# IN-SITU INVESTIGATIONS ON PORE PRESSURES IN SOFT CLAYS

# RECHERCHES IN-SITU SUR LES PRESSIONS INTERSTITIELLES EN ARGILES MOLLES

# ПОЛЕВЫЕ ИССЛЕДОВАНИЯ ПОРОВОГО ДАВЛЕНИЯ В МЯГКИХ ГЛИНАХ

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SYNOPSIS. Two large scale in-situ investigations on the behaviour of soft, normally consolidated, non sensitive clays have been performed. In this paper the results concerning pore pressures induced by the installation of displacement type sand drains and driven piles and by the construction of large embankments are reported.

The pore pressures induced by driving are first discussed; they have been found to equal or even exceed the overburden pressure. The subsequent rapid decrease of the pore pressure is analyzed; the factor controlling it seems to be total stress relaxation rather than consolidation.

The pore pressures induced by surface laods are related to the increment of total stress in the subsoil. The occurrence of gas pockets exerts a significant effect on undrained pore pressure distribution; it has been possible to account for it in a simple way.



## 1. INTRODUCTION

The development of two important projects involving soft clay deposits has requested broad field investigations on the behaviour of the clays during the installation of displacement type sand drains and of driven piles and the construction of large embankments.

The investigation has been made under carefully controlled conditions and the behaviour of the subsoil has been studied by means of a large number of instruments with the same characteristics at the two different sites. The measurements are still going on.

Extensive reports of both investigations will be published elsewhere. This paper is only devoted to a discussion of the pore pressures induced in the clays by driving and surface loading.

## 2. SUBSOIL CONDITIONS AND FIELD TEST INSTALLATIONS

The first site, Porto Tolle, is located in a deltaic environment (Po river) very near to the sea. Ground level is about 1,5 m below mean sea level; a reclamation plant keeps ground water about 1 m below soil surface in a large area.

The average subsoil conditions, as derived from a number of deep boreholes, are summarized in fig. 1, together with some results of laboratory and field tests.

As it appears, a thick layer of normally consolidate silty clay is found between 8 and 29 m of depth. Thin layers of fine sand have been frequently found within it in every borehole, but their continuity has not been ascertained.

The clay lies between two sand deposits. The upper one contains silty and clayey interbeddings and some organic matter; in the lower one, that extends at least to a depth of 120 m, a few layers of organic clay are present between 30 and 40 m. Some gas pockets have been found here during the execution of boreholes. Below 40 m the sands become cleaner and they do not contain gas.

A group of 10 tubolar steel piles with a diameter of 40 cm and a spacing of 1,30 m have been driven through the upper sands and the clay layer into the deep clean

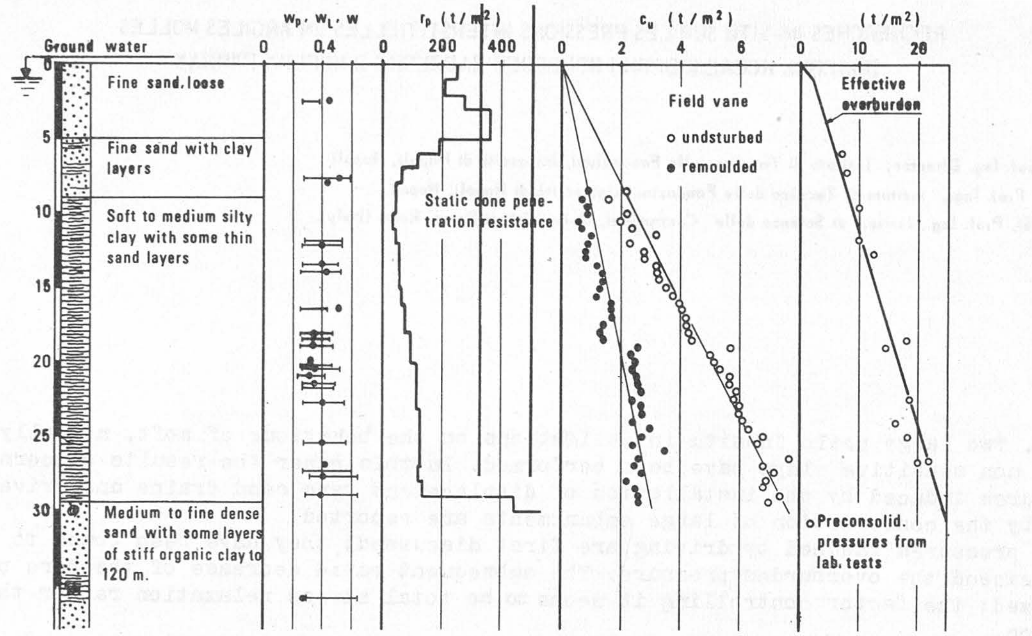


Fig. 1. Subsoil conditions at Porto Tolle

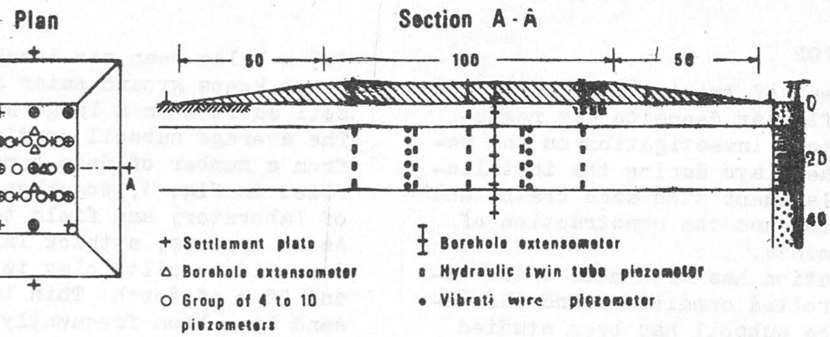


Fig. 2. Test embankment and instrumentation at Porto Tolle

sands at 40 m below ground level. Pore pressures induced by driving have been measured at different depths within the piles group and outside.
In a nearby area a rectangular fill with base 200 x 250 $m^2$ and heigth 7 m has been constructed; the geometry of the fill and instrument location is shown in fig. 2.
The second site, Fiumicino, is located near the sea on coastal deposits; it belongs also to a reclamation area. The subsoil conditions in the field test area, as resulted from many boreholes and long Kjellman samples, are shown in fig. 3. Beneath an upper layer of brown dessiccated clay followed by peat and organic clay, a very thick stratum of soft clays of recent deposition (olocene) is present. These clays have been deposited in brackish water in a coastal lagoon delimited by a bar of dunes. They are generally grey and contain whole, or fragments of, shells. Sandy and silty fractions are generally scarce; some sand is diffused in the clay mass. Very thin layers (1-3 mm) of shell fragments and fine sand are often found; thicker layers (5-10 mm) of sand ha-

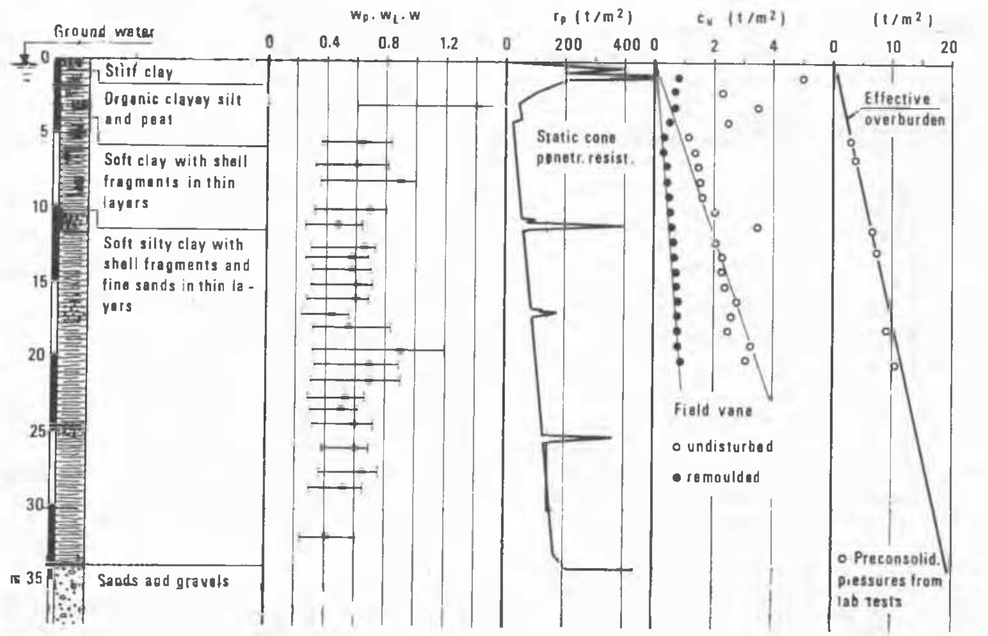


Fig. 3. Subsoil conditions at Fiumicino

ve been found in rare instances.
The clays are underlain by donse sands and gravels at a depth of 34
The test fill is strip-shaped, with a length of over 400 m, a base width of 60 m and a heigth of 3 9 m Before the construction of the fill a mesh of displacement type sand drains with a diameter of 35 cm and a spacing of 3 m had been driven to a depth of 10 m. Pore pressures have been measured at different;depths during sand drains installation and embankment construction.
Details of test installation are shown in fig. 4.

## 3. PORE PRESSURES INDUCED BY DRIVING

At Porto Tolle pore pressures have been measured continuously while driving the test piles. Driving operations required 30÷40 min. for each pile, including a pause to weld steel tubes. In the first five piles the driving tube was withdrawn, leaving an inner steel casing coated with bitumen; in the subsequent piles the driven tubes wwere left in place.
The very short response time of the vibrating wire piezometric cells, the duration of driving and the characteristics of the recording system allowed to pick up the peaks of the pore pressure induced by each pile at any stage of the work.
The values of the excess pore pressure $\Delta u$ recorded by two piezometric cells located within the pile group are reported in fig.5. Very high peaks of pore pressure are produced by driving.
A detailed examination of measurements records has shown that $\Delta u$ reaches a maximum when the pile tip is slightly above the elevation of the piezometric cell, and rapidly decreases as the tip overpasses the cell.
The driving of other piles, at a rate of one pile a day, results in a further increase of the pore pressure.
However, as it clearly appears from fig. 5, subsequent increments of pore pressure sum up progressively until the excess pore pressure reaches a value, which is not further increased, $\Delta u_{max} = 1,4\ \sigma_v'$. For the conditions of the site this means that the pore pressure exceeds the total overburden stress by 20%.
The general trend of measurements and the measured values of $\Delta u$ corroborate the findings of Lo and Stermac (1965).
It may be noted that values of $\Delta u_{max}$ exceeding $\sigma_v'$, such as recorded, are only possible if significant shear stress occurs.
The observed excess pore pressures, however, decrease below the effective overbur-

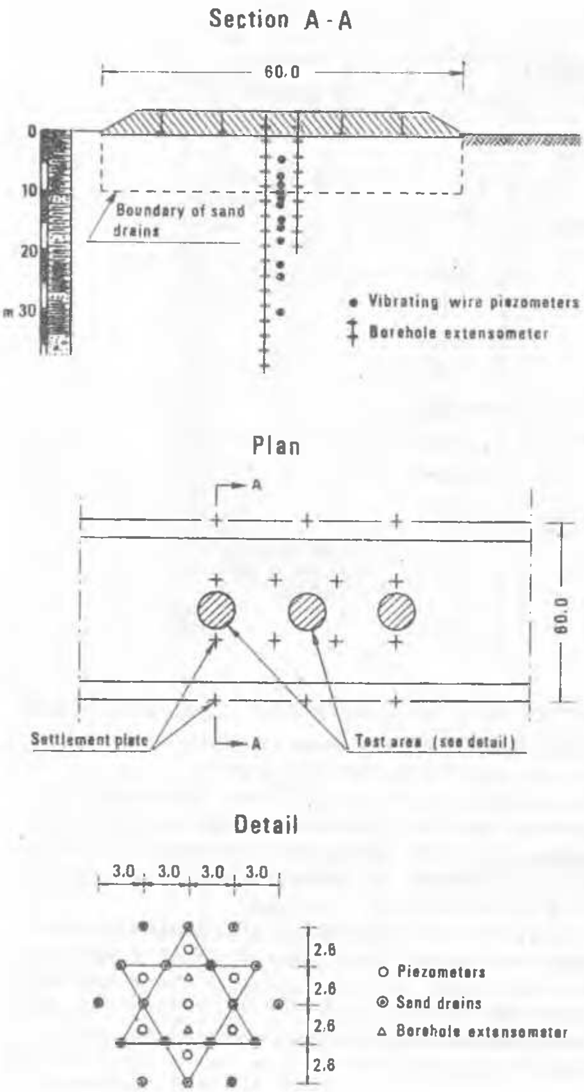


Fig. 4. Test installation at Fiumicino

den stress in a few hours.
Fig. 6 shows the distribution of the induced pore pressures in the soil surrounding the pile group at the end of driving and at two subsequent.dates.
It appears that the excess pore pressure spreads in a large area and it is still significant at a distance of about 20 m, i.e. 6 times the diameter of the pile group.
A different kind of observations has been made at Fiumicino. The installation of the sand drains required a much shorter time, and several driving machines operated simultaneously; less than 5 minutes were sufficient to drive the forming tubes to the

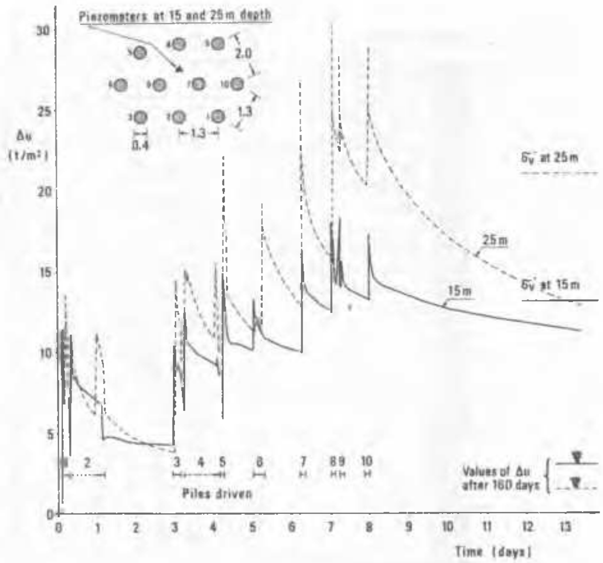


Fig 5 Porto Tolle. Excess pore pressures induced by driving a group of ten piles

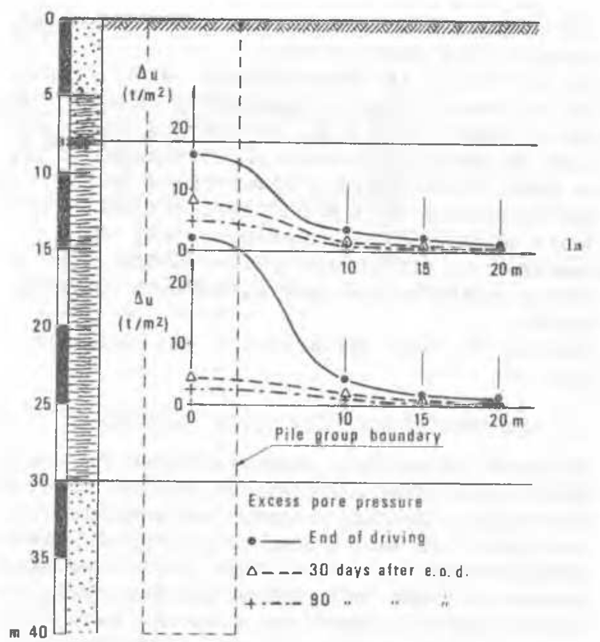


Fig. 6. Porto Tolle. Distribution of excess pore pressures induced by pile driving at the end of driving and at two subsequent dates.

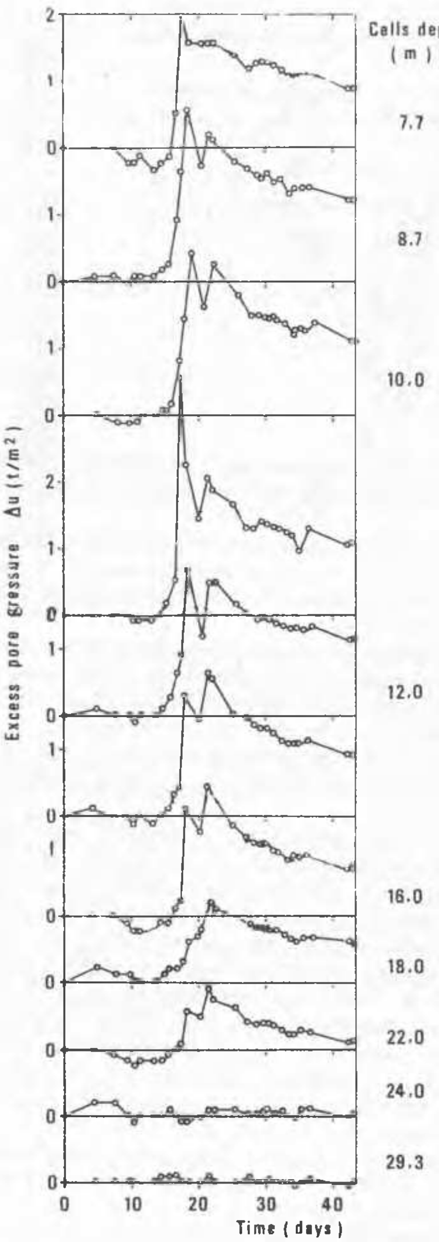


Fig. 7. Fiumicino. Excess pore pressures induced at various depths by the installations of sand drains.

prescribed depth of 10 m, and the whole net of drains in the instrumented area of the test fill was completed in few days.
The pore pressures have been measured generally at some hours intervals by an automatic scanning system. Therefore the overall effect of driving piles in a large area has been observed, rather than the instant peak values of the pore pressure.
Fig. 7 shows the values recorded along a vertical line at the center of a drain mesh; it appears that the maximum excess pore pressure left by driving occurs just below the drain tip elevation, at 11 m depth, but significant pore pressures are induced at a depth more than twice the drain length. A similar effect had been reported by Bjerrum et al. (1958).
The distribution of excess pore pressure horizontally and vertically outside the zone treated by sand drains is reported in fig.8. An increase of pore pressure has been noticed at a distance of over 100 m from the edge of the treated zone (fig. 8a). Fig. 8b shows that the excess pore pressure approaches he effective overburden pressure in the treated zone, but never exceeds it.

**The rate of decrease of pore pressure after the installation of the drains may be discussed with reference to fig.9, showing a typical $\Delta u, t$ diagram. About twenty days after driving the excess pore pressure is about 50% of the initial value; at this moment the construction of the fill begins step by step and the pore pressure again increases.**
**As it appears from fig.9 after each increment the decrease of pore pressure occurs at a slower rate as the time goes on although the initial values increase significantly as a consequence of the applied load. At the end of the construction of the fill the excess pore pressure is on the average more than twofold the value reached after driving, but it decreases at such a slow rate that in the following 30 days it can be considered practically constant.**

This clearly shows that the decrease of $\Delta u$ after driving is not due to consolidation. By subtracting the pore pressure increments due to the fill loads from the $\Delta u, t$ curve, one gets a unique $\Delta u, t$ relationship for all measuring points in the zone treated by sand drains, irrespective of the initial value of excess pore pressure.
Some of these relationships are shown in fig. 10; they are fitted rather well by the expression :

$$\Delta u = \Delta u_0 \, e^{-\alpha (t/t_0)} \qquad (1)$$

being $\Delta u_0$ the excess pore pressure induced by driving at the time $t = t_0$ . The value of $\alpha$ does not depend on $\Delta u_0$ and is of the order of 0,034.
A relaxation of the total stress in the

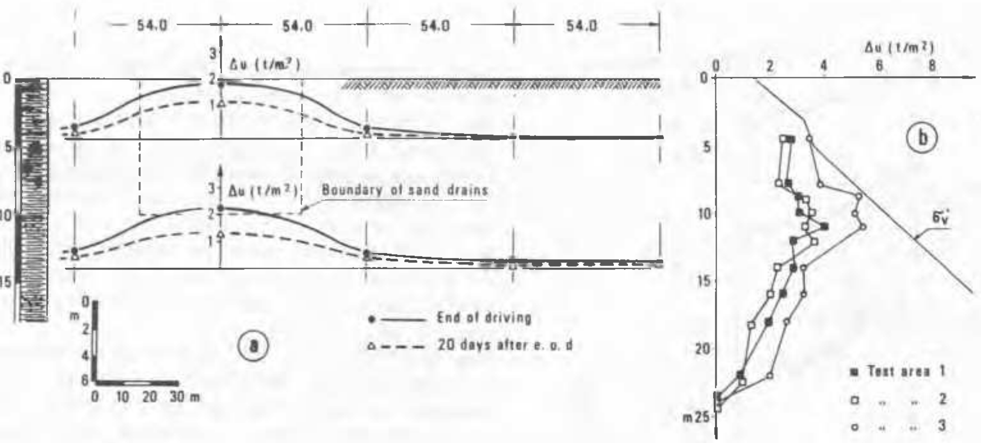


Fig. 8. Fiumicino. a) Test area 2; distribution of excess pore pressures induced by driving. b). distribution of excess, pore pressures with depth at the end of sand drains installation

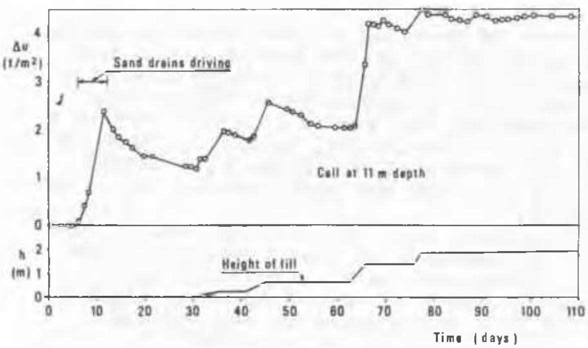


Fig. 9. Fiumicino. Typical pore pressure variations with time.

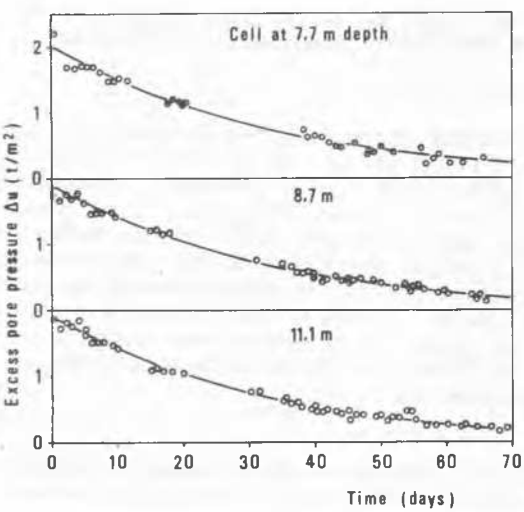


Fig.10. Fiumicino. Decrease of excess pore pressures induced by driving; typical curves.

highly stressed zone around the drains following the initial soil displacement produced by driving must be at the origin of the observed phenomena.
It is noterworthy that disregarding this effect could result, at least in some instances, in a sensible overestimation of the consolidation rate due to sand drains.
These findings are corroborated by the results obtained at Porto Tolle and shown in fig. 5.
160 days after driving the excess pore pressures have decreased to very small values; an analysis of the eventual consolidation process based on work by Soderberg (1962) and Banerjee (1969) has shown that the measured rates of dissipation are many times faster than those corresponding to the consolidation behaviour of the clay, as resulting from other in-situ measurements. Also in this case a stress relaxation is then believed to control the pore pressure decrease, at least in the early stages; nevertheless, due to different boundary conditions (geometry of the pile group, metal piles instead of sand drains) a shape of Δu,t curve different from eq. 1 is found.

## 4. PORE PRESSURES INDUCED BY EMBANKMENT LOADS

Only some results obtained at Porto Tolle will be discussed here.
The test embankment has been constructed in 14 regular layers 50 cm thick in a period of 2,5 months.
In fig. 11 the values of excess pore pressure measured under the central part of the embankment at the end of construction and

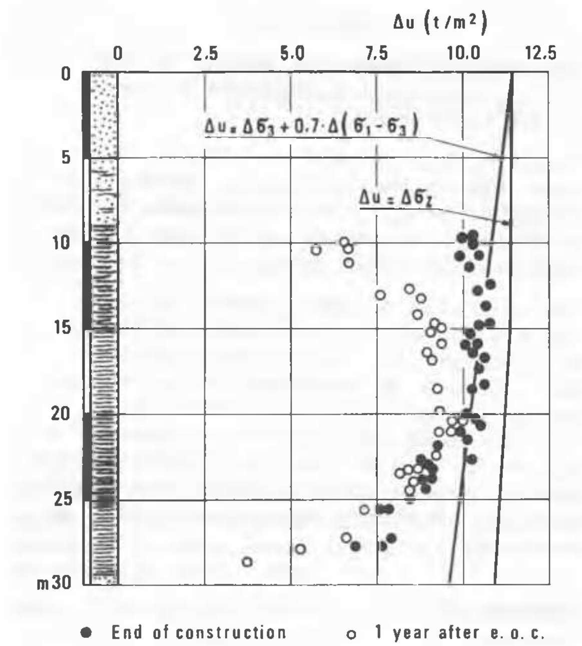


Fig. 11. Porto Tolle. Excess pore pressure induced by fill load under the central part of the embankment.

one year later are reported.
A finite differences consolidatio analysis, based on one year of field observations, unquestionably demonstrates that during the construction period no significant consolidation occurs in a major part of the clay layer. Therefore, with the exception of two narrow zones near the drainage boundaries, undrained conditions apply during embankment construction.
The excess pore pressures at the end of construction between 12 and 23 m depth are very nearly equal to the values predicted by Skempton's expression :

$$\Delta u = B \left[\Delta\sigma_3 + A\,(\Delta\sigma_1 - \Delta\sigma_3)\right]$$

with B = 1 and A = 0,7 as derived by undrained triaxial compression tests on undisturbed samples. Total stress increments have been calculated in the hypothesis of elastic homogeneous isotropic half space.
Near the edges of the embankment the calculated total stress increments differ slightly from those reported in fig. 11. and excess pore pressures follow closely these differences.
In the upper part of the clay layer, between 8 and 12 m depth, excess pore pressures are smaller than undrained values. Actually the theoretical analysis shows that this zone consolidates during construction period and this appears confirmed by the large dissipation of pore pressures observed in the following year.
On the contrary the excess pore pressures in the lower part of the clay layer between 23 and 29 m are from the beginning significantly smaller than the expected ones, but remain practically unchanged in the following year with the exception of a narrow zone at the contact with deep sands. Therefore the differences between measured and predicted values cannot be ascribed to partial consolidation.

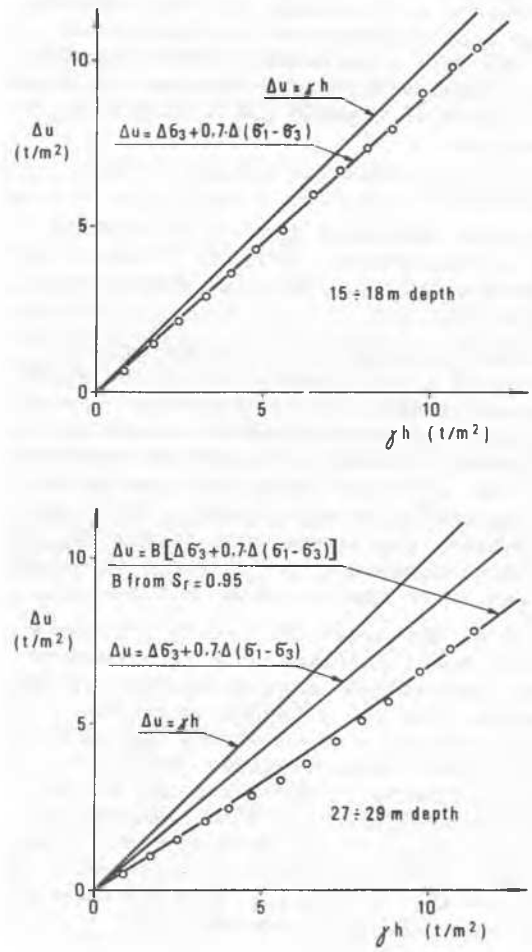


Fig. 12. Relationships between excess pore pressures and embankment loads.

The presence of gas pockets, which were noticed at this depth in all borings, seems to be the cause of these differences. Considering the gas pockets uniformly diffused in the soil mass values of Skempton's B coefficient may be calculated by means of the well known Hilf (1948) expression of pore pressure in partly saturated soil, as a function of saturation degree $S_r$ , the initial pore pressure and the compressibility of soil skeleton. It has been verified that in this case a very small percentage of gas filled voids can explain the observed behaviour. Actually by assuming $S_r$=0,95÷0,97 to calculate a B value, the relationship between pore pressure and applied stress fits very well experimental data (fig.12). Similar results have been found at Fiumicino in layers of organic clays containing gas pockets.

## 5. CONCLUSIONS

As for pore pressures induced by driving piles or sand drains, from the field investigations at Porto Tolle and Fiumicino it resulted that :

1. Driving adjacent piles in soft clays produced pore pressure increments which summed up until a limiting value was attained. The peak values of excess pore pressure exceeded effective overburden stress $\sigma_v'$ and could be approximately predicted by Lo and Stermac (1965) expression. The excess pore pressures, however, decrease in a few hours to values close to or smaller than $\sigma_v'$ .
2. Outside the area affected by driving a significant increase of pore pressures was observed at large distances; at Fiumicino over 100 m (about twice the width of the treated strip) and at Porto Tolle 20 m (about 6 times the piles group diameter). These results should be compared with the data compiled by D'Appolonia (1971), showing that for a single pile the excess pore pressure is practically negligible at a distance of 16 times the pile diameter.
3. The decrease of pore pressure after driving was very rapid and independent of the hydraulic gradient towards the drains. Therefore it cannot be explained through a consolidation process. A total stress relaxation is believed to be the factor controlling the observed behaviour.

The excess pore pressures caused by the load of a large test embankment at Porto Tolle has shown that :

4. Stress analysis based on elastic half-space theory and laboratory determined values of Skempton's A coefficient led to excess pore pressures in good agreement with observed ones.
5. The occurence of gas pockets has been found to exert a significant influence on undrained pore pressures distribution. It can be accounted for by considering the gas uniformly diffused in the soil mass; in the treated case a value of $S_r$ = 0,95 led to a relationship between excess pore pressures and applied loads fitting very well experimental data.

## 6. REFERENCES


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