exists :

$$E_z = \alpha \sigma_r$$

It is well known that the radial pressure in the ground below a foundation is due to the weight of the soil plus the radial component of the applied pressure. That is :

$$E_z = \alpha(K_0 \gamma z + \sigma_r) \quad (4)$$

where :

K_0 is the coefficient of earth pressure at rest,

γ is the specifit gravity of soil and

z is the depth

Substituting (4) in (1), we have :

$$w = \frac{1}{\alpha} \int_0^{\infty} \frac{(\sigma_z - \sigma_r)}{(K_0 \gamma z + \sigma_r)} dz \quad (5)$$

The coefficient α can be derived from previous experience. In São Paulo it is about 1 000, based on the observed settlement of buildings in this district.

Table II shows a summary of settlement observation in seven tall buildings founded on the São Paulo sands. The first two are a mat and footings respectively ; four are founded on piles and the last one has a special type of foundation described later.

The table shows also the values of α obtained from formula (5) knowing the settlement and computing the distributed pressures σ_z and σ_r in the soil, by the normal procedure based on the Theory of Elasticity formulae :

Table 2

Settlement of Tall Buildings on Sand in São Paulo (Brazil)

Tassements des grands bâtiments fondés sur sable à São Paulo (Brésil)

Name of Building	*No. of Stories*	*Foundation type*	*Covered area* (m²)	*Soil pressure* (t./m²) *Load on piles* (t.)	*Penetration resistance*			*Settlement* mm			α
					Ave.	*Max.*	*Min.*	*Ave.*	*Max.*	*Min.*	
Banco do Brasil	25	Concrete mat	1 500	25 t./m²	12	25	5	21	28	15	900
CBI-Esplanada	33	5 large footings	1 950	40 t./m²	15	30	5	22	26	17	1 150
Hotel São Paulo	20	205 piles	600	47·5 t.	15	28	2	12	15	8	2 175
Banco do Estado	33	317 piles	700	87 t.	—	—	–	19	24	8	1 140
Azevedo Vilares	23	143 piles	270	42 t.	8	16	2	20	22	14	1 600
Hotel Jaraguà	25	295 piles	700	80 t.	6	20	4	26	30	14	1 600
Copan	34	Caissons (piles)	2 500	80 t./m²	5	10	2	26	29	14	——

5. The Copan Building

The Copan Building, with its reinforced concrete structure now completed, will be the largest concrete structure ever erected in Brazil. It is about 130 m high and covers an area of abour 2 500 m². The floor of the basement of the building is 5 m below street level.

The building was designed to be founded on sand with the aid of pneumatic caissons at 13 metres below street level. This sand was considered to be too loose to carry the pressure transmitted to it by the caissons. It was therefore decided to compact the sand by driving 8-metre precast concrete piles, spaced one metre apart, into the soil. These piles were driven before the caissons were sunk, with thc aid of a follower.

Some time before that, the same type of foundation was used in a viaduct over one of the main avenues in São Paulo. Thus a "modulus of compressibility" could be computed from observation of the settlement of the viaduct and therefore the probable settlement of the Copan building could be predicted. The settlement so computed, however, is three times greater than the observed settlement of the completed structure. Probably the final total settlement will be only half of the computed value or even less than that. If the settlement had been computed with an assumed α coefficient of 1000, then the computed settlement would have been much closer to the value of the observed settlement.

6. Conclusion

Observation of the behaviour of the foundations of seven tall buildings in São Paulo have shown that allowable pressure can be safely determined by correlation between penetration resistance and allowable pressures derived from plate loadings tests. Estimated settlement can be made accurately by the use of Theory of Elasticity formulae, assuming that the "modulus of compressibility" increases proportionaley with the confining pressure in the soil.

7. References

[1] Pichler, E. (1948). "Regional Study of the Soil from São Paulo (Brazil)" *2nd Int. Conference of Soil Mech. Found. Eng.* Rotterdam.

[2] Rios, L. and Pacheco Silva, F. (1948). "Foundation in Dowtown São Paulo" *2nd Int. Congress. Soil Mech. Found. Eng.* Rotterdam.