DAMAGE TO STRUCTURES ON PRECONSOLIDATED CLAY

DEGATS CAUSES AUX BATIMENTS SUR ARGILES PRECONSOLIDEES

A. KOMORNIK, D.Sc., Senior Lecturer

J.G. ZEITLEN, M.Sc., Professor of Soil Engineering

Israel Institute of Technology, Haifa, Israel

SYNOPSIS Damage to apartment buildings located on unsaturated well-preconsolidated clays has appeared at a number of typical sites in Israel. Foundations were underreamed cast-in-place piles at shallow depths. Instead of movements which can be attributed to expected swelling forces, it appears that the tendency for differential settlement was basically responsible for load transfer within the buildings, causing cracking and rupture of columns.

INTRODUCTION

When foundations are planned in clay soils, good design practice requires designing the footings or piles for a sufficiently low pressure so that the expected differential settlements can be accommodated by the structure, and designing the structure to take the stresses resulting from loads being rearranged within the supports of the building. For common types of residential buildings in Israel, of four story height, the structure is usually of reinforced concrete with block walls. Differential movements which can occur without damage are limited to several millimeters. Ordinarily the structure may be designed with sufficient rigidity as to produce the necessary load transfer between the foundations when the subsoil is relatively soft. In the case of a saturated clay subsoil, the increase of load on particular columns produce sufficiently increased settlement of its foundation so that the structure is not deformed. Settlements and loads may be predicted with present methods of theory and practice with a fair degree of certainty (Lambe, 1964; Seed, 1965). For areas in which the clays are well preconsolidated, attention has been directed at avoiding damage from swelling. Consolidation was not considered a serious problem; the attitude of designers agreed with the views as expressed in Terzaghi and Peck (1967), that "the differential settlements of footing foundations on such clays seldom exceed those of adequately designed footings on sand". In Israel, foundations on preconsolidated clays were most often of the shallow bored pile type, and were ordinarily successful. Site investigations were aimed at determining variability of soil types, moisture conditions, swelling behavior, and strength. Because of the difficulties involved in any accurate prediction of differential settlements of foundations in preconsolidated clay strata, such analyses were not usually made for normal light structures. Instead, design bearing values were selected which were less than 1/3 of the ultimate bearing capacity of the soil. Where the clay is not saturated present practice requires the foundation to extend below the estimated zone of seasonal moisture changes. The allowable bearing value is reduced to allow for the possibility of reduced shear strength if, on the pessimistic side, moisture increases. It is not considered desirable to use too low a pressure because of the danger of swelling.

The possibility of some differential movements because of the uneven swelling of unsaturated clays is taken into account, considering both swelling and settlement. The superstructure is stiffened, and various sections separated by expansion joints. However, details easily overlooked may in particular include the danger of columns being overloaded well beyond the ordinary factors of safety used in structural design. As a result, a number of cases have arisen where severe damage has been caused in Israel to structures founded in stiff, highly plastic, preconsolidated, clay strata although precautionary measures were thought to have been taken to minimize the effect of differential movements on the structures. Columns between the piles and the floor beams have been cracked and ruptured , as shown in Fig. 1. Level measurements of the buildings showed settlements to occur of more than 30 cm. Investigations in three locations, which were carried out to determine the causes of these damages, are reported herein.

Studies included consolidation and swelling tests performed on undisturbed samples taken from different depths, determination of seasonal moisture variations, and vane shear tests. At one site, a loading test was carried out on a typical pile of the type used for founding these structures, with wetting of the subsoil under the design load.

Fig. 1 Column Destruction at Expansion Joint (Site A)

TYPICAL DESIGN CONDITIONS

Column foundation designs call for under-reamed cast-in-situ piles to a depth of 3 to 4 meters, loaded to 20 to 30 tons, with contact pressures between 2.5 kg/cm^2 and 3.5 kg/cm^2 .

Seasonal moisture variations in these areas have been found to be of the order of 2.5 m in depth. The shear strength of the clays tested by the vane shear apparatus in the field varied usually between 2.5 kg/cm^2 to 3.5 kg/cm^2. The contact pressures used for the pile foundations were chosen high enough to counteract the expected swelling forces from the clay strata, without allowing the clay to be overstressed in shear. The resulting factor of safety, of about 6, was considered to be adequate. The superstructure ordinarily consisted of four stories built on columns, with suspended floors. The walls of the first floor were often of cast concrete for greater rigidity. Reinforced frame type construction was used for the other floors, with walls filled with concrete blocks.

SITE A

Four story structures were built during 1957-58 in groups of two to five sections. Each section was about 15 meters long and 9 meters wide, completely separated from the neighboring sections by joints in the superstructure.

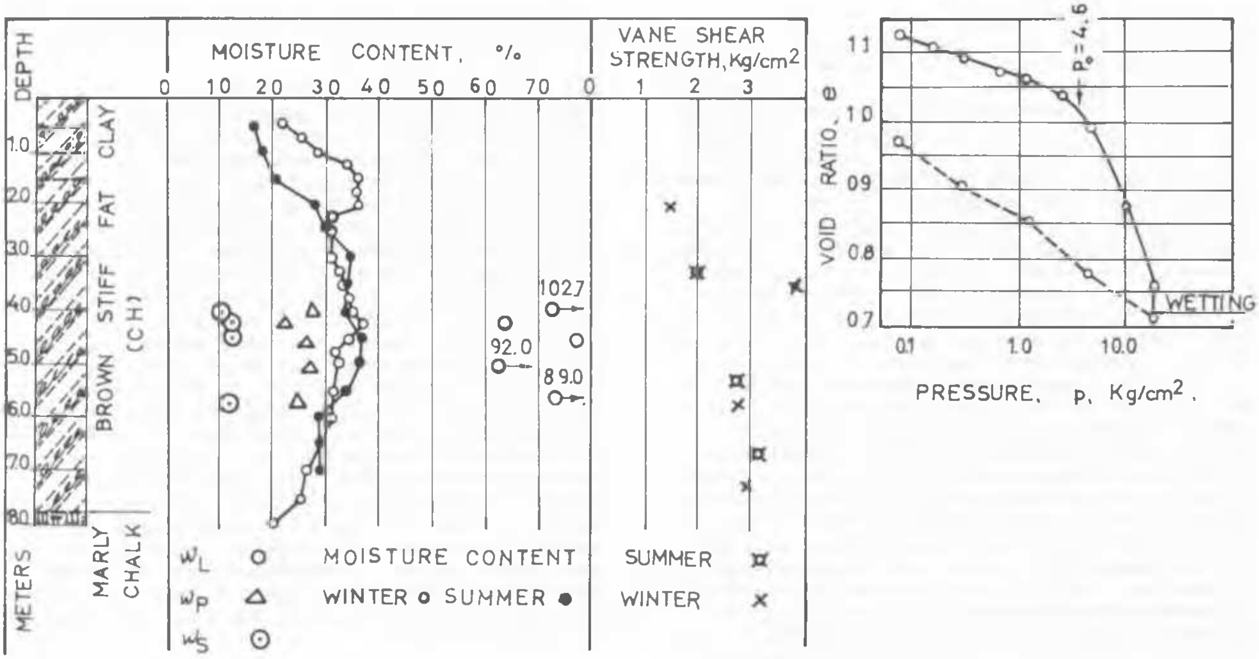

Fig. 2 Typical Soil Profile and Characteristics (Site A)

The superstructure was built as a reinforced concrete frame with the walls of the first floor fully cast in concrete in order to give the structure rigidity against small differential movements. The floors were suspended above the ground on columns of about 60 cm height. A portion of the ground floor walls formed the sides of buried shelters, and were built with well reinforced walls of 40 cm thickness instead of the usual 20 cm.

The walls of the upper three stories were built of concrete blocks with extra horizontal continuous structural beams cast above door and window openings to give greater rigidity.

The lower columns were 20 x 40 to 30 x 30 cm in dimensions, properly reinforced with longitudinal bars and stirrups, according to usual code of practice standards. As the free height of the cloumns was relatively small, there was no cause to expect any buckling of the columns under the designed loads.

The foundations designed for these structures were underreamed cast-in-situ piles to a depth of about 3 to 4 meters, a meter below the depth of the seasonal moisture variations. Column loadings were of the order of 20 to 30 tons, with pile spacing usually between 2 to 4 meters, depending upon location. The usual allowable end bearing pressures varied between 2.5 kg/cm^2 to 3.5 kg/cm^2 The piles were reinforced with both longitudinal bars (at least 4 bars of 12 mm diameter) and spiral stirrups.

In the area at least 17 structures showed various degrees of structural damage. Differential settlements and tilting of the various sections occurred, causing some of the columns near the joints to rupture (Fig. 1). In another building in this project, differential settlement of several inches occurred between adjacent columns and the building itself was distorted throughout its full height. A typical soil profile of this area is shown in Fig. 2,

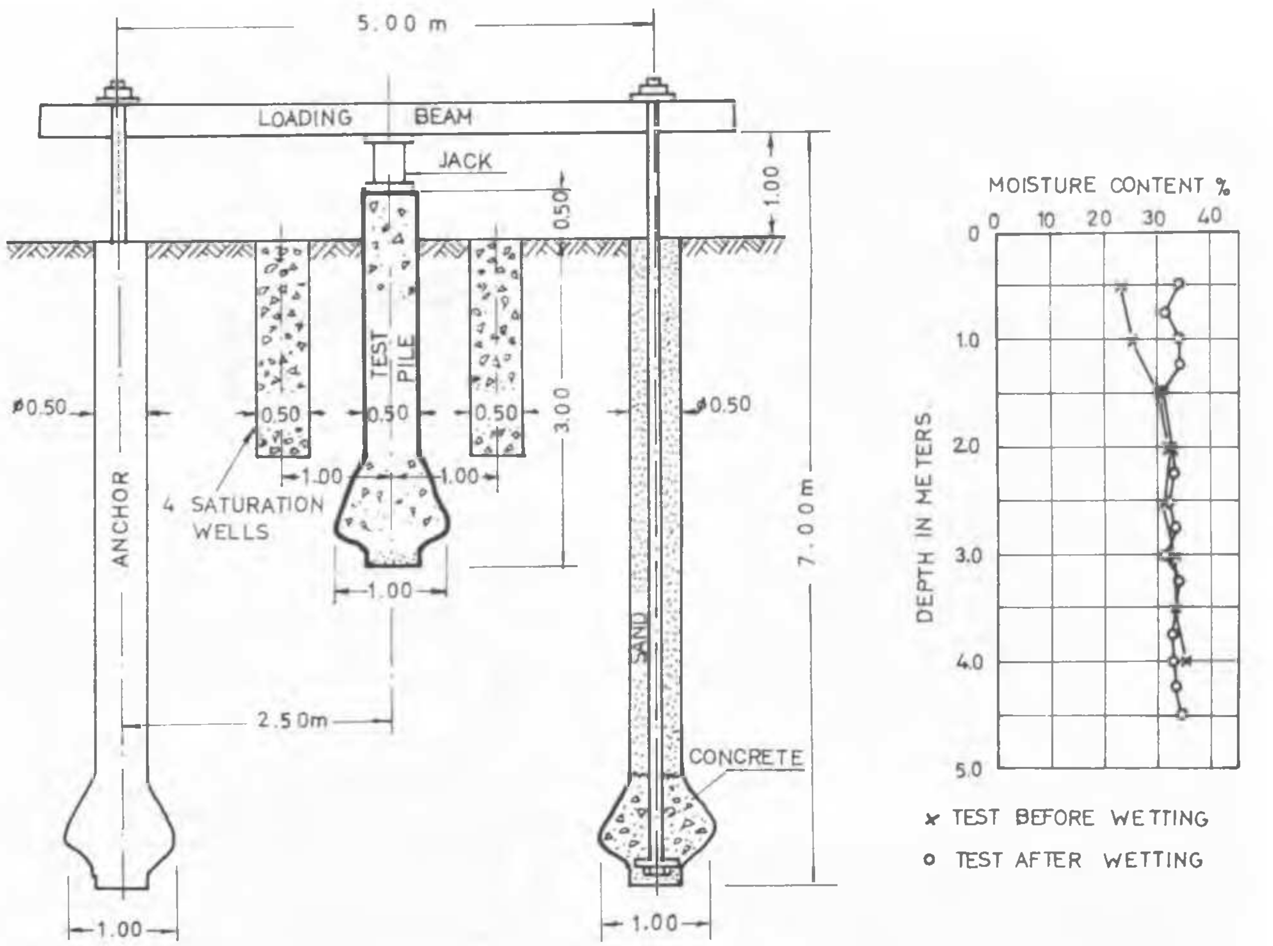

Fig. 3 Loading Test Arrangement and Moisture Profiles

and can be described as follows: the upper layer (8 meters thick) is a desiccated highly plastic stiff clay, mainly montmorillonite, overlying a bedrock of chalk and marly chalk layers. Water table is usually found at an elevation of about +1.0 m while the area is at above +12 m elevation. The clay has a liquid limit varying between 109 to 64 and plasticity index of 75 to 42. The shrinkage limit varies between 10 to 13. Moisture studies in this area indicated the major seasonal variations to occur in the upper 2.5 m of soil with moistures varying from 16 to 36 per cent. At greater depths variations were relatively small and the moisture content is about 5% higher than the plastic limit, which varies between 28 to 22 percent. The vane shear strength of the clay tested both in winter and in summer varies from 2 kg/cm^2 to 4 kg/cm^2, with most of the results more than 3 kg/cm^2 for depths below three meters.

Undisturbed samples were taken at the end of summer (dry season) from 4 meters and 6 meters depths for swelling pressure and consolidation. Typical swelling pressure results measured were 1.40 kg/cm^2 at 4 meters depth and 1.1 kg/cm2 at 6 meters depth.

A consolidation test is shown in Fig. 2 for a sample tested at its natural moisture content and wetted only at 20 kg/cm^2 pressure. It should be noted that the addition of water at a high pressure caused an immediate increase of settlement("slump" phenomena). This type of phenomena had been also found in similar clays tested under lower pressures but at loads higher than the preconsolidation pressure.

During investigations at a site, A', adjacent to A, the influence of wetting was studied in the course of a loading test on a typical bored pile, 3 meters deep, with an underreamed bell diameter of 1 meter. The soil around the pile was wetted by saturation wells extending to 2 meters depth (Fig. 3), The total settlement increased from 5 mm to 23 mm during six days under a constant load of 25 tons (Fig. 4). Determination of the moisture content profile, before and after saturation, showed no change in the value of about 32 percent at the depths of the pile tip, The increased settlement was probably due partly to decreased resistance of the upper clay around the stem, as well as to decreased shear resistance of the pile end. The wetting action of the wells may have caused decreased suction in the pores of the lower bearing clay, not accompanied by a noticeable water content increase.

Settlement measurements of these structures were taken after the damage to the structures became obvious, from 1961 to 1963. Results of these level measurements are given in Fig. 5 for two structures. The curves for the settlement of each point with time show a clear tendency for the piles to settle in summer (during the dry spell) and to level up and even to swell a little bit during the winter period (rainy season). This phenomena repeated itself in the other structures when detailed levelling was performed. This can be explained by the fact that during the summer, cracks form in the clay, relieving the lateral support on the stems of the piles and allowing full transfer of load to the pile bulb.
In winter, due to the swelling of the soil, the clay "grips" the side of the pile and tends to raise it. The total settlement increased with every season and varied between 3 cm to 10 cm during the period of measurements. Differential movement of the various blocks at different times show up clearly in the plots on the right side of Fig. 5. It should be noted that in several structures one or two columns tended to settle more than the rest of the structure, as was evidenced by minor cracking in the walls.

Corrective measures for the main portion of the buildings to date have mainly included replacing the broken columns. Performance since has been satisfactory.

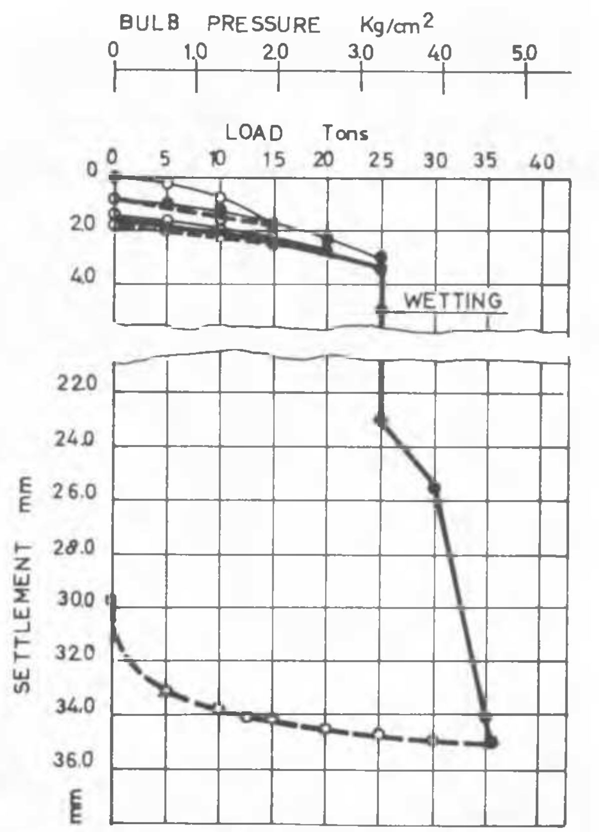

Fig. 4 Load Test Results (Site A')

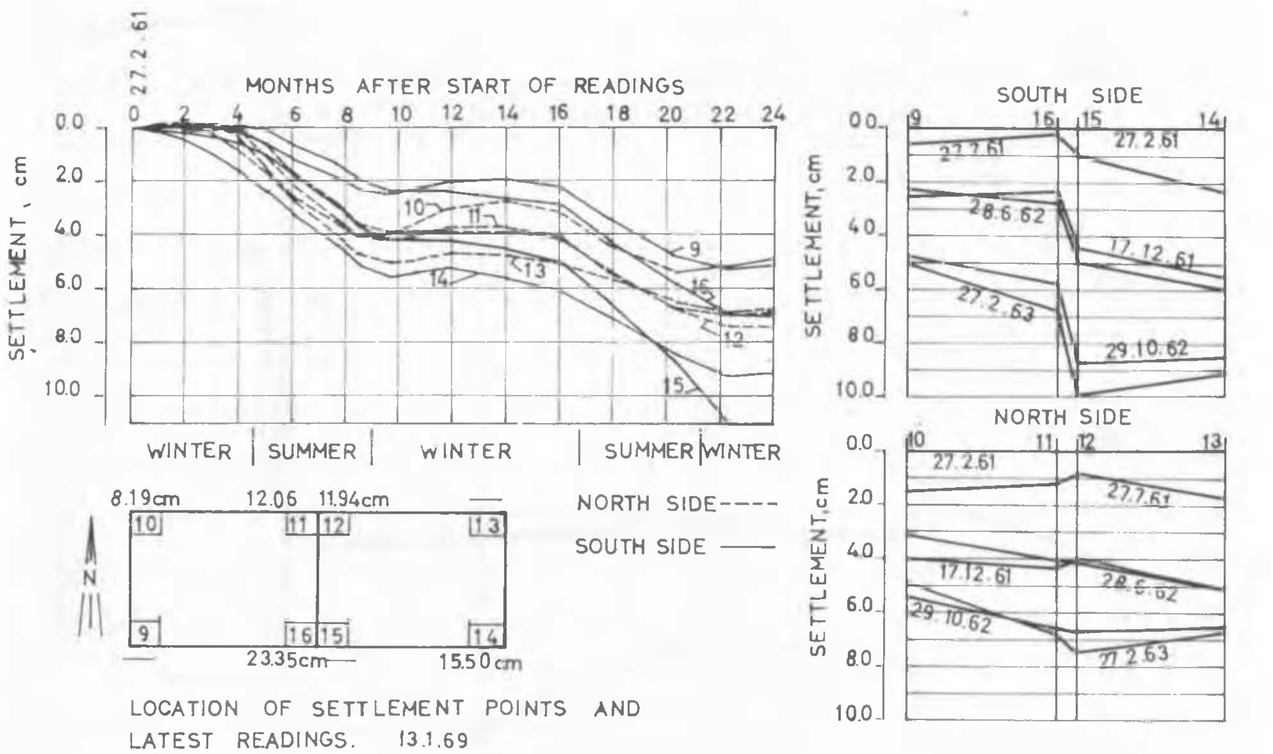

Fig. 5 Level Measurements of Typical Structure (Site A)

SITE B

In another area seven apartment buildings were erected, using similar design procedures in a similar soil profile. However, the four dwelling stories were built about 2-1/2 meters above ground, using columns, so that the shelters were not buried. The heads of the piles were then connected by reinforced concrete beams 35 x 20 cm, for lateral support.

The foundations, as in the first site, were underreamed piles at a depth of 3 meters with contact pressures varying from 2.3 kg/cm^2 to 3.1 kg/cm^2 for loads between 34 tons, to 23 tons, except for 3 small piles under the shelter walls, carrying 10 ton loads, which were designed for higher pressures.

In one of these buildings, the underreaming was not properly executed, thus causing overstressing of the clay layer and giving rise to large settlements (between at least 10 cm to 30 cm) and tilting of the sections. Minor damage occurred to the superstructure.

Other structures in this area have settled much less (several centimeters) but serious cracking of columns has occurred. The columns were 30 x 30 cm in size and 2.5 meters in height (between the top of the foundation beam and the first floor).

Level measurements were initiated after large differential settlements were observed. Results are shown in Fig. 6.

Fig. 7 shows the soil profile at this site, with moisture content, shear strength and Atterberg limit variations with depth and seasons.

Consolidation and swelling tests were performed on undisturbed samples taken at the foundation depth of 3.0 meters. A specimen from this depth evidenced a swelling pressure of 4.9 kg/cm^2. The building having excessive settlement is about to be underpinned on new bored straight piles founded on top of the rock layer at a depth of 7 meters. The damaged columns have been already encased in a cover of additional reinforced concrete.

SITE C

A four story apartment building of dimensions 11 x 30 m was erected in two sections, using typical reinforced concrete frame construction and shallow underreamed bored piles. The piles were founded in sandy clay, at about 1.5 to 3 meters depth, with designed bearing pressures of 2.5 to 3.5 kg/cm^2.

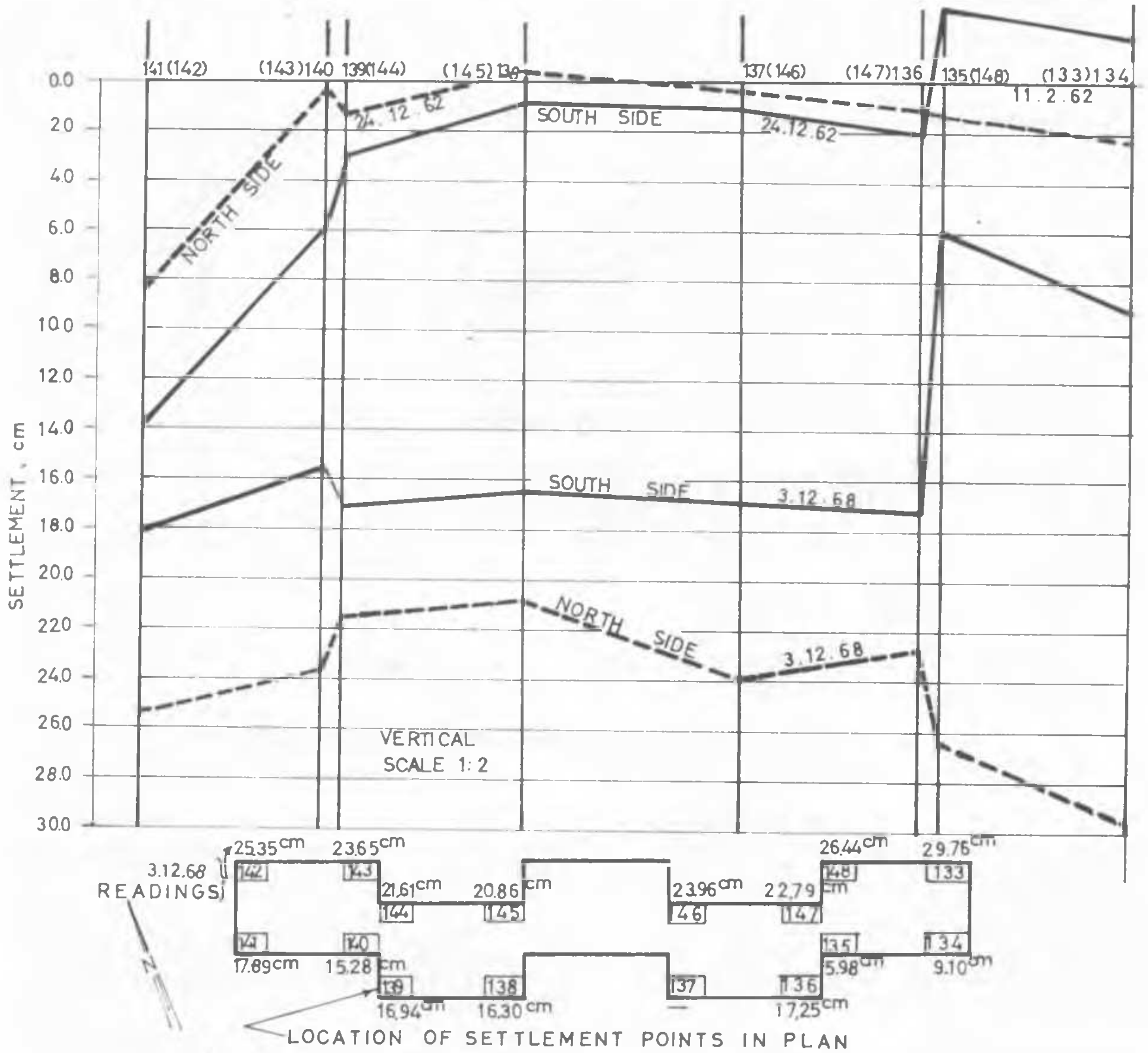

Fig. 6 Vertical Movements of Building (Site B)

During the final work on the building almost the whole of one section suddenly settled about 30 cm, following a long rainy period (Fig. 8). Investigations to date indicate that the foundations themselves did not settle appreciably, but that the settlement was due to collapse of 20 x 40 cm short columns under the section.

One corner was on an improperly executed pile, which did not have under-reaming as designed, in an area where a septic tank had soaked the ground. It is believed that the weakness of the corner, compounded by the rain and softening of adjacent foundations, kept transferring load onto other columns until one failed, starting a "domino" action. Failure did not occur at the end of the section near the center of the building, because of a shelter construction able to take the loadings. The other section of the building was undamaged, since it was designed with grade beams resting on the pile caps.

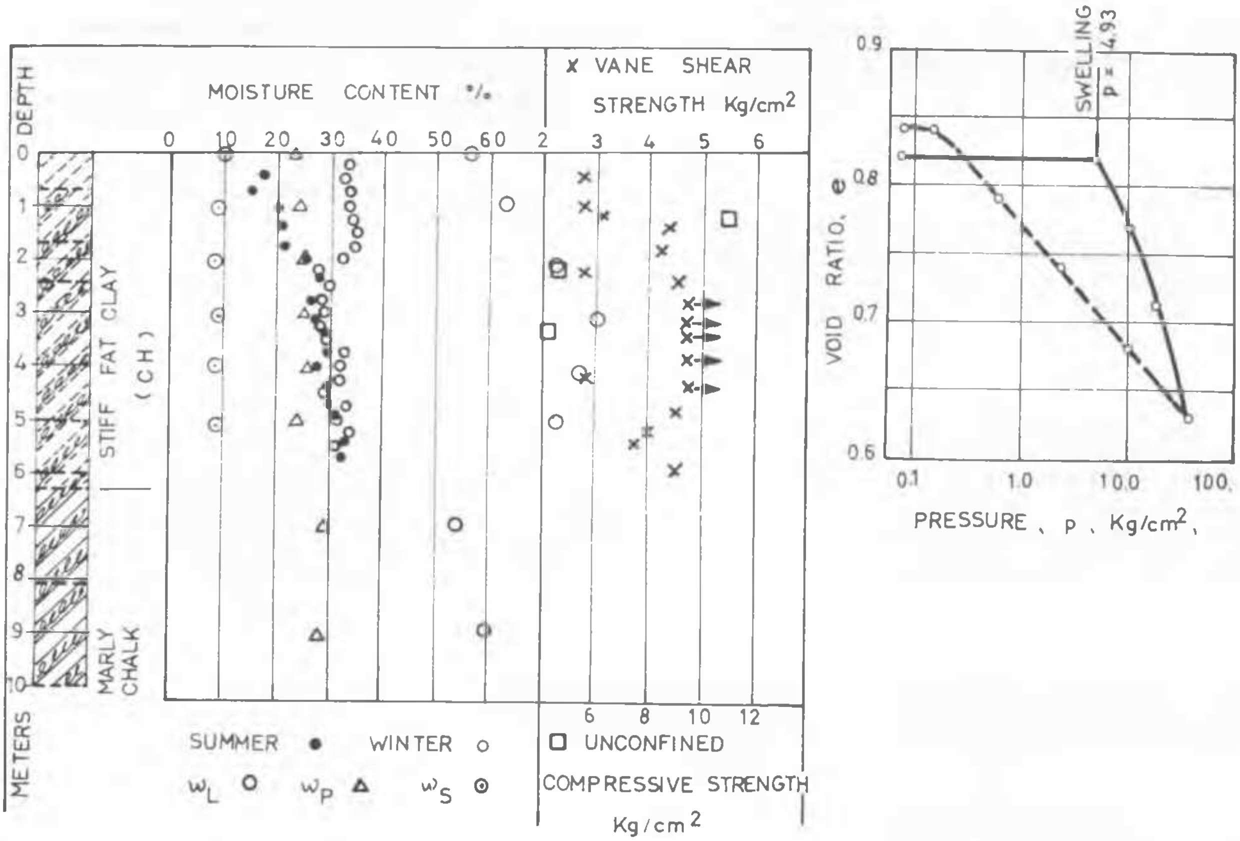

Fig. 7 Typical Soil Profile and Characteristics (Site B)

Fig. 8 Building at Site C, Showing Settlement of 30 cm in Right Hand Portion of Building

CONCLUSIONS

The danger of differential settlements occurring in unsaturated preconsolidated clays appears to have received insufficient attention to date. Use of relatively high bearing loads to resist possible swelling forces results in the possibility of some foundations tending to settle more than others under the planned load when the clay is wetted, throwing excess loading on to adjacent supports .

Soils investigations should include study of the predicted settlement occurring when the clay is wetted at different pressures.

The structural design and execution must take into account the possibilities of these extra loadings on individual members, particularly free standing columns. When a portion of the building is relieved of load, the columns resting on relatively stiff, unwetted soil may easily receive twice the design loading, thus drastically reducing their factor of safety. Where the structural arrangement is such that individual columns, if overloaded, cannot further transfer loads without rupture, it is recommended that the usual factor of safety be doubled.

REFERENCES

Lambe, T.W. (1964), "Methods of Estimating Settlement", Jour. Soil Mechanics and Foundations Division, Proc. A.S.C.E., Paper 4060, Vol. 90, No. SM 5, p. 43.

Seed, H.B. (1965), "Settlement Analyses, A Review of Theory and Testing Procedures", Journ. Soil Mechanics and Foundations Division, Proc. A.S.C.E., Paper 4275, Vol. 91, No. SM2, p. 39.

Terzaghi, K. and Peck, R.B. (1967), "Soil Mechanics in Engineering Practice", John Wiley & Sons, New York, p. 501.