SPECIAL DEWATERING METHODS FOR SOIL STABILIZATION

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ABSTRACT

The necessity of protecting open pit mines against ground water in soft, non-consolidated soils is dictated, first of all, by the distribution of ground-water inflows and by the resistance of soils in the pit slopes and bottom to the pressure of flowing water. Development of the deposits associated with weak soils, such as silt and clay, is very difficult and requires special methods of soil treatment. Two special dewatering methods have been used most often to stabilize low-permeable water-bearing soils. They are: electro-osmotic drainage and prefabricated drains. These methods are widely adopted in the construction dewatering practice but in mine-drainage they are quite rare despite the fact that they were developed over 40 years ago and the field of their application in mining is undoubtedly very wide. Electro-osmotic systems and prefabricated drains are applied to water-bearing fine-grained soils where gravitational movement of ground water through porous media is difficult and additional force is required to move the water. In the case of using electro-osmosis, that force is direct current electrical power which causes water movement in the soil, reduces pore-water pressure and increases the shear strength of the soil. The prefabricated drains consist of a plastic core of vertical channels with a filter sleeve of fibrous material. Drains can be installed either statically or dynamically, using a push-type machine or vibratory device. Theories and principles of these methods are discussed and their practical applications are illustrated in case histories.

INTRODUCTION

The problem of slope stability in low permeable water-bearing soils is one of the most complicated encountered with ground water flow. Water, entering mine workings in such conditions must be captured and discharged in spite of its extremely low flow rate.

Water appears in 3 basic states - solid, gas or liquid. In geological formations they appear as the following:

1) solid state - ground water appears in rock or soil as ice,

2) gas state - ground water occurs as steam; and

3) liquid state, which subdivides into two general groups;

   . physico-chemically combined water, and
   . uncombined or gravitational water.

Gravitational or uncombined water of the liquid state is the one most generally encountered in dewatering situations. Gravitational water which freely moves through water bearing formations without destroying their structures must be dealt with and evacuated by dewatering systems. In such conditions, in order to protect excavations against watering, it is mandatory to intercept the water before it enters the excavation and to reduce its level below the lowest subgrade elevation. This is accomplished by determining the optimum quantity of water, by selecting the necessary suitable equipment and having the proper design and installation.

In low permeable formations though due to the attachment of the combined water particles to the soil granules under molecular and surface tension forces, there is a tendency for soil granules to move together with the water. This combined or joined movement of the "soil-water system" is the origination of the destruction of the initial soil structure and is the anticedent of slides and deformations of slopes and working subgrades. This phenomona is the determinant of many problems in mine construction and operation.

Two special methods of dewatering for low-permeable soil stabilization are discussed in this report: electro-osmosis and vertical drains.

ELECTRO-OSMOSIS

Electro-osmotic dewatering is a drainage method particularly suitable to fine-grained soils, such as silts or clays, which cannot be dewatered or stabilized by conventional methods because of their very low permeability and specific yield. Dr. Leo Casagrande put the electro-osmotic application into the dewatering practice in the 1930's.

To better understand this method, we must discuss the basic phenomena of physical chemistry related to the movement of ground-water through porous media. Water in a porous medium moves in response to an applied electrical potential from a positive electrode (anode) towards a negative electrode (cathode). This phenomenon was discovered by Reuss in 1807 and elucidated by Helmholtz in 1879.

Helmholtz explained that in a cylindrical capillary tube within a porous medium two layers of water exists: free-water and constrained water, bonded to the wall of the capillary.

The thin film of water immediately adjacent or bonded to the capillary wall is negatively charged. A positively charged, thicker layer of water lies on the film of the negatively charged water. This combination of water layers is known as "the double layer of Helmholtz". The initial thin layer of water is non-movable. An electric potential, when applied to the capillary, has the positive charges moving from the anode to the negative pole-cathode and pulling the water molecules of the movable part of the double layer; this layer, then, in turn, pulls the free water enclosed inside the cylinder surrounded by the double layer. The rate of free water movement velocity would be constant if no other forces were applied to the free water cylinder.

In the 1930's, Dr. Leo Casagrande determined that the coefficient of electro-osmotic conductivity for most soils is constant and is in the range of 5 x 10^{-5}cm/sec for a gradient of 1 volt per cm. This is comparable to the hydraulic conductivities of the fine-grained soils. It follows from this that we can remove pore water and dewater fine-grained water-bearing soils, such as silts and silty clays, by applying electro-osmosis. The method, however, is not effective in the coarser soils.

Dr. Casagrande also discovered that "...electro-osmosis creates in compressible, fine-grained soils tension in the pore water, and compressive forces and a corresponding amount of consolidation in the grain skeleton." By this means "...electro-osmosis can move water in the pores of fine-grained soils much more effectively than by gravity, and thus compressible fine-grained soils can be consolidated" .

Pore water, which flows toward the excavation, can be reversed by electro-osmosis and slope stability be ensured since we can isolate the slope from the recharge area of the aquifer and, as a result of that, substantially decrease the hydraulic pressure on the slope.

The electro-osmotic drainage method, as practiced in dewatering situations, is applied to fine-grained soil that requires an additional force to move the water. The force necessary is direct current electrical power. Metal electrodes (anodes) and dewatering devices (cathodes) are installed in the ground and the electrical current applied. The positive charges move from the anode to cathode taking with them pore water and depositing the water at the cathodes where pumping removes the water. This application develops tension in the soil, reduces the water content of the soil, causes a basic exchange of ions in the soil, and controls seepage forces.

Electro-osmotic drainage method costs are generally higher than those of conventional systems because of the additional costs of the very extensive electrical distribution system and the power necessary to operate its.

Our example of an application of electro-osmotic drainage is in the construction of a bridge - specifically in the dewatering for bridge piers. The bridge was designed for a 4-span steel truss having a total length of 218 meters and a deck elevation of over 31 meters above the river level, 3 piers and 2 abutments.

The soil investigations indicated that sound bedrock was exposed for the most part on the west bank or near side; however, the east bank (far side) and soils below river bottom consisted of a thick deposit of inorganic silt (rock flour) underlain by a dense silty sand just above bedrock.

The silt stratum tapered in thickness from 37 meters at the top of the slope to 21 meters at the lower edge. The upper 3 to 6 meters were of a very loose consistency with Standard Penetration Test blow counts of 0 to 6 blows per foot. Below this loose surface, the density increased gradually until the bottom 6 to 9 meters showed blow counts of 6-20 blows per foot. The water level was one-half a meter below natural ground at the top of the slope at Pier #2, about 6 meters below natural ground at Pier #3 and 12 meters below natural ground at the east abutment.

Pier #1 and the abutment on the west side were seated on rock. On the east side, Piers #2, #3 and the East abutment were to be supported by vertical and battered H piles driven to rock. After Pier #2 was excavated, timber friction piles 9 meters long were driven to support the pile-driving equipment required for driving the H piles. During the driving of the timber piles, a substantial slide developed on the slope.

The slide had a 61 meter width and extended the full length of the slope and resulted in a 5 meter slump at the top. In order not to precipitate further movement, construction was transferred to the East abutment some 91 meters away from Pier #2. During the driving of an H pile at this location, a second slide occurred - with the slope sliding an additional 5 meters into the river. A test H pile driven at Pier #3 was tilted in a manner suggesting deep-rooted movement.

At this time, construction was halted to prevent slope deterioration and to analyze constructive measures. Those measures considered were freezing, chemical stabilization, caissons, flattening of the slope and electro-osmosis. Consideration of design change eliminating the east side piers showed that it would be more economical to stabilize the slopes than to use that alternative. After consideration of all methods and factors including cost, electro-osmosis was chosen as the best overall solution.

Four rows of electro-osmosis equipment were installed for the 61 meter width of the slide - two deep rows of about 24 meters and about 43 meters depth and two rows of shallow 15 meters to 18 meters depth. Anodes were jetted and cathodes were installed using a sand casing.

Installation took place during the winter months (-23°C to -37°C) in order that construction could take place during the summer months. For three months the equipment operated once the installation was completed.

Very little water was evacuated - 4.5m^3/h; however, this small quantity lowered the water 10 meters at the top of the slope, about 12 meters at the toe of the slope and lowered the water content by 4%. Construction proceeded after cessation of the equipment. Slopes held at 1:1; original design of the slope was 1:2.5. Periodic surveys after completion indicated no further movement of the slope.

VERTICAL DRAINS

The application of vertical drains for dewatering is a method that is used to decrease pore water pressure and to increase shear strength. The greatest advantage of this method is the reduction in the period of consolidation by virtue of the shortening of the distance the water must flow out from compressible soils. For example, according to Hannon, Walsh & Seim (1981), in the San Francisco Bay mud, the theoretical time of consolidation was 100 years; this period of time was reduced to less than a year by using prefabricated drains.

History of Vertical Drains

Until recently, vertical drains constructed of sand were used to accomplish this consolidation. Sand was placed in the area to be treated in a vertical volume, generally cylindrical in shape and on selected spacing. They have varied in size from 1 cm to 1 meter, either a displacement type or non-displacement type depending on the method used for installation. Sand drains have been installed using mandrels, closed-end pipes, augers, open-end pipes and jetting apparatus as a means of securing the soil void and have employed jet water, vibration, augering and pile driving and other means to establish the access; select sand, properly graded, in sufficient quantities filled the created void. A vertical drain of sand was the result.

Since the first cardboard or Kjellman type drain was installed in Sweden in 1937, improvements have been made in vertical drains. During the last 10 years especially, advancement has been accomplished in the form of prefabricated or wick drains, their use and their installation. The prefabricated drains now have resolved themselves to the general shape of 100 mm wide and 3 to 6 mm thick and consist, generally, of plastic core of vertical channels with a filler fabric around it (see Fig. 1). A prefabricated wick drain of a fabric covering with a sand filter is also used.

Some advantages of the prefabricated drains over sand drains are:

- no necking down or discontinuity during installation;
- elimination of the shear hazard;
- high integrity of the installed drains;
- less displacement of natural soils;
- ease of installation;
- economy;
- no jetting.

Soil and Drain Parameters

Suitable soils for the use of prefabricated drains are the compressible soils in the silt, silty clays, and inorganic clay ranges which have little secondary compression. Vertical access, afforded by the drains, allows the water, contained in these soils, to flow horizontally to the drain and then vertically inside of the drains and out through a permeable material when a load, surcharge, or pumping is applied. The result of this dewatering is the lowering of the pore water pressure and the increase in the shear strength of the soil.

Some important soil data for the study of potential drain applications and drain design are:

. density;
. natural water content;
. Atterberg limits (liquid limit and plastic limit);
. undrained shear strength;
. consolidated properties (preconsolidation pressure, coefficient of consolidation in horizontal pore water flow, C_h, and coefficient of consolidation in vertical pore water flow, C_v);
. oedometer compression modulus;
. pore water pressure distribution with depth;
. sensitivity of soil.

Design of vertical drains is generally based on Barron's theory. According to this, the time of consolidation can be evaluated from the following equation:

$$t = \frac{D^2}{8C_h} \cdot (\ln(n)) \frac{1}{1 - U_h}$$

where:

t = time of consolidation
D = diameter of dewatered soil cylinder
C_h = coefficient of consolidation in horizontal pore water flow
n = D/d
d = diameter of drain
U_h = average degree of horizontal consolidation

Diameter d_w, the equivalent diameter of band shaped drains with width b and thickness t, is expressed as shown by Mitchell (1981) by:

$$d_w = \frac{2\,(b+t)}{\pi}$$

In practice, however, Hansbo (1979) suggests using 50 mm to allow for remoulding and well resistance effects.

The discharge capacity of prefabricated drains or their ability to drain off water is an important factor in wick drain use. Hansbo (1981) has observed that for the prefabricated drain wicks, that exist on the market today, discharge capacities vary from near zero to $20m^3$/year. No existing drain has a higher discharge capacity than $20m^3$/year.

Measurement of the rate of consolidation, generally, can be accomplished by measuring either the settlement or the excess pore pressure dissipation. However, Hansbo, Jamiolkowski and Kok (1981) recommend the use of settlement as a measure of consolidation since they have observed, in some cases, excess pore pressure remaining even though further long term settlement was negligible.

Installation Methods

Installation methods for prefabricated drains, at this time, are the static and dynamic methods. These methods are essentially the same with the exception of the installation energy applied. Both methods utilize a crane or back-hoe together with a mast which contains a hollow mandrel or lance through which the drain material is threaded. An anchor plate or device is attached to the end of the drain and serves, not only to keep the soil out of the inside of the lance, but primarily, to keep the drain anchored in the soil at the proper installation depth when the mandrel is removed. Neither method employs jetting.

In the static method, hydraulic pressure pushes or inserts the mandrel into the soil. In the dynamic method, a vibratory hammer, with its vertical energy, is the power source for the mandrel installation and removal. Both methods have merits. The static method can be used in very sensitive soils and on steep slopes; the dynamic method can penetrate higher density soils, eliminate some pre-drilling and extracts easily.

Recently, both methods were employed at Aziehanen in Holland on the same large scale project. According to Hansbo, Jamiolkowski and Kok (1981) comparison results showed:

1. No difference in performance of drains installed by either method (see Fig. 2).

2. Pore water buildup with the dynamic method, but a dissipation in 24 hours (see Fig. 3).

Concerning the dynamic installation method, Kok (1981) said that after 24 hours, in very bad peaty clay, approximately 3 kPa or only 1 foot of water column excess pore pressure remained.

Case History

Difficult foundation conditions were encountered at the Basrah Barrage Site. The barrage, which consists of a navigation lock and a weir, is located in a delta area in the vicinity of Basrah, Iraq.

Very soft clay deposits, exceeding 15m in thickness, had to be improved before excavation could be commenced. Soft, silty clays, close to liquid consistency, could not provide stability in the foundation excavation slopes.

To improve the stability, a consolidation process was induced. Consolidation of the soft clay was not achieved in the usual way, by a preloading embankment, but by means of dewatering of an underlying permeable layer. By pumping water out of this layer, the soft clay was "loaded" due to neutralization of the uplift. The consolidation process was accelerated significantly by the use of prefabricated drains. The shear strength of the soft clay was increased to such an extent that excavation work could be executed without difficulty.

The soil deposits at the construction site are composed of a soft or very soft, 15m to 17m thick, layer of silty clay with very thin lamination of fine or silty sands.

The soft clay rests on permeable or semi-permeable interbedded layers of sands and gravels with lenses of loam.

The field test comprised sampling, static sounding, Swedish weight sound and vane tests. Laboratory tests comprised triaxial and oedometer tests as well as index property tests.

The average subsoil conditions evaluated from field and laboratory tests are given in Fig. 4. The 17m thick layer of silty clay contains lamination of fine sand or silty sand, less than 1 mm to several mm's in thickness. The average natural water content amounts to 45%, and the average degree of saturation S_r to 94%. The salinity of the ground water varies with the limits of 1 - 8%. The plasticity index I_p varies between 20 and 35%.

With respect to the undrained shear strength within the soft clay deposit, three layers could be distinguished:

- top layer (crust) with vane shear strength varying between 30 and 40 kPa
- soft layer, between 4 and 10m depth, with shear strength between 20 and 35 kPa
- very soft layer, between 10 and 20m depth, with shear strength varying between 15 and 30 kPa

- hard layer with shear strength exceeding 40 kPa, resting on top of the permeable layer.

The oedometer tests indicated that the soil is normally consolidated, with a compression index C_c varying between 0.2 and 0.49. The coefficient of consolidation in the vertical direction c_v, evaluated from oedometer tests, varies between $1.3 \times 10^{-7} m^2/sec$ and $0.4 \times 10^{-7} m^2/sec$, when effective pressure changed from 10 kPa to 400 kPa. The coefficient of consolidation in the horizontal direction, determined in a triaxial apparatus, varied between $3.5 \times 10^{-7} m^2/sec$ and $0.4 \times 10^{-7} m^2/sec$ when the pressure changed within the above-mentioned limits.

Construction of the Basrah Barrage was designed to be carried out in an open excavation. However, the clayey subsoil of very soft consistency made the foundation excavation work impossible. Due to this, it was decided to stabilize the excavation slopes by consolidation prior to excavation. This soil stabilization was not for the barrage foundation itself, as this was designed to be founded on a bearing stratum of sand, by means of slurry trench walls. Thus, only the excavation slopes were stabilized by consolidation.

The consolidation was initiated by dewatering of the permeable layer which underlays the soft clayey deposit. The dewatering caused a decrease of the uplift, giving the same result as would be given by a preloading embankment. To accelerate the consolidation process, prefabricated drains were installed over the design excavation slope area with a spacing of 2m in a triangular pattern. To achieve a good hydraulic contact with the permeable layer, the wick drains were driven 0.5m into this layer. The principle of the consolidation system is schematically presented in Fig. 5.

The consolidation technique described was applied to improve the stability of the foundation excavation slopes. In natural soil conditions, the safety factor of the slope, shown in Fig. 6, calculated with the Swedish method, using Bjerrum's correction coefficient (Bjerrum, 1972), amounted to F = 0.93. Assuming, on the basis of triaxial and oedometer tests, that the shear strength would increase to approximately 150% of the initial values, the improvement of stability, resulting in an increase of the safety factor to F = 1.3, was deemed satisfactory.

The installation of prefabricated drains, carried out with Rodio equipment, was quick (approximately 3,000m of drain per day) and efficient. Prefabricated drains reached the desired depth (average 17.5m) according to design. It should be observed that the drains were driven about 0.5m into the hard sand layer underlying the clay layer.

The course of the consolidated process - a slow increase of settlement values (Fig. 7) and a decrease of the pore pressure (Fig. 8) was not noticeable a few days after pumping was commenced, but these processes suddenly accelerated when the drains were installed.

Four months after the installation of the prefabricated drains, the recorded settlement amounted to approximately 32 cm, corresponding to about 70% of the total settlement (degree of consolidation U = 0.7). The good concordance of predicted and measured settlement can be seen in Fig.7. The settlement analysis was made according to Barron's (1948) formula, using an iterative formula (Wolski et al, 1979). The vane shear strength, checked in the same places where previous vane tests had been made, showed approximately a 30 - 70% increase of the undrained shear strength (50% was anticipated in the design). Results of vane tests prior to and after the improvement process are shown in Fig. 9.

It is worth pointing out that, if the wick drains had not been installed, the desired increase of shear strength, corresponding to a degree of consolidation of 70%, would have taken over three years.

The soil improvement work at the Basrah Barrage site has shown the usefulness of prefabricated drains in a technique of consolidation modified as described in this paper. In the case of a soft soil layer underlain by a permeable one, the improvement of soil conditions (decrease in natural water content) could be achieved by dewatering of the permeable layer and the installation of wick drains in the soft layer. No preloading embankment was needed.

The observed increase of shear strength of the soft silty clay, caused by the consolidation process, has demonstrated that the technique described in this paper can be used for ensuring stable excavation slopes in soft clay.

During more than two years of dewatering of the foundation excavation, the prefabricated drains showed full efficiency despite the rather high salinity of the ground water.

The construction work was performed by the Polish contractor, Budimex, for the Iraq Authorities, represented by the State Organization of Dams and Reservoirs. The design of the soil improvement, as well as geotechnical investigations in the field and in the laboratory, were carried out by the Geotechnical Department of Warsaw Agricultural University.

CONCLUSION

Modern technology has helped us to be able to improve the properties of the weaker soils. The above methods are just two of the proven techniques that can be used in the low permeable soils. Electro-osmotic applications are much less numerous than vertical drain situations, yet, once one has been identified, the results can be outstanding. The future of prefabricated drains, throughout the world, should be one of increased employment and application. Not only can these drains be used in combination with surcharge and pumping, but the addition of vacuum to the drains has already been accomplished in Europe. They have also been used in conjunction with heavy tamping in the Far East and Europe. The prefabricated drain, a relatively simple device, and electro-osmosis should prove to be valuable assets to the mining and construction industries in the world since deposits and land, once too expensive to be used or considered for use, can now be rendered suitable for use in consolidation or slope stability situations at reasonable costs.

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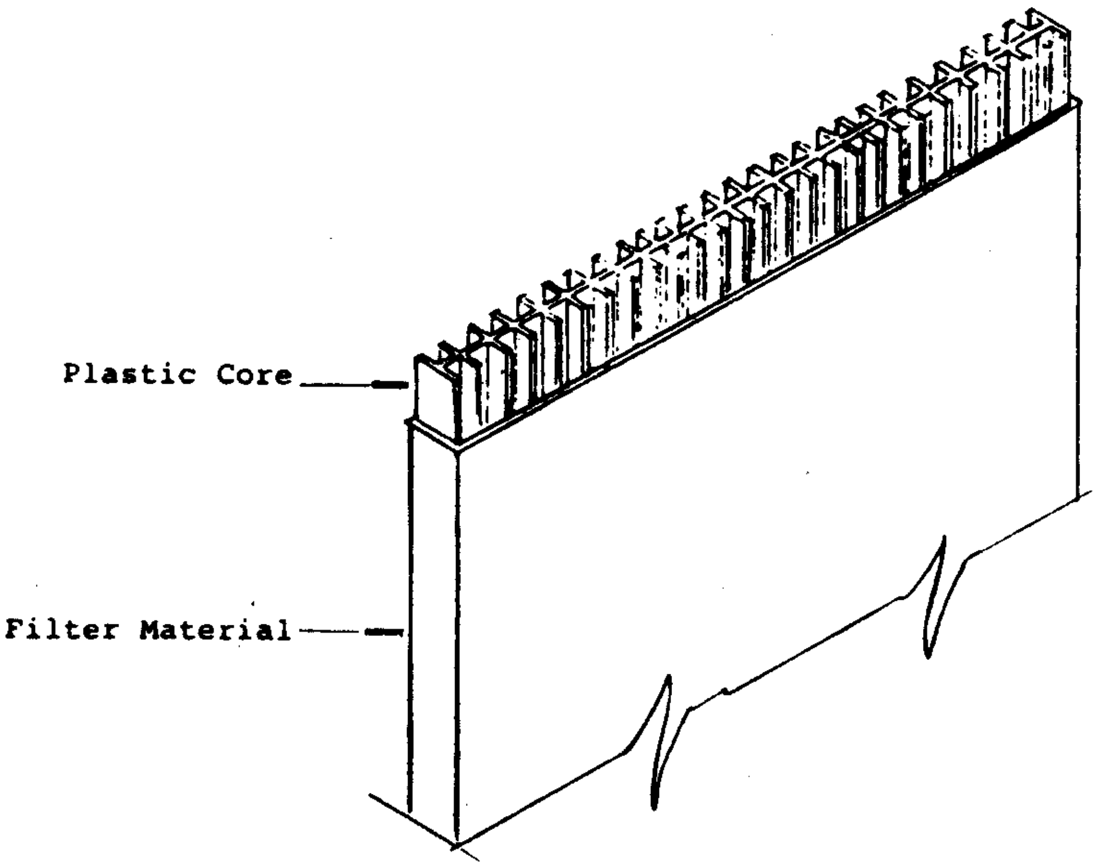

Fig. 1. Prefabricated Wick Drain

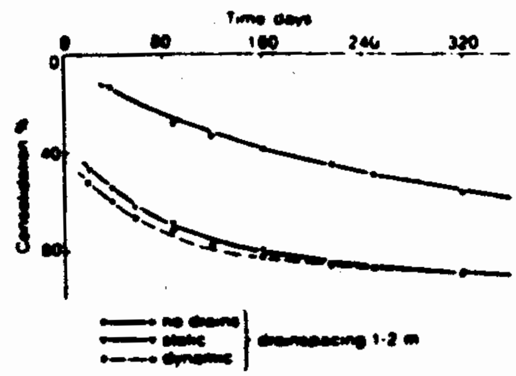

Fig.2 Rate of Consolidation Aziehaven
(after Hansbo, Jamiolkowski & Kok, 1981)

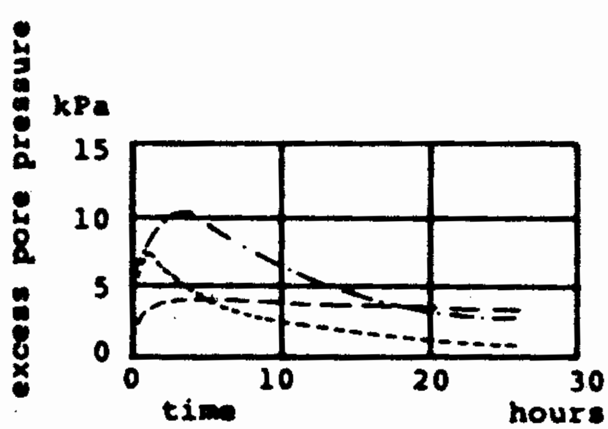

Fig.3 Pore Pressure Dissipation of
Dynamic Installation
(after Kok, 1981)

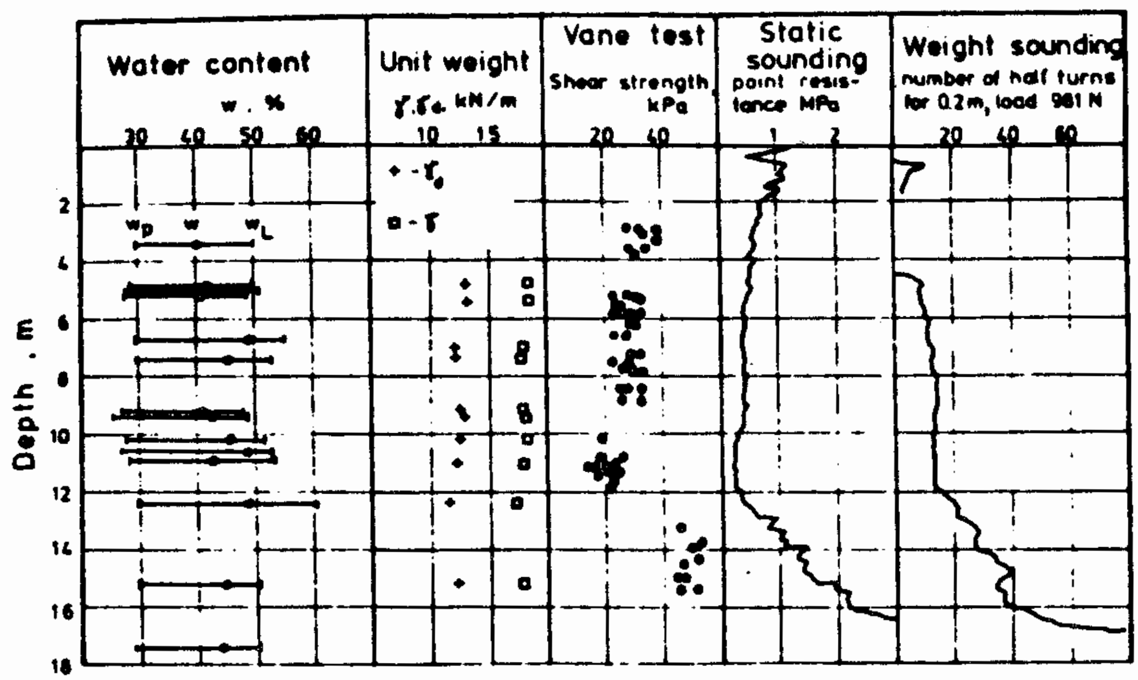

Fig.4. Properties of the Subsoil

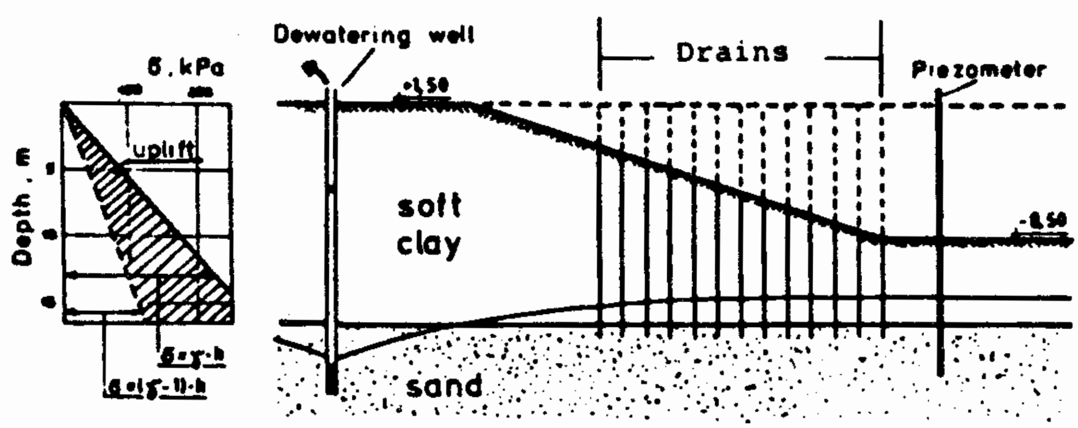

Fig.5. Cross Section of the Excavation

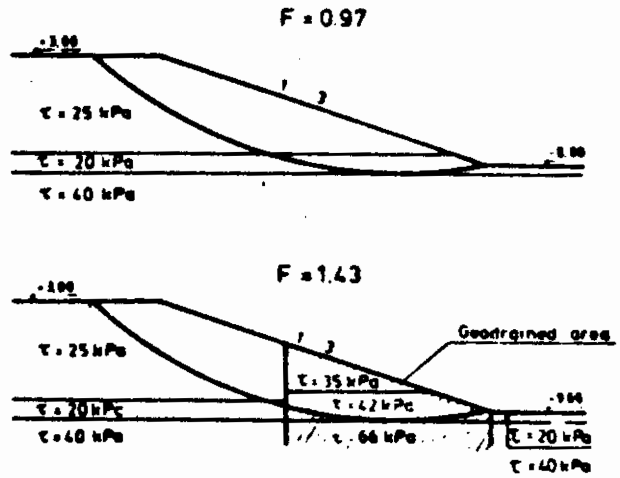

Fig.6. Comparison of Safety Factors of Slopes in Natural and Improved Conditions

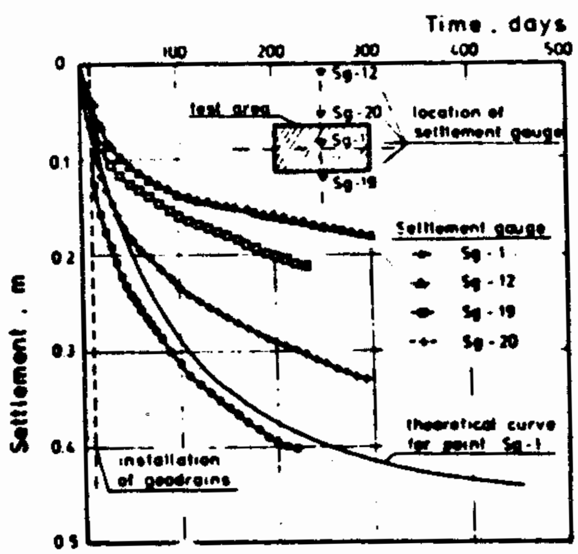

Fig.7. Settlement Measurements

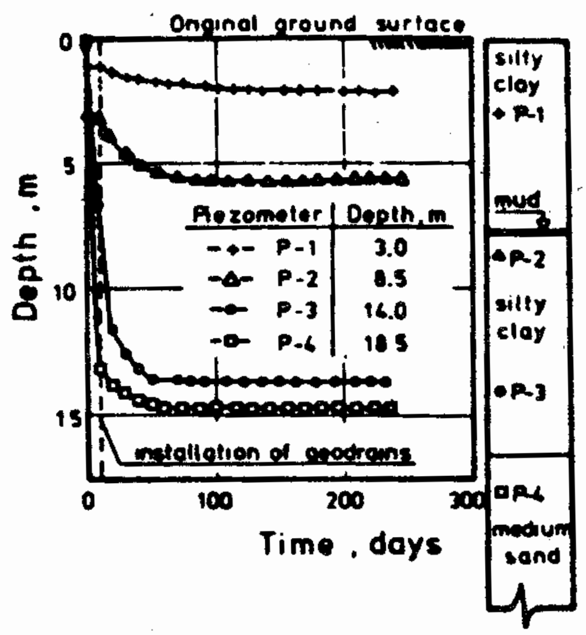

Fig.8. Pore Pressure Measurements

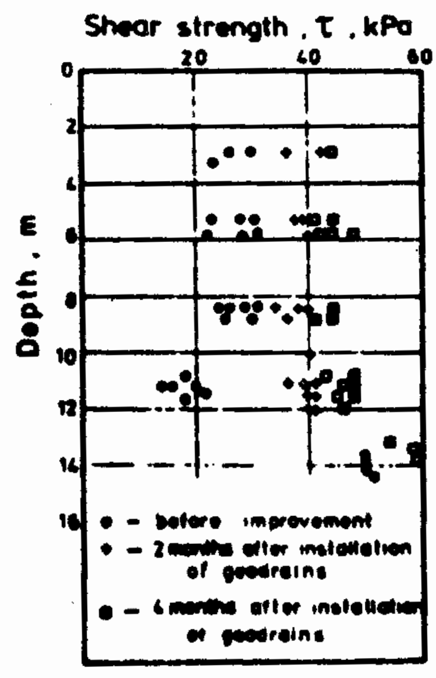

Fig.9. Increase in Shear Strength of Soft Clay