Settlements of Three Buildings Founded on Stratified Soils

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ABSTRACT

This paper describes the movements experienced by three residential buildings located in Avellino (South Italy). A common feature of the buildings is the unsymmetrical superstructure that, for lack of construction joints, makes the resultant of the vertical loads on foundation to be highly eccentric. At the end of December 1983, when most of the dead loads had been applied, the buildings exhibited conspicuous settlements, so construction was stopped and the vertical displacement of several points of the foundation was measured during a period of almost one year. The subsoil was investigated by boreholes, CPT and conventional laboratory tests; it consists of a sequence of compressible layers of silty sand and clayey silt, overlying a gravel formation. The thickness of these layers was found to be very different from borehole to borehole. An analysis of the movements occurred is conducted using a finite element code. Good agreement is found between theoretical prediction and experimental measurements. The analysis has also shown that the compressibility and heterogeneity of the subsoil along with the eccentricity of loads on foundation were the main causes for the movements occurred.

INTRODUCTION

In 1983, three residential buildings, located in Avellino (South Italy) about 50 km from Naples, experienced conspicuous settlements while being built. Due to settlement magnitude, construction was stopped and the buildings were monitored by means of topographical survey. The vertical displacement of several survey points was measured during a period of almost one year. Moreover, the subsoil was investigated by boreholes, penetrometer tests and laboratory tests.
In the following sections, after a description of the buildings, soil conditions and movements occurred, a prediction of the measured settlements is performed using a finite element code. Moreover, the influence of factors such as soil heterogeneity, load eccentricity and ground surface slope on the movements occurred is also analysed.

DESCRIPTION OF THE BUILDINGS AND MOVEMENTS OCCURRED

The three buildings are sited on a gentle slope; they are pointed out by letters A, B and C on the location map in Fig. 1. The buildings are identical except for the number of stories, which is five for buildings A and B, and six for building C. Each building covers an area of approximately 18 m by 23 m. The buildings have a reinforced concrete (r. c.) frame structure, and r. c. mixed with brick floors. Moreover, all three buildings have a ground floor used as garage. The foundation is a grid of r. c. beams stiffened by a r. c. wall, 30 cm thick, built around the perimeter of the ground floor. The foundation beams are 1.30 m high. All the infill walls are made of light bricks. Figures 2 and 3 show the layout of the foundation plan and the transversal cross section of one building, respectively. As can be noted from Fig. 3, the superstructure consists of two fabric bodies of very different heights and weights, but having the same foundation. Such an unsymmetrical superstructure, along with the lack of construction joints, makes the resultant of the loads on foundation to be highly eccentric. Moreover, the foundation is not uniformly embedded, to such a point that the beams on the back side of the buildings (right-side in Fig. 3) largely emerge from the ground surface.
At the end of December 1983, when the carrying structures and the infill walls had been recently completed, all three buildings experienced conspicuous settlement that caused an inclination of the floors, $\Delta w/L$, of about 4 cm for buildings A and B, and 8 cm for building C, over a distance L=10.5 m (Fig. 3). As a consequence of these movements, construction was stopped and it was decided to monitor the buildings. To this purpose, the vertical displacement of several points of the foundation, which are indicated in Fig. 2, was measured during the time period from December 1983 to September 1984, by means of topographical survey. In general, the measurements pointed out a movement prevailingly of tilting

type developing in the transversal direction of the buildings, and with the greatest values of settlement at the points located on the back side of the foundation (Fig. 3).

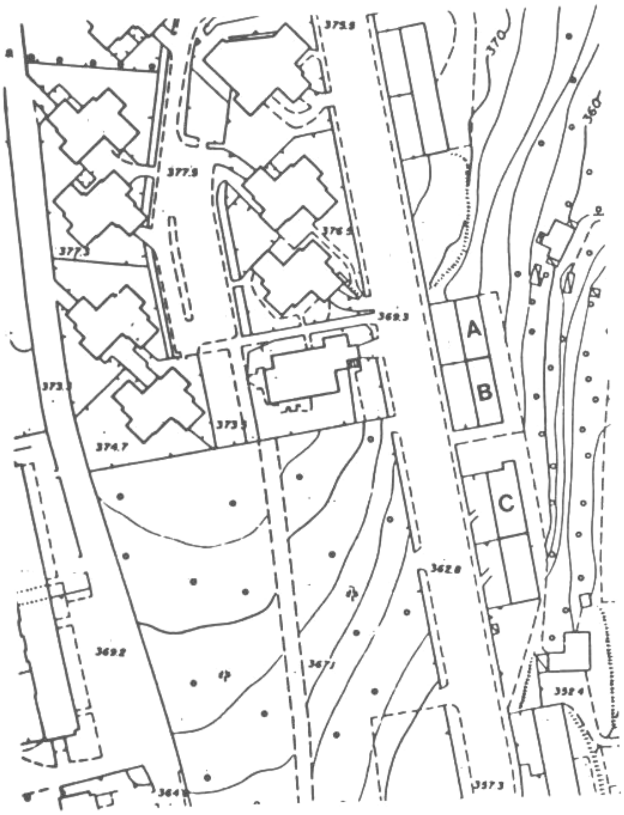

Fig. 1. Location map of the buildings.

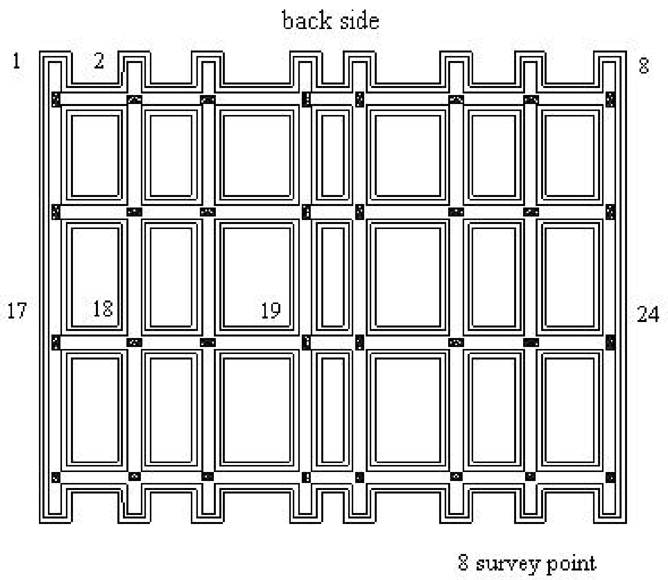

Fig. 2 Layout of the foundation plan and location of the survey points.

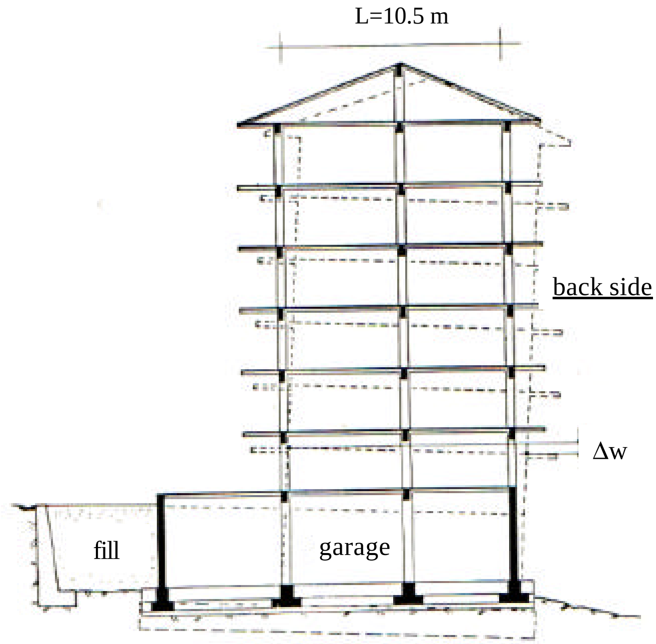

Fig. 3. Transversal cross section of one building, with a scheme of the movements occurred.

The measured settlement of some survey points is shown in Fig. 4; for the sake of clarity, for each building, only the time-settlement diagram of two meaningful points is reported. As can be seen from this figure, building C was affected by greater settlements than buildings A and B, whereas these latter buildings exhibited similar vertical displacements. It should be noted that the increase in settlement recorded about the middle of May 1984 (Fig. 4) occurred in consequence of a storage of building materials that increased the dead loads. In spite of the importance of the movements, which in addition occurred in a short time, no cracking in the structural elements nor even in the infill walls was observed. Such an occurrence was undoubtedly favoured by the high stiffness of the foundation that mainly led to a rigid motion of the buildings. Nevertheless, due to the excessive inclination of the floors and notable difference in verticality of the buildings, taking also into account that a portion of the dead loads and all the live loads had to be yet applied, it was decided to underpin the buildings with micropiles (Dente 1989).

SOIL CONDITIONS

The subsoil was investigated by boreholes, CPT and laboratory tests. It consists of a sequence of compressible layers of volcanic origin (cover soils) overlying a sandy gravel formation, which was found at a depth ranging between about 5 and 11 m below ground level. In general, the upper layers of the cover soils consist of gravelly sand and silty sand, and the lower one consists of clayey, sandy silt. The index properties of the cohesive soils are summarized in Tab. 1. According to Atterberg limits and Casagrande’s classification, these soils may be classified as inorganic silts of high compressibility. The thickness of the soil layers was found to be very different from borehole to borehole. Figures 5 to 7 show the soil profiles from the boreholes and the results of the CPT tests located just uphill and downhill of the buildings. As can be noted, the thickness of the cover soils pronouncedly increases moving from uphill to downhill of the buildings in the transversal direction of them. This makes the subsoil markedly heterogeneous. Moreover, Figs. 5 and 6 indicate that the foundation beams of buildings A and B are almost completely embedded in the gravel formation on the fore side of the buildings, whereas those on the back side rest on the cover soils. The CPT profiles account for the described stratigraphical situation and the mechanical properties of the soils. The tip resistance, q_c, ranges on the average between 0.5 and 2 MPa in the cover soils, and sharp increases at the top of the gravel formation. The water table is located at a shallow depth from the ground level. Such a geological situation along with the structural characteristics of the buildings and the topographical conditions of the area account for the movements occurred.

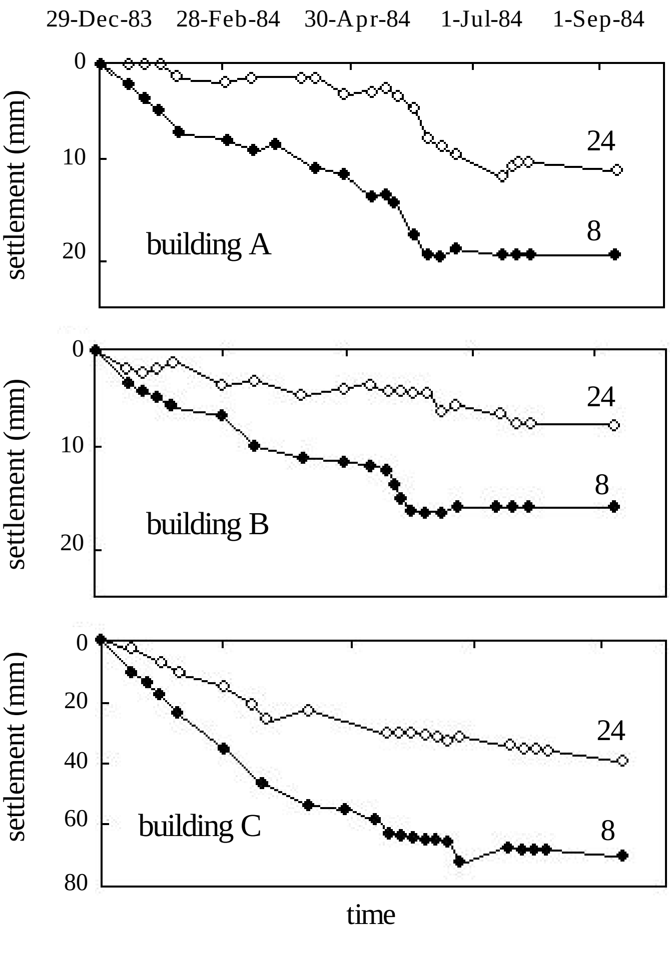

Fig. 4. Observed time-settlement diagram at some survey points.

Table 1. Index properties of the cohesive soils (mean values)

w (%)	γ (KN/m³)	w_L (%)	Ip (%)	n (%)
48.7	16.9	62.5	25.6	55.9

SETTLEMENT PREDICTION AND ANALYSIS OF THE RESULTS

The prediction of the observed movements was carried out using the finite element code PLAXIS (Brinkgreve and Vermeer 1998). In this section, only the results from the analysis of building C, which was affected by greatest settlement, are presented. The subsoil model adopted in the calculations is shown in Fig. 8. The involved soils were modelled as elastic-perfectly plastic materials, and the Mohr-Coulomb failure criterion with non-associated flow rule (ψ=0) was adopted. The soil parameters used in the analysis were obtained from the available in-situ and laboratory tests (CPT, conventional triaxial and oedometer tests), and are shown in Tab. 2. Nevertheless, the values of the coefficient of permeability for the granular soil layers as well as Poisson's ratio were reasonably assigned for lack of suitable experimental measurements. The resultant of the vertical loads acting on foundation at the end of December 1983 was about 27 MN, and its eccentricity was 2.3 m.

The analysis was carried out in three main steps:

1) calculation of the initial stress state due to gravity loading;
2) calculation of the stress-strain field induced by the loads on foundation;
3) calculation of the time history of settlement at some points of the foundation.

Figure 9 shows the deformed finite element mesh and the movement of the foundation due to the external loads. As can be seen, the foundation exhibits a rigid motion as really occurred. Moreover, in Fig. 10 a comparison is presented between the time-settlement diagram recorded at some survey points during the observation period, and that calculated for the same points using PLAXIS. The agreement of predicted and measured settlement may be judged very close, except for some differences between theoretical and experimental results appearing during the final stage of the time-settlement diagram. These differences could be ascribed to the increase in dead loads occurred, as said, before the middle of May 1984, which was not considered in the analysis.

As previously pointed out, the main causes for the occurred movements have to be attributed to the eccentricity of loads, compressibility and heterogeneity of subsoil, and slope of ground surface. In order to ascertain how these factors affected

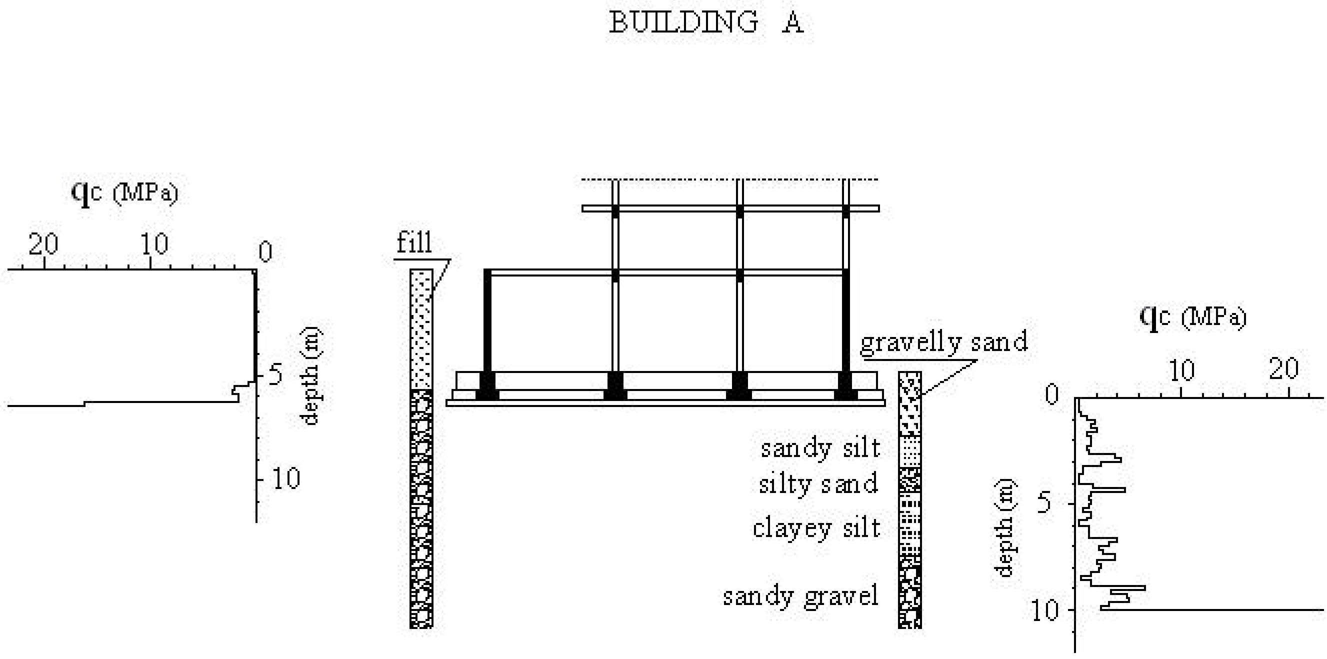

Fig. 5. Building A: soil profiles and CPT tests.

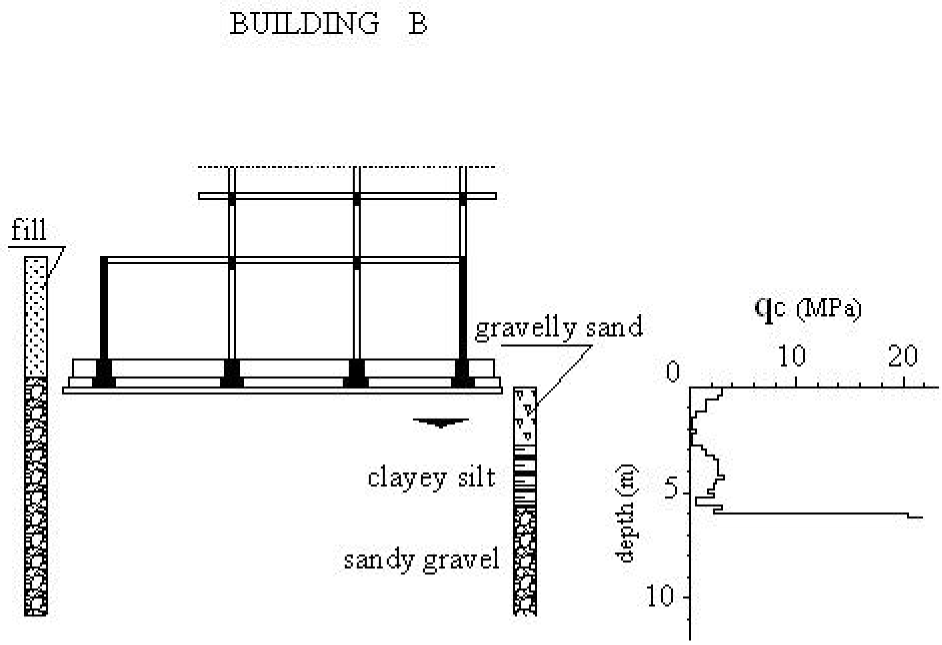

Fig. 6. Building B: soil profiles and CPT test.

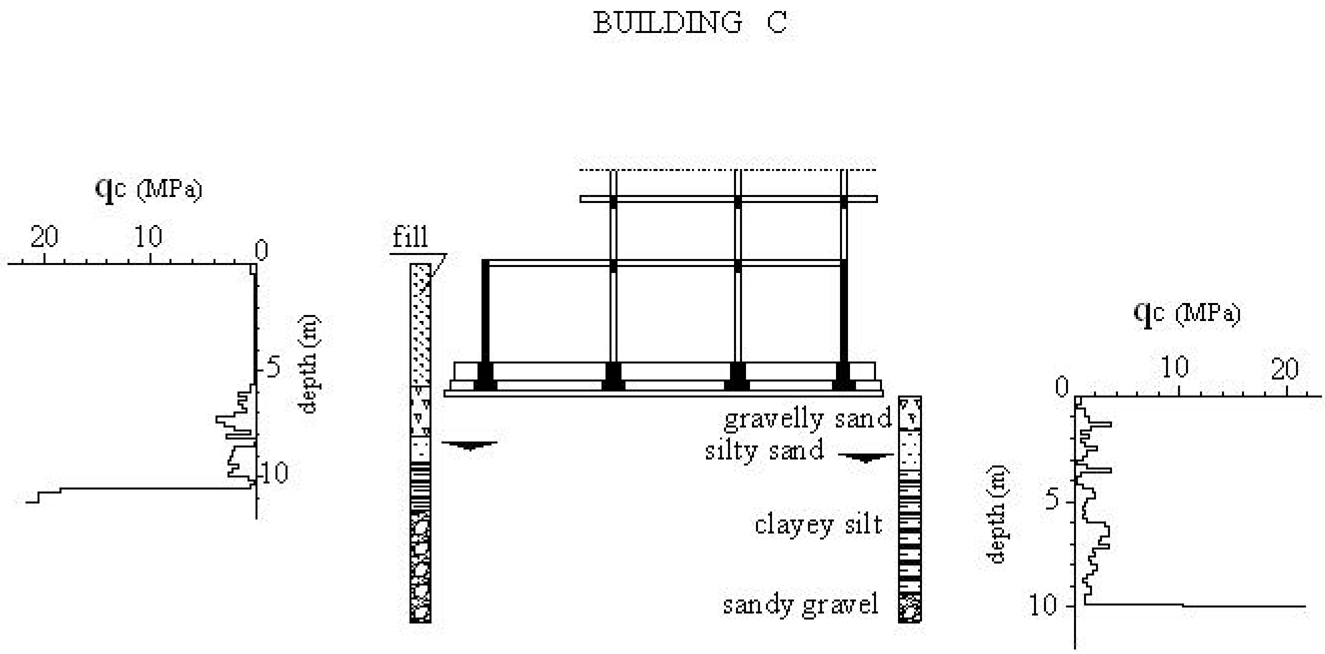

Fig. 7. Building C: soil profiles and CPT tests.

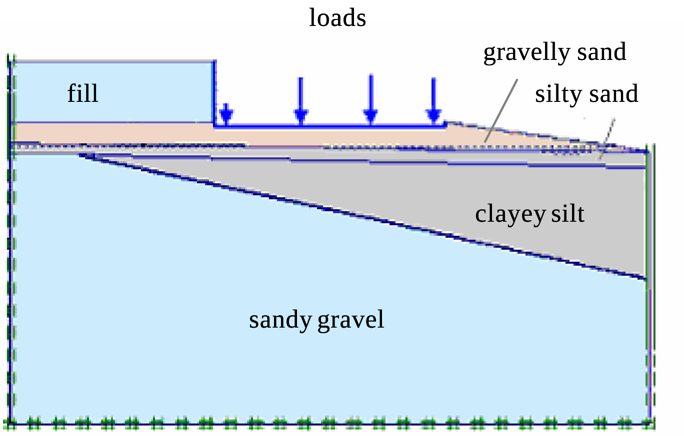

Fig. 8. Subsoil model used in the analysis.

the movements of the buildings, further calculations were carried out under some assumptions. Specifically, in a first analysis, it was assumed that the ground surface on the back side of the building is flat (case A), and then that the resultant of the vertical loads on the foundation is centrally located (case B). The results are presented in Fig. 11 along with those obtained in the previous analysis, in which all three of the factors affecting the movements occurred were considered (case C) in order to predict the measured settlements.

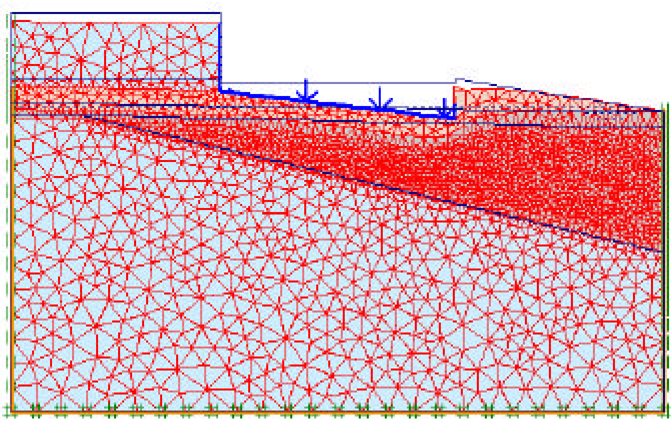

Fig. 9. Deformed F.E. mesh and foundation movement.

Table 2. Soil parameters used in the analysis

	E' (MPa)	ν'	c' (kPa)	φ' (°)	k (m/s)
Gravelly sand	7.5	0.25	0	35	10^{-4}
Silty sand	5	0.25	0	30	10^{-5}
Clayey silt	4.7	0.25	10	22	10^{-9}
Sandy gravel	75	0.25	0	40	10^{-3}

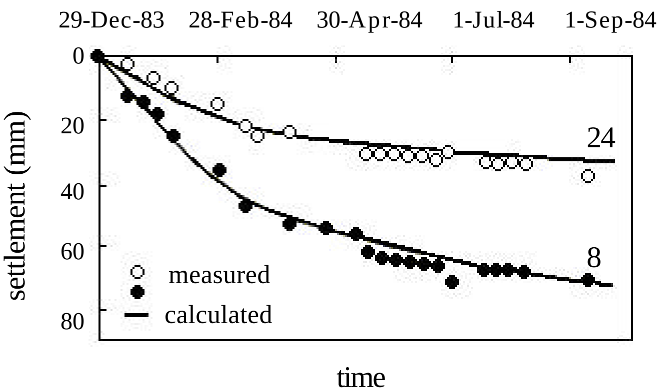

Fig. 10. Computed and observed settlement of some survey points versus time.

As can be seen from Fig. 11, the time-settlement diagram calculated at point 24 is essentially the same for all cases considered. For point 8, which is located on the back side of the foundation, the results of case A practically coincide with those of case C. This implies that the influence of ground surface slope on the settlement occurred may be ignored. On the contrary, the final settlement at this point due to the eccentric load (case C) is notably greater than that calculated when the load is assumed to be centrally located (case B). As a result, the differential settlement between the points considered that is obtained for case B is about half that of case C. In other words, the load eccentricity significantly contributed to increase the tilt of the buildings. Therefore, it may be concluded that the observed movements were undoubtedly caused by the compressibility and heterogeneity of the subsoil, but the load eccentricity played an important role.

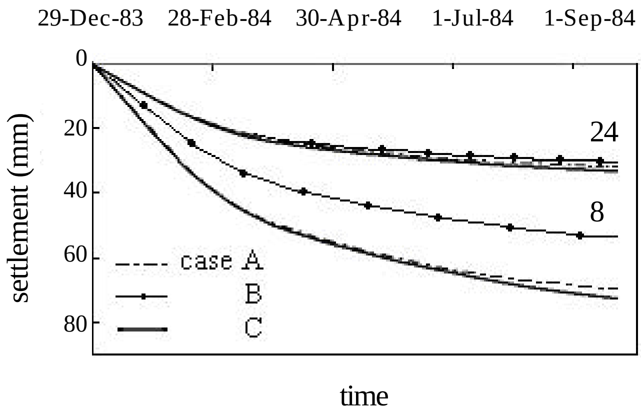

Fig. 11. Influence of ground surface slope, load eccentric and soil heterogeneity on the occurred settlement.

CONCLUDING REMARKS

The movements experienced by three buildings founded on stratified soils have been described. Due to the structural characteristics of the buildings, these movements were essentially of tilting type and caused excessive inclination of the floors and notable difference in verticality of the buildings. A prediction of the settlements measured during a period of almost one year, has been conducted using the finite element code PLAXIS. A good agreement has been found between theoretical prediction and observed settlements. Moreover, from the results of the calculations carried out, it may be concluded that the main factors affecting the movements occurred were the eccentricity of loads on foundation, and the high compressibility and marked heterogeneity of the subsoil.

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