

Description

BACKGROUND OF THE INVENTION

Field of the invention

The present invention relates to a method of stabilizing soft ground which supports roads, river banks or the like and soft ground which is susceptible to movement resulting from earthquakes.

Description of the prior art

In geographic areas with limited open spaces, it is increasingly important for developing industrial infrastructures such as water fronts, to ensure that soft ground is stabilized and is maintained in good condition. Furthermore, steady increase in traffic flow, combined with increase in size of vehicles, has caused problems which must be urgently solved; it is necessary to maintain existing road networks in good condition and to provide new roads.

Also, in recent years, earthquakes have become more frequent in some geographic areas, such as the Japanese Islands, and, therefore, it is an urgent problem to ensure that seismic disasters are alleviated.

In US-A-4309129 and US-A-4540316 there is reference to consolidating and draining soft ground by a piling method and a combined piling and drainage method designed to reduce consolidation time as much as possible.

However, the piling method or the combined piling and drainage method takes several months to several years for an 80% consolidation, although depending on the soil properties of soft ground, and needs much labor, time, and cost for ground maintenance and control. One leading reason is that several piling operations must be performed step by step until as-planned height is reached because when a given piling structure is at once laid on the soft ground, surrounding ground layers or structures built up on them are deformed or displaced due to its sliding destruction, and another reason is that long times are needed to make the soft ground stable with respect to settlement or subsidence, sliding destruction, and nature changes. Another defect of these methods is that much difficulty is involved in their application to ground found at residential quarters and marshland, along rivers, and at slopes, or ground disturbed as by earthquakes. In view of design, management and construction control considerations, the amount and time of subsidence may be theoretically estimated or predicted but, in many instances, practice differs from theory.

Accordingly, whenever the movement of the piling structure placed on the soft ground is observed for a certain period, what form and condition the ground subsides in must be found. However, there is still no effective design or control procedures capable of being practiced within

a short period of time.

A particular problem with the piling method is that it is prima face effective for temporarily bringing ground disturbed by sliding destruction, earthquakes, or the like back to the old condition provided that the height of the soiling structure thereon lies within a certain range, but it is not suited for permanently recovering or enhancing the strength of disturbed ground, or preventing seismic disasters.

A piling structure laid on soft ground must be normally stable with respect to piling loads, and dynamic loads and vibrations produced by traffic loads. In addition to such piling, and traffic loads, the piling structure must also resist vibrations produced by an earthquake.

An essential requirement for achieving the stabilization of such a piling structure is to improve the property of the soil forming the piling soil structure and the foundation without disturbing them, so that the strength needed for design and construction can be instantaneously created, thereby constituting a homogeneous pre-consolidated (over-consolidated) ground layer in which the piling structure is united with the foundation.

A primary object of the present invention is to provide a consistent solution to the following five problems the aforesaid conventional piling methods involve in connection with (1) consolidation or construction time, (2) construction environment, (3) design management, and construction control, (4) restoration of ground disturbed by sliding destruction, and ground or structures damaged by an earthquake, and (5) applicability to prevention of ground and structures against disaster.

SUMMARY OF THE INVENTION

The present invention has been accomplished with the aforesaid object in mind, and is basically characterized by improving the nature of the soil of the ground to be reconstructed while the ground is not disturbed at all, using an instantaneous consolidation method, so that the ground can be in situ reconstructed within 24 hours in an instantaneous operation on the basis of four basic principles for soft ground improvement, viz., (1) consolidation and dehydration, (2) drainage, (3) solidification, and (4) replacement. The present invention is also applicable to (1) every soft ground inclusive of natural stratified ground, man-made ground, and ground disturbed by destruction, (2) free creation of the required strength over the range needed in view of design and construction according to a ground improvement plan, (3) restoration and reinforcement of ground disturbed by destruction, and (4) prevention of ground and structures again seismic disasters. Thus, the present invention provides a technique that makes use of the effective soil covering stress of the original ground to reconstruct it into a stable ground layer capable of resisting piling loads, traffic loads, and vibration loads additionally applied to the original ground.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a process wherein using a specific impregnation machine, a specifically formulated impregnation material is injected into ground by a consolidation impregnation method controlled according to the design and construction standards, so that there can be obtained a homogeneously stable yet complex ground zone in which a solidified portion is united with an over-consolidated portion obtained by compression effect due to in-situ dehydration and drainage by consolidation, and post-injection in-situ replacement and solidification effect.

FIG. 2 illustrates a process wherein by effecting the aforesaid consolidation impregnation method using the impregnation material being injected as a load in place of a piling or other load, a soft and viscous ground zone or a loose sandy ground zone can be destroyed to form crevices therein.

FIG. 3 illustrates a process wherein with a further continued injection of the impregnation material on the same breaking criteria, the ground zone is successively destroyed to cause quantitative and qualitative growth of the crevices, so that the impregnation material starts to flow while the crevices are filled therewith, thereby creating a sheet form of fluid body in an oblique or vertical direction.

FIG. 4 illustrates a process where while the fluid body flows through passages and grows, ground portions contiguous to the breaking interfaces are in situ subjected to forcibly rapid loading and dehydration actions in a transverse direction.

FIG. 5 illustrates a process wherein by the in-situ loading and dehydration actions of the fluid body, pore water is entrained, simultaneously with the injection of the impregnation material, from the ground to be consolidated into the fluid body, and then dynamically discharged, and during the injection of the impregnation material, the water is discharged mainly through water discharge passages formed by boundaries between the ground to be consolidated and the fluid body, and then discharged into underground, and ground-surface sand layers together with water separated from the impregnation material.

FIG. 6 illustrates a process where by a chain effect of the fluid body on in-situ loading, dehydration and drainage, the ground to be improved can be instantaneously consolidated without being disturbed at all, resulting in a successive ground strength increase, and the fluid body itself is solidified within 24 hours in its as-injected state to create an in-situ solidified replacement skeleton structure in the ground to be consolidated.

FIG. 7 is diagram showing the relation between consolidation yield stress and pre-consolidation stress.

FIG. 8 illustrates in section a plan for the creation of a road with a low piling structure laid thereon.

FIG. 9 a table showing the nature of the soil forming the ground to be reconstructed, and a profile diagram

showing the effective soil covering stress profile of a piling structure.

FIG. 10 is a diagram showing the relation between penetration resistance values obtained by Swedish sounding tests performed at a depth of up to 5 meters and undrained shearing strength values (for the reconstructed ground) obtained by vane shear tests.

FIG. 11 is diagrams for making estimation of the effect on ground improvement by cone penetration tests using a portable cone penetrometer.

FIG. 12 is a diagram showing the relation between consolidation yield stress P_c and pre-consolidation stress P_c' , both in tf/m^2 , to thereby illustrate the first results of the reconstructed peat ground.

FIG. 13 is a diagram showing the second results of the reconstructed peat ground.

FIG. 14 is a diagram showing the third results of the reconstructed peat ground.

FIG. 15 is a table showing the constituent of the soil forming the ground to be reconstructed, and a diagram showing a plan for reconstructing a road with a low piling structure laid thereon.

FIG. 16 is a diagram providing an illustration of how a piling structure subsides.

FIG. 17 is a diagram showing the effective soil covering stress profile of piled ground (clay of marine origin), and the results of ground improvement.

FIG. 18 is a diagram showing the relation between pre-consolidation stress P_c' and undrained shearing strength C_u (of clay of marine origin).

FIG. 19 is a diagram showing the effective soil covering stresses of the original ground (clay of river origin) and piled ground, the consolidation yield stress of the original ground, and the consolidation yield stress of the original ground (clay of river origin) upon reconstructed.

FIG. 20 is a diagram providing an illustration of how the ground subsides during reconstruction, and after reconstruction.

FIG. 21 is a diagram showing the void ratio of undrained shearing strength of the ground before and after reconstruction.

DETAILED EXPLANATION OF THE PREFERRED EMBODIMENTS

The present invention will now be explained at great length with reference to the accompanying drawings.

When earth, or a piling structure is laid on the surface of land or structures are built up on the surface of land, newly added loads are transmitted through the ground. Stresses produced by the transmission of the loads through the ground often cause ground settlement or subsidence, and if the loads exceed a certain limitation, the ground will then be destroyed.

Accordingly, when it is attempted to investigate ground destruction or ground settlement, it is required to learn stress occurring at a certain depth of the ground due to the weight of soil, and the magnitude of stress

increased by newly added loads such as traffic, and seismic loads.

Pressure that a horizontal plane at a certain depth of ground receives by the weight of soil placed above it is called soil covering pressure or stress.

When soil exists above a ground water level, on the one hand, soil covering pressure δ_z is given by

$$\delta_z = \gamma \times Z \text{ (tf/m}^2\text{)}$$

where γ is the unit volume weight of soil, and Z is depth.

When soil exists below a ground water level, on the other hand, soil covering pressure δ_z' is given by

$$\delta_z' = \gamma_{\text{sub}} \times Z \text{ (tf/m}^2\text{)}$$

where γ_{sub} is the submerged unit volume weight of soil obtained by subtracting buoyancy from the unit volume weight of soil, and Z is depth. The pressure δ_z' is a sort of pressure transmitted directly between soil particles, and called effective stress. The soil covering pressure (stress) represented in terms of effective stress is then called effective soil covering pressure (stress).

An undisturbed viscous soil sample gathered from ground at a certain depth is subjected to consolidation testing, while incremental loads are added thereto. Void ratios are plotted per loading, with void ratio on an arithmetic scale as ordinate and consolidation load on a semi-logarithmic scale as abscissa. It is then found that at the initial loading stage the void ratio e decreases following a gentle curve; upon a certain load exceeded, however, it decreases sharply from that gentle curve, and changes in a linear form. This point of inflection, viz., consolidation load under which soil is shifted from an elastic phase into a plastic phase is referred to as consolidation yield stress P_c . In the case of naturally stratified, saturated ground, the consolidation yield point is often in substantial agreement with the maximum consolidation load the ground have received in the past. When a load less than such load is applied to the ground, there is little, if any, ground settlement.

This invention provides a ground improving method capable of creating ground unlikely to subside by means of the aforesaid instantaneous consolidation technique, according to which impregnation of ground can be used in place of loading such as piling based on the consolidation principles mentioned above.

When the consolidation yield stress P_c of soil at a given depth of ground is equal to the soil covering pressure that soil receives currently, that soil is referred to as soil that has been subjected to normal consolidation. When the consolidation yield pressure P_c is larger than the soil covering pressure that soil receives currently, that soil is referred to as soil that has been subjected to over consolidation, indicating that it has so far been subjected to load larger than that receiving currently.

It is believed that leading reasons for over consolidation are that, in the past, soil has been exposed to load larger than the current soil covering load, a repeated cycle of drying or dry-wetting, a large ground water level change, and the action of gluey substances.

At present, practically feasible means for over-consolidating ground having a certain depth is to apply a load larger than the current soil covering pressure to that ground by piling or other loading methods. As already mentioned, however, it is difficult to create ground having a high degree of over consolidation within a very short period of time by piling or other loading methods, and it is nearly impossible to instantaneously achieve the strength required for design and construction over the range needed for the ground to be over-consolidated, using available piling methods. Nonetheless, there is still no alternative with the exception of piling or other loading methods.

This invention provides a technique which enables over-consolidated soil (ground) having the required strength to be instantaneously created at the depth, and over the range, needed for design, using the instantaneous consolidation method.

The application of the aforesaid means makes it possible to create homogeneous pre-consolidated ground (over-consolidated ground) comprising an integral structure of the foundation and a piling structure laid thereon. The term "pre-consolidated ground" used herein is understood to refer to improved and reinforced ground which can resist every external force newly added to the effective soil covering pressure of the original ground, for instance, static loads produced by a piling structure laid thereon or structures built up thereon, dynamic loads produced by traffic vehicles, and loads produced by vibrations, and earthquakes.

The present invention will now be explained in further detail with reference to some examples.

In the instantaneous consolidation method by impregnation of ground which is practiced according to predetermined design for ground improvement, a predetermined amount of one impregnation material selected from the group consisting of mortar material, cement material, and a mixture of mortar and cement materials is injected at a predetermined pressure into very soft, viscous ground or loose sandy ground through a preselected array of injection points. Simultaneously with impregnation, the soft ground is destroyed to form crevices therein, which are then filled with the impregnation material. In such an impregnation process, both the amount of the material impregnated and the impregnation pressure are controlled according to the aforesaid design, so that the end degree of consolidation can be instantaneously achieved.

(1) Some load is required to improve the nature of ground itself to take effect on its consolidation, and so piling or other loading means have been used so far in the art. In the inventive method, however, such

consolidation effect is achieved by the impregnation material injected into the ground, which is tantamount to the piling structure (soil) laid on the ground, and the impregnation pressure which is tantamount to the load corresponding to the thickness of the soil laid on the ground. See FIGS. 1 to 5. (2) By consolidation, the ground is so dehydrated that pore water is discharged. For this reason, natural drainage due to a soil load applied on the ground has conventionally been used alone or in combination with a drain. In the inventive method, however, the impregnation material being injected into the ground is used as dehydration and discharge means.

Example 1 - Instantaneous consolidation method by impregnation of ground.

(i) Using a specific impregnation machine, a specifically formulated impregnation material is injected into ground by the consolidation impregnation method controlled according to the design and construction standards to be described later. Through the mechanisms explained in (2)-(6) below and shown in FIGS. 2-6, there can be obtained a homogeneously stable yet complex ground zone in which a solidified portion is united with an over-consolidated portion obtained by compression effect due to in-situ dehydration and drainage by consolidation, and post-injection in-situ replacement and solidification effect. See FIG. 1.

(ii) By effecting the aforesaid consolidation impregnation using the impregnation material being injected as a load in place of a piling or other load, a soft and viscous ground zone or a loose sandy ground zone can be destroyed to form crevices therein. See FIG. 2.

(iii) With a further continued injection of the impregnation material on the same breaking criteria, the ground zone is successively destroyed to cause quantitative and qualitative growth of the crevices, so that the impregnation material starts to flow while the crevices are filled therewith, thereby creating a sheet form of fluid body in an oblique or vertical direction. See FIG. 3.

(iv) While the fluid body flows through passages and grows, ground portions contiguous to the breaking interfaces are in situ subjected to forcibly rapid loading and dehydration actions in a transverse direction. See FIG. 4.

(v) By the in-situ loading and dehydration actions of the fluid body, pore water is entrained, simultaneously with the injection of the impregnation material, from the ground to be consolidated into the fluid body, and then dynamically discharged. During the injection of the impregnation material, the water is discharged mainly through water discharge passages formed by boundaries between the ground

to be consolidated and the fluid body, and then discharged into underground, and ground-surface sand layers together with water separated from the impregnation material. See FIG. 5.

(vi) By a chain effect of the fluid body on in-situ loading, dehydration and drainage, the ground to be improved can be instantaneously consolidated without being disturbed at all, resulting in a successive ground strength increase. On the other hand, the fluid body itself is solidified within 24 hours in its as-injected state to create an in-situ solidified replacement skeleton structure in the ground to be consolidated. See FIG. 6.

FIG. 7 clarifies the effect of the inventive instantaneous consolidation method by impregnation of ground through an accumulation of experimental data.

In FIG. 7, the numbers on the abscissa indicate a consolidation load or, more exactly, the consolidation yield stress P_c of the original ground found by soil testing, and the consolidation yield stress, again found by soil testing, of the ground improved by the application of the inventive method of impregnation of ground. In FIG. 7, the latter consolidation yield stress is denoted as pre-consolidation stress P_c' to define around the former consolidation yield stress. The numbers on the left ordinate stand for void ratio e and a compression index C_c while the numbers on the right ordinate represent undrained shearing strength C_u . Data on void ratio e , compression index C_c , and undrained shearing strength C_u of the ground before and after reconstruction are plotted with respect to the consolidation load on the abscissa. White symbols refer to the original ground before and after reconstruction, and ground with soil laid on it, while black symbols refer to the ground after reconstruction. It is here to be noted that the ground with a soiling structure laid on it was created before seven years with a piling structure of 4.5 meters in height.

Example 2 - Peat ground

FIG. 8 shows a road widening project in section for a given road with a new piling structure placed on an adjoining rice field, and penetration resistance values of the ground before and after reconstruction for the purpose of comparison. FIG. 9 illustrates the soil constitution of the ground to be improved, the effective soil covering stress, consolidation yield stress, and pre-consolidation stress profiles of the ground to be improved, and ground with a piling structure laid on it.

(1) Soil constitution of the ground to be reconstructed, and range for making investigation of how soft ground is improved

As can be seen from FIG. 9, the ground to be reconstructed includes a surface soil layer of 0.6 meters in thickness, beneath which highly compressible, very

soft, and organic viscous soil composed mainly of peat or humus soil is distributed at a thickness of about 4.0 meters, and a relatively rigid and hard subsoil layer composed of alternate sub-layers of sandy soil, silt soil, and viscous and sandy soils. In view of design and construction considerations, therefore, the very soft layer having a depth of about 4.0 meters must be reconstructed.

(2) Non-consolidated ground, normally consolidated ground, and pre-consolidated ground

Referring here to general stratified ground, the maximum load that the ground has so far received, for instance, through accumulated loads of deposits constituting the ground is consolidation yield stress P_c and, in many cases, the profile of consolidation yield stress P_c within the ground is in substantial agreement with that of the effective soil covering stress of the original ground. When a fresh piling structure is placed on the original ground, a load produced thereby causes the profile line of consolidation yield stress P_c of the original ground to become close to that of the piled ground layer with the progress of consolidation. Therefore, the piled ground layer continues to subside until the profile line of the consolidation yield stress of the original ground coincides with that of the effective soil covering stress of the piled ground layer. However, if the consolidation yield stress of the improved ground obtained by the inventive method, viz., the value of pre-consolidation stress P_c' is set on or above the profile line of the effective soil covering stress of the piled ground layer, any ground subsidence would not theoretically occur. Indeed, the thus improved pre-consolidated ground is observed to undergo no subsidence at all, or an allowable, if any, degree of subsidence, and is found to be effective for earthquakes as well.

Basically, such concepts underlie the present invention; it is the inventive method of stabilizing piled ground, or ground with a low piling structure placed on it that enables pre-consolidation stress P_c' of the soft ground to be reconstructed to be set on or above the profile line of the effective soil covering stress produced by piling, traffic, and seismic loads.

(3) Estimation of traffic loads on piling structure according to the invention

Loads, if produced by piling, can be well detected. However, traffic loads, for which there is still no established estimation method, may be measured in the present invention, as follows.

To improve the soil of the ground to be reconstructed while the ground is kept undisturbed, there is still nothing but a piling method according to which the ground is dehydrated using a piling or other load, so that pore water can be discharged from the ground for the purpose of consolidation. In this piling method, the following equation (1) is used:

$$C_u' = C_u + m'(P_O + Ux\Delta P) \quad (1)$$

where

C_u' is the undrained shearing strength of the consolidated ground,

C_u is the undrained shearing strength of the original ground,

P_O is the effective soil covering stress of the original ground,

m' is a percentage of strength increase due to the consolidation load of the piling structure, and

U is the degree of consolidation under investigation of the piling consolidation load of the piling structure.

The inventive method is distinguishable over the prior art in the following points.

(i) If a piling structure is placed on soft ground, several months to several years are then taken for an 80% consolidation, as already mentioned. Consequently, the degree of consolidation U is determined depending on how many days elapses after consolidation. For instance, given the strength achieved by an 80% consolidation, then $U = 0.8$. In the inventive instantaneous consolidation method, by contrast, $U = 1.0$ for every ground irrespective of when the degree of consolidation is investigated.

(ii) Symbol m' is the percentage of strength increase due to the piling consolidation load. If the percentage of strength increase is found at the time of piling, it is then required to gather a soil sample from the ground under investigation, and subject it to indoor soil testing, i.e., uniface shear (consolidation undrained) testing or triaxial compression (consolidation undrained) testing. This is also true of when the percentage of strength increase is measured during piling works. Thus, it is required to perform soil testing for each piling. No target strength is obtained without pressurization at the consolidation load needed in view of design. In the inventive method, on the contrary, empirical values have been predetermined through experimentation per ground, viz., for peat or humus ground, clay ground of marine origin, and clay ground of river origin, respectively. Thus, the inventive method can be instantaneously effected using the predetermined strength needed in view of design.

(iii) Conventional methods are performed on the basis of the effective soil covering stress P_O of the original ground. Strictly speaking, however, much difficulty is involved in the precise calculation of the effective soil covering stress of the original ground. In the inventive method, on the contrary, design, and construction precision is high because the in-

ventive method can be practiced on the basis of the consolidation yield stress P_c .

(iv) In the matter of the present invention, ΔP is the consolidation yield stress (pre-consolidated stress) of the ground improved by impregnation of ground, as already noted, and can be calculated in the form of the target value for compressibility improvement, as designed.

In the inventive method, it is essentially important that

$$Cu' = Cu + m(Pd - Pc) \quad (2)$$

where

Cu is the undrained shearing strength in tf/m^2 of the original ground,

Cu' is the undrained shearing strength in tf/m^2 of the ground upon improved,

P_c is the consolidation yield stress in tf/m^2 of the original ground,

P_d is the consolidation stress in tf/m^2 needed to obtain the undrained shearing strength Cu' in tf/m^2 of the ground upon improved or the pre-consolidated stress P_c' in tf/m^2 of the ground upon improved, and m is the percentage of strength increase due to the piling consolidation stress.

In equation (2), the soil constants of the original ground are defined by $Cu = 1.5 \text{ tf/m}^2$, and $P_c = 5.0 \text{ tf/m}^2$. These soil constants may be found by subjecting the original ground to consolidation testing, triaxial compression or uniface shear testing by non-consolidation undrained testing, uniaxial compression testing, or vane shear testing. Accordingly, if the percentage of strength increase m and the target value Cu' for ground improvement are determined, the consolidation stress P_d (or the pre-consolidation stress P_c' of the ground upon improved) can then be used to calculate the height of the piling structure of soil as the traffic load. From the results of experimentation using the inventive method, shown in FIG. 12, $m = 0.4$ is chosen from the range of $m = 0.39$ to $m = 0.42$.

Of importance is here how to determine the target value Cu' for ground improvement. If a follow-up survey is run on the current stability (the amount of road subsidence, and whether or not surrounding ground layers or structures built up thereon are deformed and displaced, and if so, to what degree?) of an existing road with a low piling structure placed on it, which is laid on peat ground identical with, or similar to, the ground under investigation in terms of soil constitution, soil nature, soil constants, and thicknesses of layers, as well as on the strength and compressibility properties of the piling structure and the foundation, it is then possible to clarify or estimate the stability and conditions for stability of,

and problems with, the ground under investigation.

The results of follow-up surveys run so far on existing roads with low piling structures laid on them reveal that (1) the mean value of the undrained shearing strength is $Cu' = 2.5 \text{ tf/m}^2$ for some roads found to undergo slight subsidence and little soil nature changes but offer no particular obstacle to the traveling of vehicles thereon, and (2) the undrained shearing strength is $Cu' > 3.0 \text{ tf/m}^2$ for some roads observed to undergo little, if any, subsidence and soil nature changes or to be kept stable. See FIGS. 12, 13, and 14.

On the basis of these results of surveys, now assume that the reference value for the undrained shearing strength for the roads as mentioned in (1) above is $Cu' = 2.5 \text{ tf/m}^2$. Then, the consolidation stress P_d (pre-consolidation stress P_c') with respect to this reference value is found by

$$Pd = (Cu' - Cu + m \times Pc)/m \quad (3)$$

Substitution of $Cu' = 2.5 \text{ tf/m}^2$, $Cu = 1.5 \text{ tf/m}^2$, $P_c = 5.0 \text{ tf/m}^2$, and $m = 0.4$ into equation (3) gives

$$Pd = (2.5 - 1.5 + 0.4 \times 5.0)/0.4 = 7.5 \text{ tf/m}^2$$

For the stably maintained roads, too, assume that the reference value for the undrained shearing strength is $Cu' = 3.0 \text{ tf/m}^2$. Then, the consolidation stress P_d (pre-consolidation stress P_c') with respect to this reference value is also found by equation (3).

That is to say, substitution of $Cu' = 3.0 \text{ tf/m}^2$, $Cu = 1.5 \text{ tf/m}^2$, $P_c = 5.0 \text{ tf/m}^2$, and $m = 0.4$ into equation (3) gives

$$Pd = (3.0 - 1.5 + 0.4 \times 5.0)/0.4 = 8.75 \text{ tf/m}^2$$

In FIG. 9, curves 3 and 4 show underground stress profiles wherein the consolidation stresses P_d (pre-consolidation stresses P_c') as calculated above are distributed in the ground to be reconstructed, corresponding to the effective soil covering stress of the original ground. Here, assume that the unit volume weight of the piling structure is $\gamma_t = 1.8 \text{ tf/m}^2$. For the case as set forth in (1) above, pile height as calculated as traffic loads is 2.5 meters if pile height as planned is 1.0 meter, and for the case as set forth in (2) above, pile height as calculated as traffic loads is 3.2 meters if pile height as planned is 1.0 meter.

(4) Results of construction works according to the invention

In exemplary construction works shown in FIGS. 8 and 9, the resulting effects were ascertained and estimated firstly by Swedish sounding tests, and secondly

by subjecting typical spots to vane shearing tests, penetration tests using a portable cone penetrometer, and Dutch double-pipe cone penetration tests for the purpose of comparison. The results are shown in FIG. 10. The resulting empirical equation from the relation between the undrained shearing strength (found by the vane shearing tests) and penetration resistance values W_{SW} obtained in the Swedish sounding tests is

$$Cu' = 0.04 W_{SW}$$

While design management and construction control were effected using such penetration resistance values, construction works were performed at $Cu' > 3.0 \text{ tf/m}^2$ for portions of structures built up on ground, and at $Cu' > 2.5 \text{ tf/m}^2$ for other portions. After the completion of the construction works, neither subsidence nor changes in the nature of the soil were observed.

(5) Influences of seismic vibrations

Much is still unknown or unsettled about earthquake scales, and the form, type, magnitude, frequency, and time of seismic vibrations, and so influences of all seismic vibrations cannot be established or predicted. At least, however, inventor's experience teaches that grounds with an improved undrained shearing strength of $Cu' > 3.0\text{-}4.0 \text{ tf/m}^2$ have been hardly hit by earthquakes having a seismic intensity of 4 to 5. If general piled grounds, grounds on which low piling structures are laid and which receive traffic loads, and piling structures and foundations of filled-up grounds are improved such that their undrained shearing strengths are $Cu' > 3.0\text{-}4.0 \text{ tf/m}^2$, it will then be expected that they are not damaged by earthquakes or, if hit, suffer from a minimum damage.

Example 3 - Clay ground of marine origin

One example is explained, wherein the inventive method is applied to prevent changes of underground pipes due to consolidation subsidence of a low piling structure laid on ground composed of clay of marine origin and residual subsidence thereof due to traffic loads.

(i) The nature of the soil forming the ground to be reconstructed

Deposits constituting the ground to be reconstructed are mainly composed of a very soft clay layer of marine origin and of about 10 meters in thickness, with alluvial hard clay and sand soil distributed beneath it.

(ii) Construction history of piling structure and sewers

Subsidence of the piling structure placed on such ground after the sewers laid underground proceeded as

shown in FIG. 16, and the amount of subsidence of the piling structure reached about 170 centimeters about six years after piling. At this time, the amount of subsidence of the sewers exceeded the allowable amount of subsidence of 20 centimeters, posing a serious obstacle to the function of sewerage and the structure of the sewers.

(iii) Estimation of effect on ground improvement

The results of effect of the inventive method on low piling structures are concisely illustrated in FIGS. 17 and 18, from which it is found that the effect on ground improvement was achieved as initially planned.

Never until now was any subsidence observed. It is also observed that the sewers are neither damaged nor deformed. In the meantime, the ground was hit by earthquakes having a seismic intensity of 3 to 4, but was kept in good condition.

Example 4 - Clay of river origin

One example of this inventive method is explained, wherein the inventive method is applied to soft ground composed of clay of river origin, on which a high piling structure of 4.0 meters is placed to construct a railway.

(i) The nature of the soil constituting the ground to be reconstructed

Deposits constituting the ground to be reconstructed form a very soft ground layer of about 4.8 meters in thickness and composed mainly of clay of river origin, beneath which there is a layer composed of a gravel-containing sand layer having a relatively high density.

(ii) Construction history of piling structure and sewers

A sand mat of 0.4 meters in thickness was placed on ground, and a first piling structure having a critical height of 1.5 meters was laid on the sand mat. After the lapse of 22 days during which they were allowed to stand, the ground was reconstructed by the inventive method and, in three days later during which the ground was let alone, a second piling structure of 2.5 meters in height was laid on the ground. In this way, the ground was rapidly reconstructed within a total period of 27 days.

(iii) Effective soil covering pressure, consolidation yield stress and pre-consolidation stress profiles of the original ground and piling structure

As the consolidation yield stress of the original ground is larger than the effective soil covering stress, as shown in FIG. 19, the piling structure remains unconsolidated because its soil covering stress is lower than its effective soil covering stress, although the orig-

inal ground is an over-consolidated clay layer.

Thus, the consolidation yield stress (pre-consolidation stress) of the ground to be reconstructed is distributed in a pre-consolidation region lying above the profile line of the effective soil covering stress due to the piling loads, so that the ground can be stable with respect to both the loads produced by these piling structures and both the vibration loads produced by railway trains.

(iv) Estimation of the ground reconstructed or improved

Concisely shown in FIGS. 19, 20 and 21 are the results the stability of the piled ground for railway tracks, which was obtained by the application of the inventive method to clay of river origin. From these figures, it is found that the effect on ground improvement is achieved as initially planned.

Never until now is any subsidence observed. The ground has been stable with respect to earthquakes having a seismic intensity of 3 to 5.

In terms of undrained shearing strength, the grounds before and after reconstruction are compared with each other. The undrained shearing strength is $C_u = 1.2$ to 2.2 for the original ground, $C_u = 2.1$ to 2.6 for the piled ground, and $C_u = 2.7$ to 5.0 for the ground reconstructed according to the inventive method.

On the other hand, the compressibility of the original ground and piling structure are $P_c < 10$ tf/m² while the consolidation yield stress of the reconstructed ground is $P_c' > 10$ to 18 tf/m², indicating that apparent improvements in both strength and compressibility are obtained.

Claims

1. A method of stabilizing soft ground comprises injecting the ground with material according to predetermined parameters characterised in that a value is derived by plotting a stress profile of the ground and said profile is used as a reference for supplying the material so that said ground to be reconstructed in situ is subjected to a single concurrent operation involving four principles for reconstruction of soft ground being (1) consolidation and dehydration, (2) drainage, (3) solidification and (4) replacement whereby rapid ground stabilization is achieved and deformation and displacement of surrounding ground layers or structures built thereon is curtailed.
2. A method as claimed in Claim 1 characterised in that the method includes the step of piling and the said profile includes reference to a piling height.
3. A method as claimed in Claim 1 or Claim 2 characterised in that the said parameters include a strength property C_u' of the ground in the range $C_u' > 2.0$ to 3.0 tf/m² in a non-seismic state and $C_u' > 3.0$ to 4.0 tf/m² in a seismic state.

4. A method as claimed in any one of the preceding claims characterised in that the said parameters include, in the case of a general piling structure, a consolidation yield stress P_c' of the ground in the range $P_c' > 5$ to 10 tf/m² for clay of marine origin and clay of river origin and $P_c' > 4$ to 7 tf/m² for peat and humus soil and, in the case of ground subjected to traffic loads and seismic loads, a consolidation yield stress P_c' in the range $P_c' > 11$ to 20 tf/m² for clay of marine origin and clay of river origin and $P_c' > 7.5$ to 10 tf/m² for peat and humus soil.

5. A method as claimed in any one of the preceding claims characterised in that the said parameters include strength property C_u' and the consolidation yield P_c' of the reconstituted ground as follows:-

$$C_u' = C_u + m (P_c' - P_c)$$

$$P_c' = (C_u' - C_u + m \times P_c)/m$$

where:

C_u is shearing strength in tf/m² of the original ground,

C_u' is shearing strength in tf/m² of the reconstituted ground,

P_c is consolidation yield stress in tf/m² of the original ground,

P_c' is consolidation yield stress in tf/m² of the reconstituted ground and

m is a percentage of strength increase, provided that $m = 0.39$ to 0.42 for peat or humus soil, $m = 0.21$ to 0.39 for clay of marine origin and $m = 0.18$ to 0.21 for clay of river origin.

FIG. 1

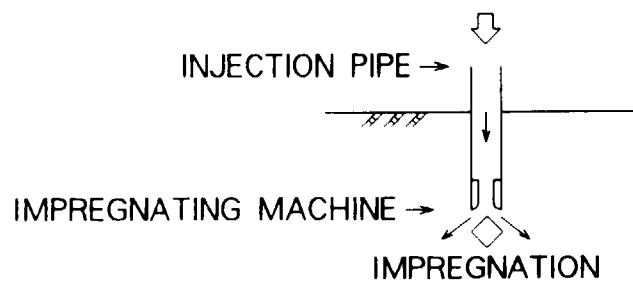


FIG. 2

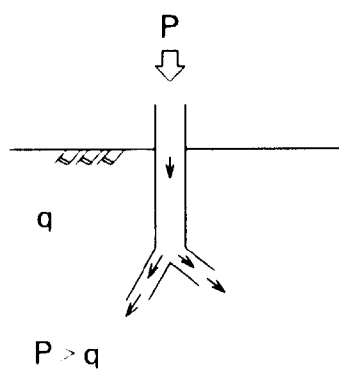


FIG. 3

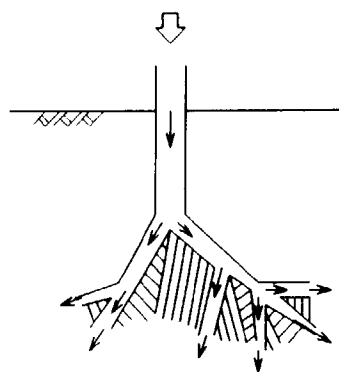


FIG. 4

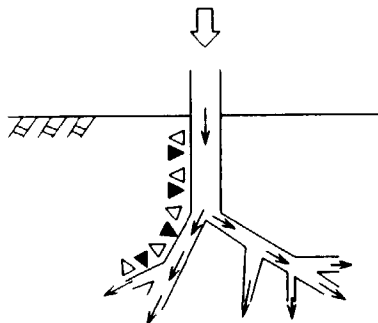


FIG. 5

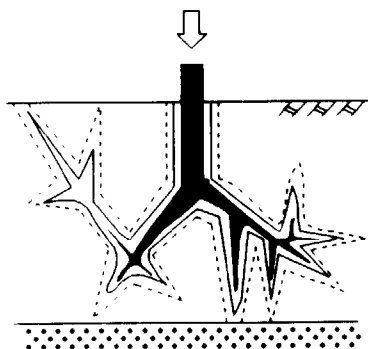


FIG. 6

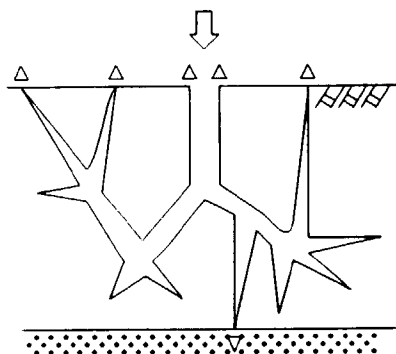
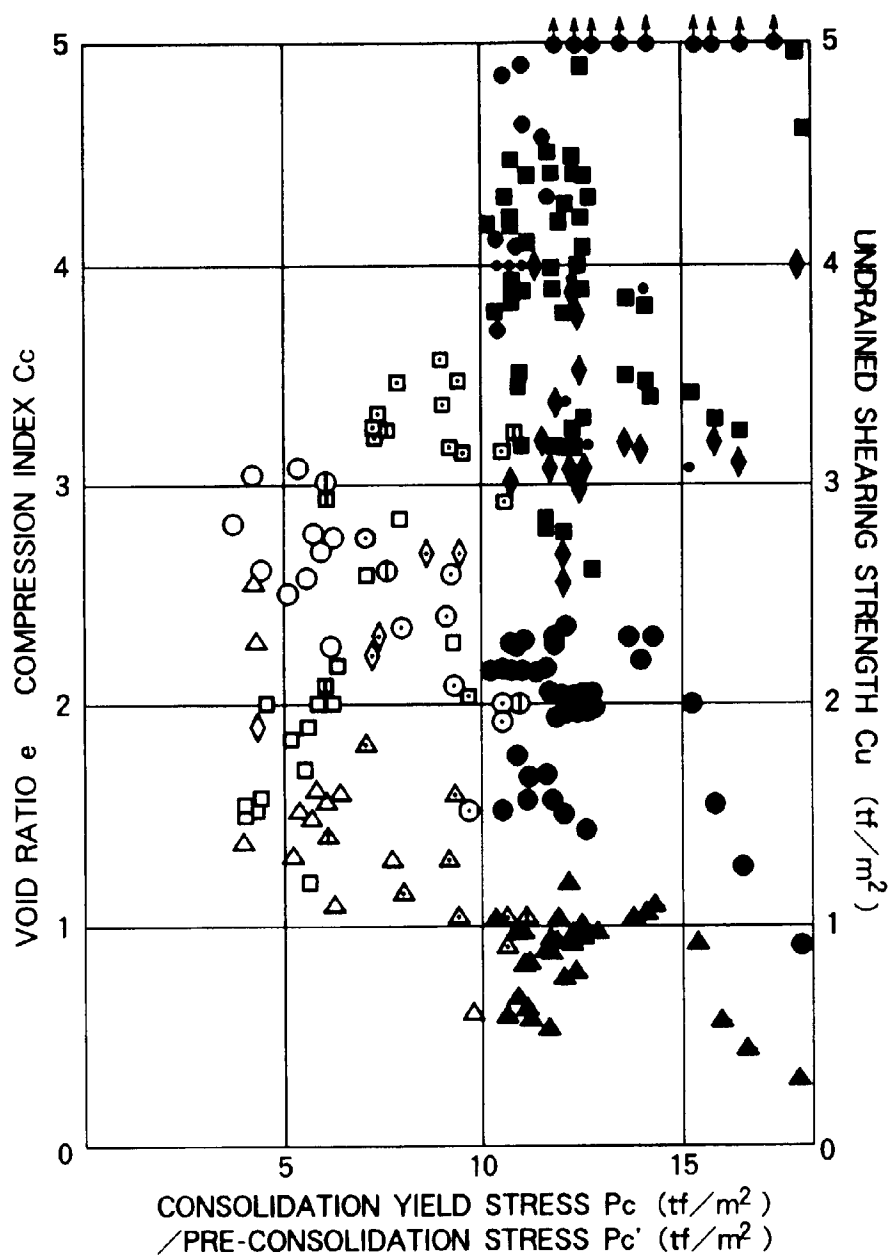


FIG. 7



ORIGINAL GROUND	PILING METHOD	SAND DRAINAGE METHOD	INSTANTANEOUS CONSOLIDATION METHOD BY IMPREGNATION OF GROUND	SOIL CONSTANT
○	⊙	⊖	●	VOID RATIO (e)
△	⊠	⊡	▲	COMPRESSION INDEX (C_c)
□	⊞	⊢	■	UNIAXIAL COMPRESSION TEST ($C = \frac{q_u}{2}$)
◇	⊠		•	UNIFACE SHEAR TEST (UU)
			◆	TRIAXIAL COMPRESSION TEST (UU)
			●	VANE SHEAR TEST

8. G. F.

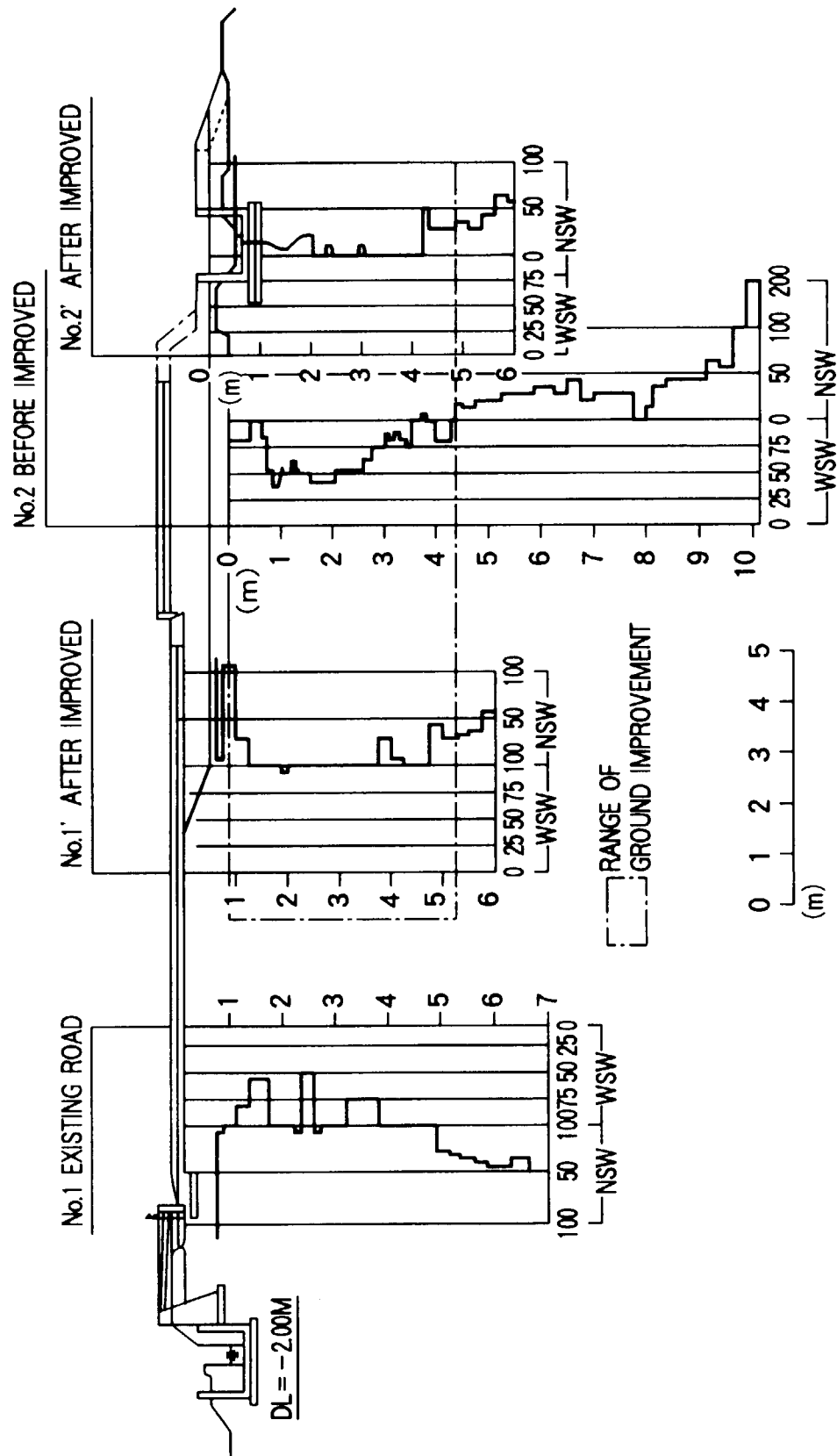
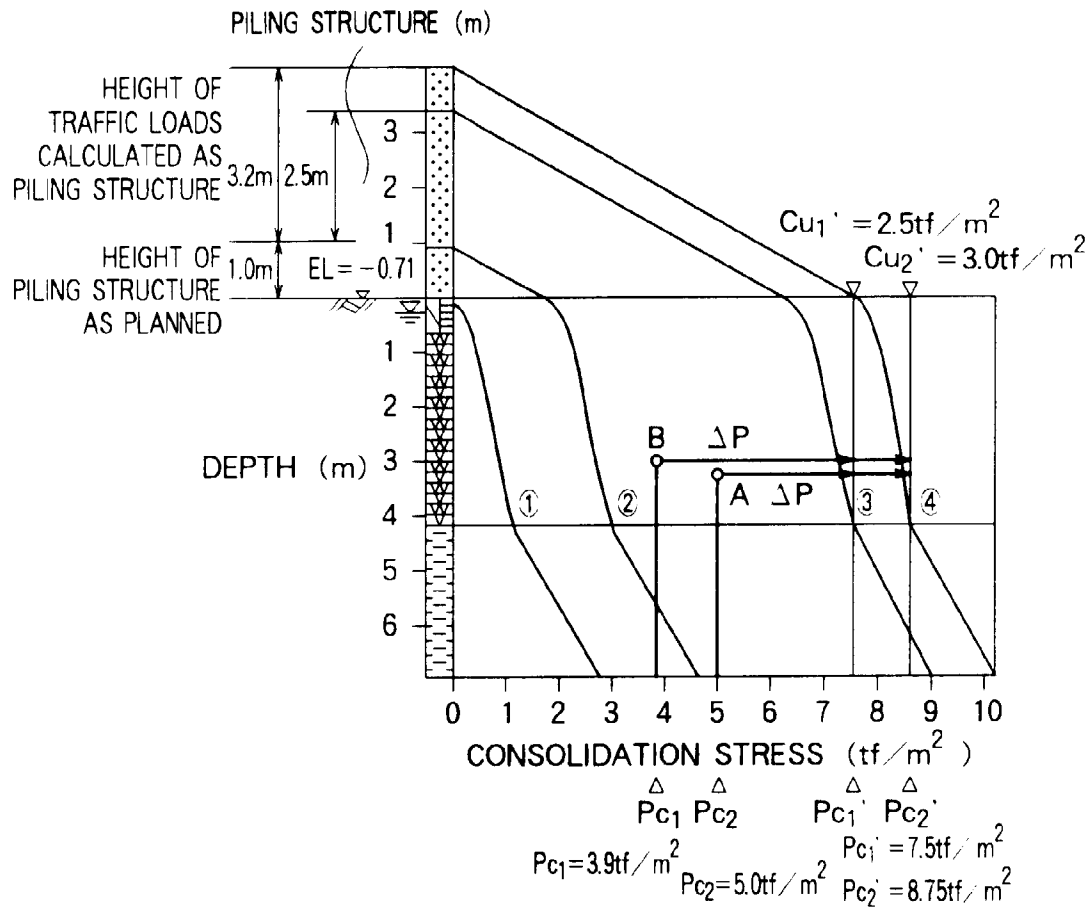


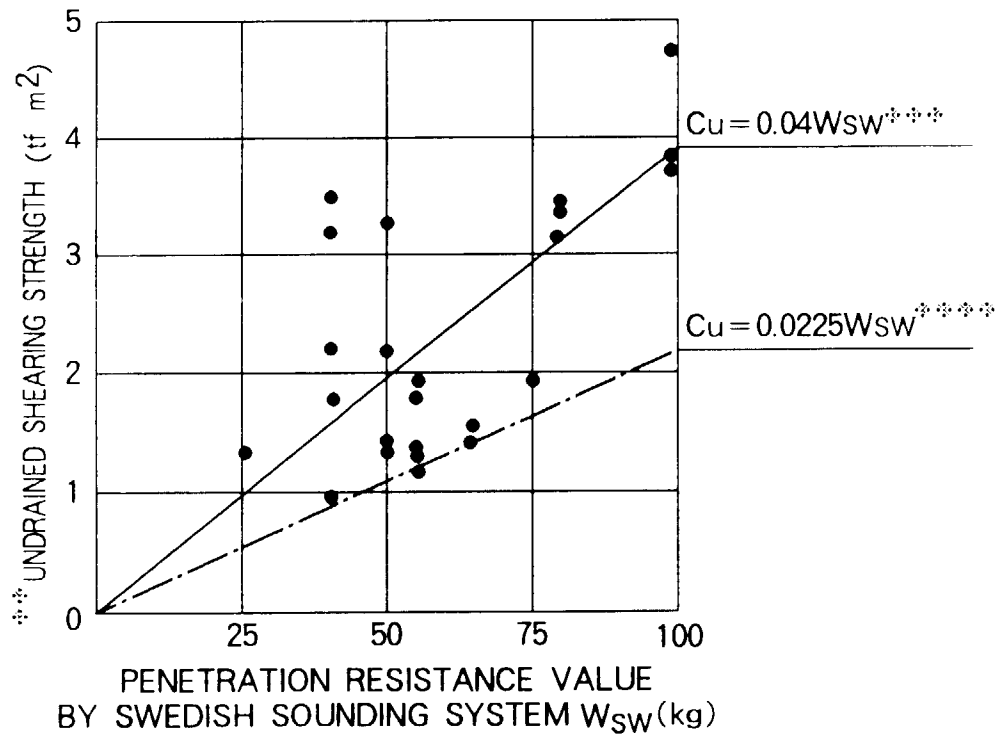
FIG. 9



	NATURE OF THE SOIL	UNIT VOLUME WEIGHT	
		ABOVE GROUND WATER LEVEL	BELOW GROUND WATER LEVEL
	PILING STRUCTURE (MEDIUM SAND)	1.8	
	SURFACE SOIL (SAND SOIL TO VISCOUS SOIL)	1.5	0.5
	PEAT TO ORGANIC SOIL	1.2	0.2
	SILT TO SAND SOIL	1.6	0.6

- ① EFFECTIVE SOIL COVERING STRESS OF THE ORIGINAL GROUND
- ② EFFECTIVE SOIL COVERING STRESS OF PILING STRUCTURE AS PLANNED HEIGHT
- ③ EFFECTIVE SOIL COVERING STRESS OF PILING STRUCTURE AT PLANNED HEIGHT, CALCULATED AS TRAFFIC LOAD HEIGHT ($Cu' = 2.5\text{tf}/\text{m}^2$)
- ④ EFFECTIVE SOIL COVERING STRESS OF PILING STRUCTURE AT PLANNED HEIGHT, CALCULATED AS TRAFFIC LOAD HEIGHT ($Cu' = 3.0\text{tf}/\text{m}^2$)
- CONSOLIDATION YIELD STRESS OF THE ORIGINAL GROUND

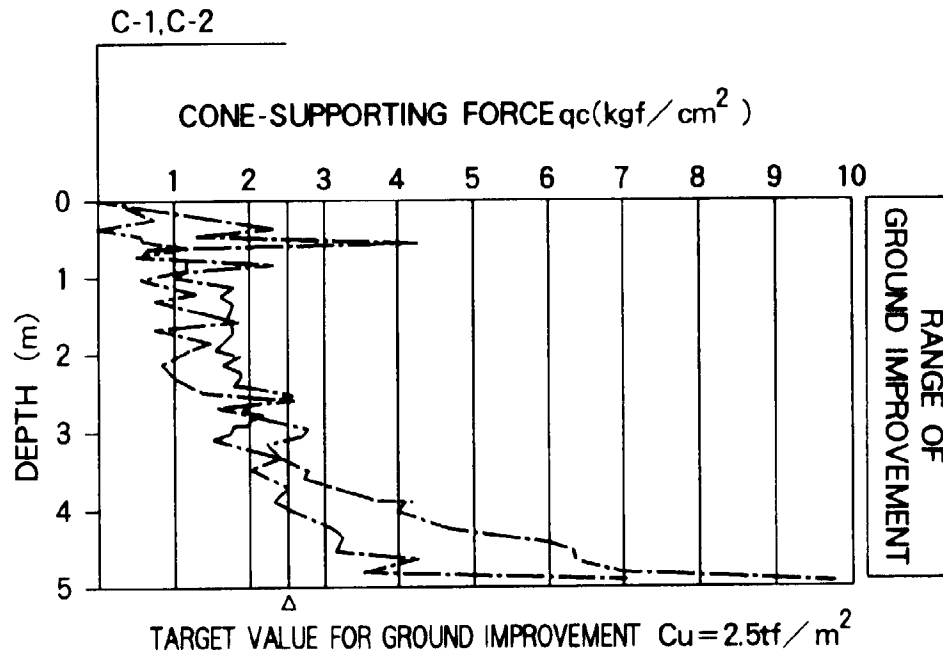
FIG. 10



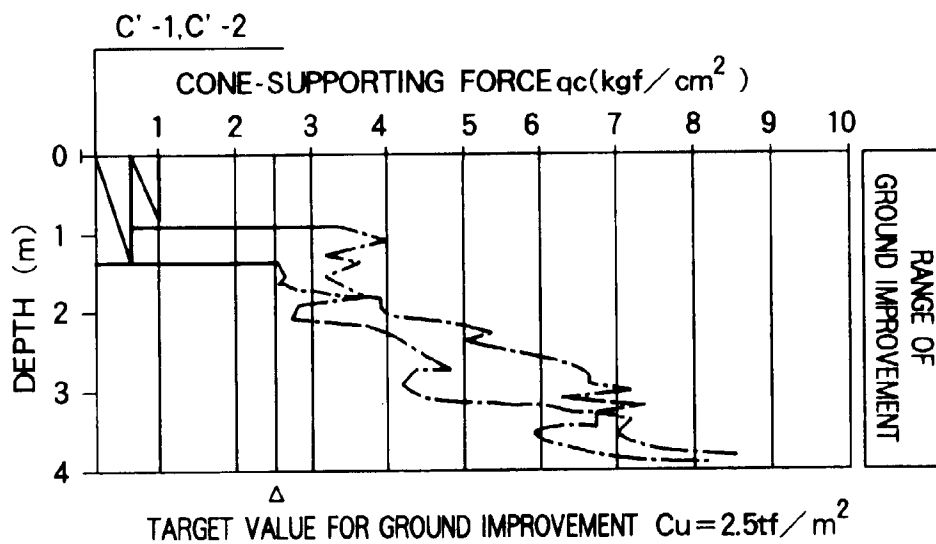
1. GROUND AFTER IMPROVED BY THE INVENTIVE EXAMPLE
2. UNDRAINED SHEARING STRENGTH MEASURED BY VANE SHEAR TEST
3. C_u TO W_{sw} RELATION FOR THE GROUND AFTER IMPROVED
(EMPIRICAL RELATION OBTAINED IN THE INVENTIVE EXAMPLE)
4. C_u TO W_{sw} RELATION FOR THE GROUND BEFORE IMPROVED
(FOUND ACCORDING TO THE SOIL INVESTIGATION METHOD
PRESCRIBED BY THE ASSOCIATION OF SOIL ENGINEERING)

FIG. 11

(1) BEFORE GROUND IMPROVEMENT



(2) AFTER GROUND IMPROVEMENT



□ IS DEPTH TO WHICH THE GROUND WAS DRILLED OR BORED
FOR PILING SAND, SURFACE SOIL,
AND IMPREGNATION MATERIAL

FIG. 12

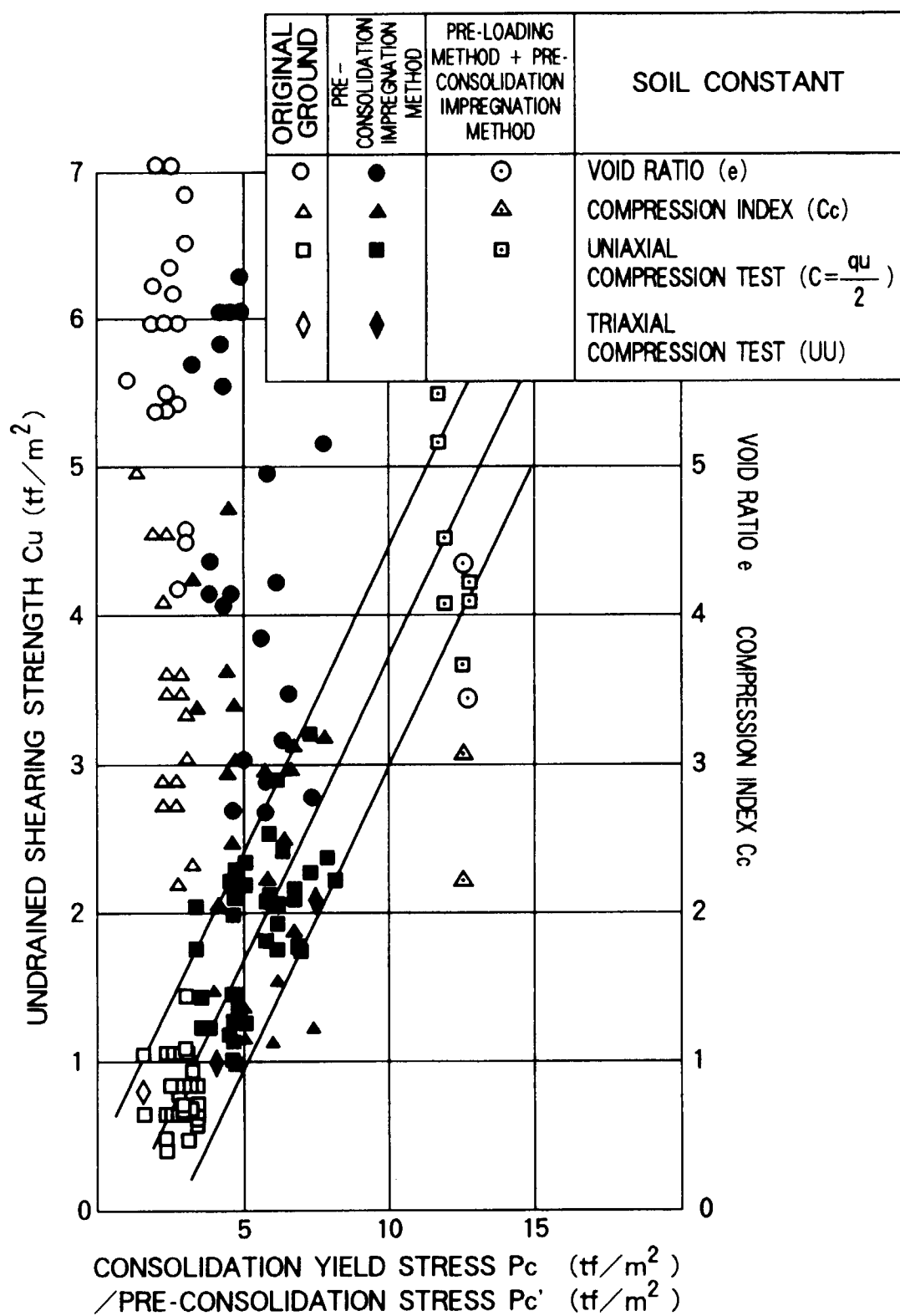


FIG. 13

(1) TARGET VALUE FOR GROUND IMPROVEMENT $Cu' = 2.5tf/m^2$ (MEAN VALUE)

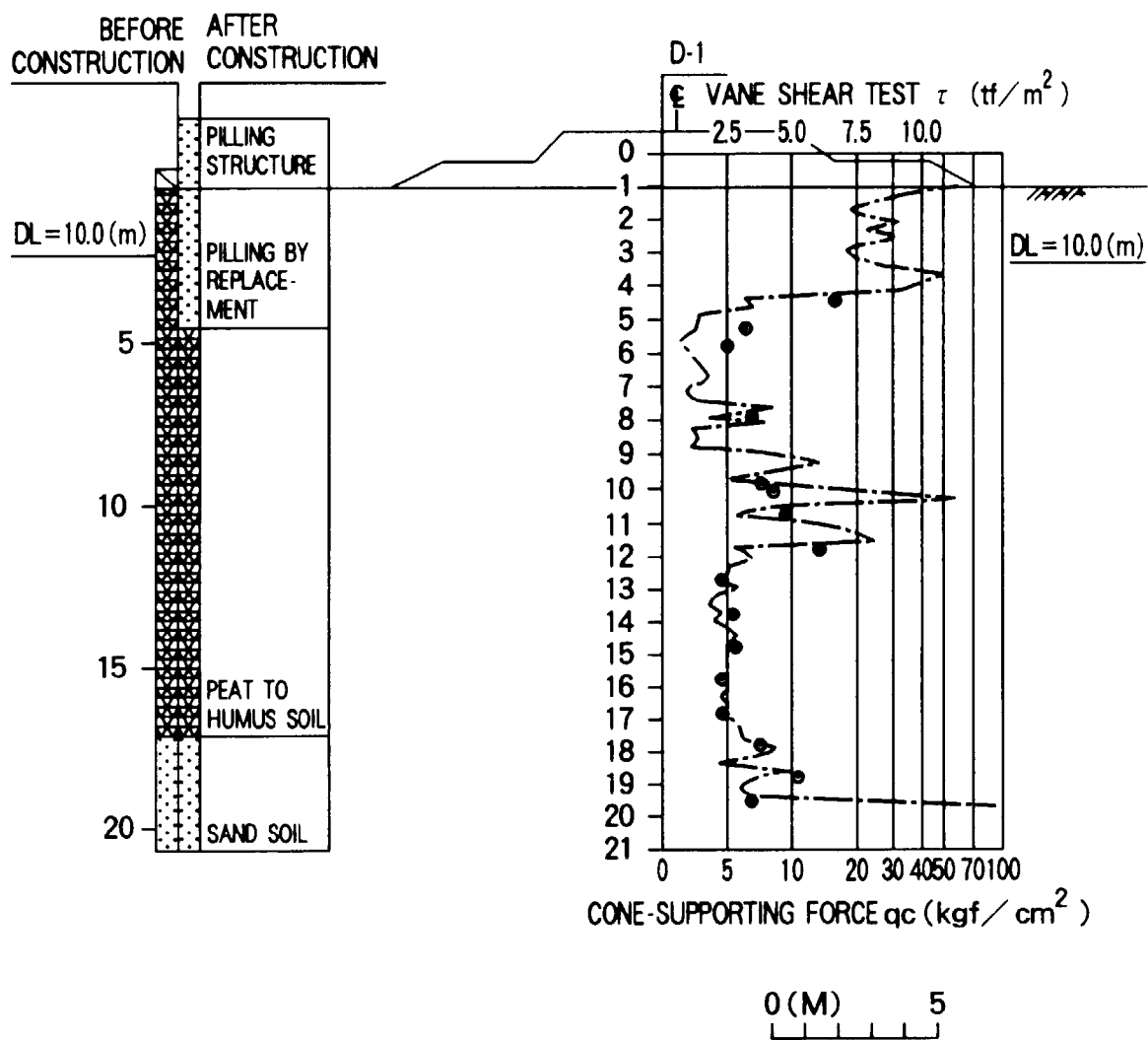


FIG. 13

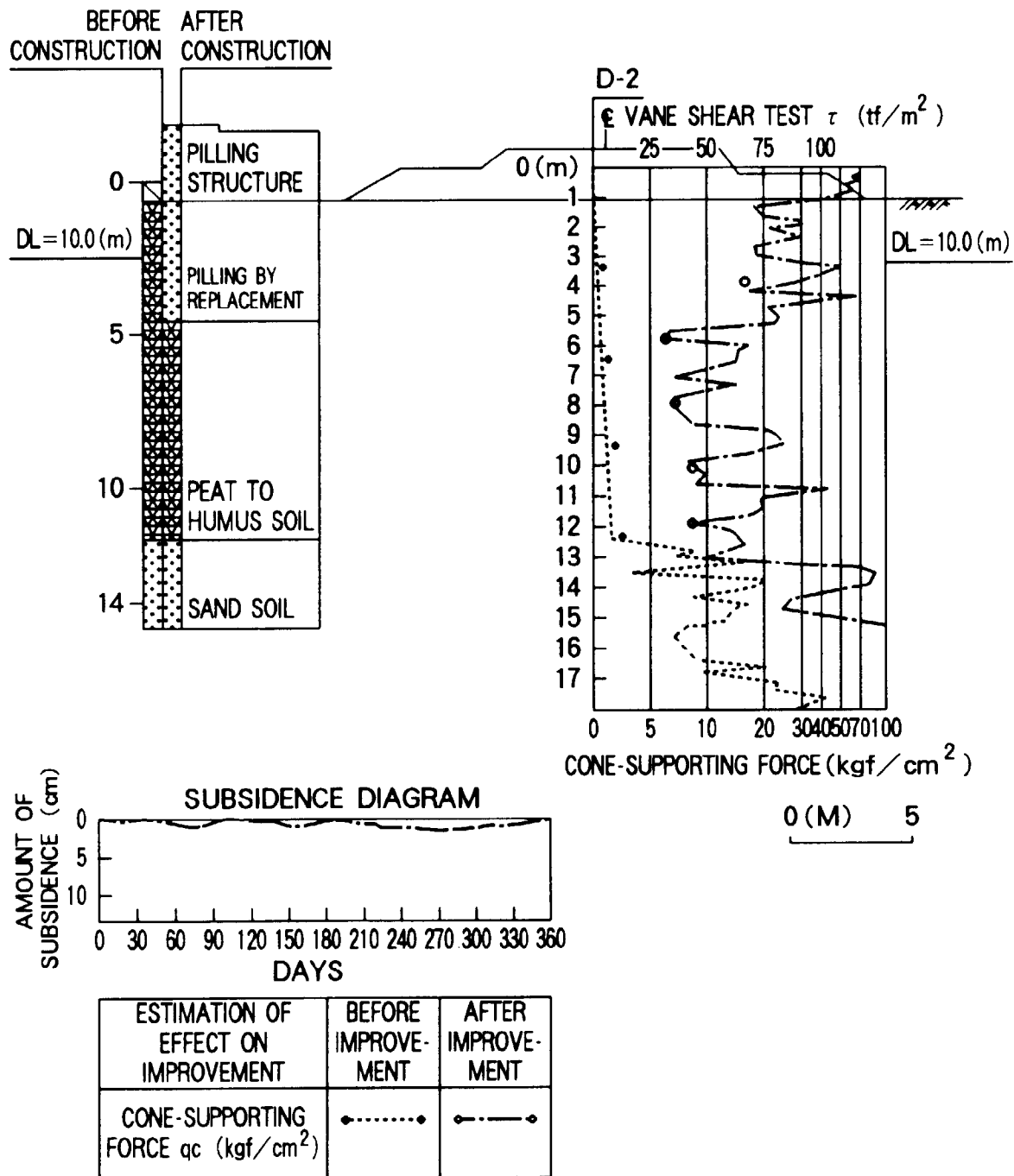
(2) TARGET VALUE FOR GROUND IMPROVEMENT $Cu' \geq 3.0tf/m^2$ 

FIG. 14

(1) BEFORE GROUND IMPROVEMENT

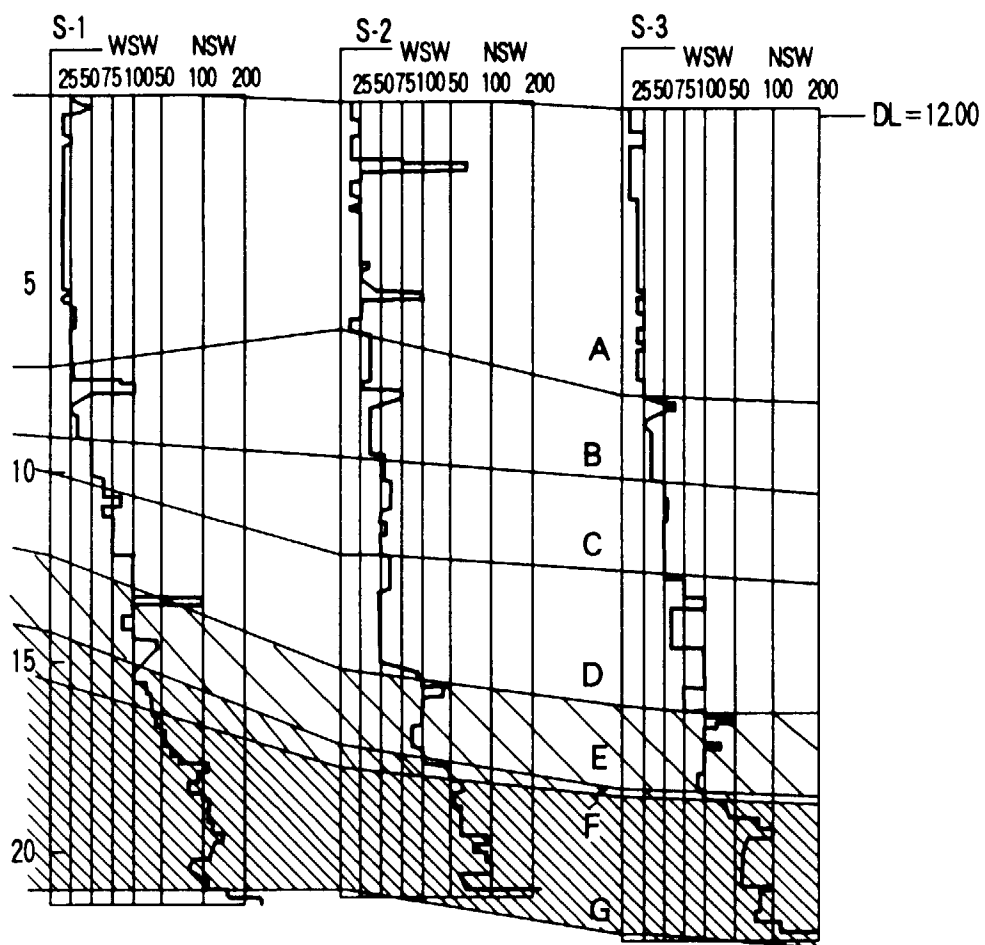


FIG. 14

(2) AFTER GROUND IMPROVEMENT

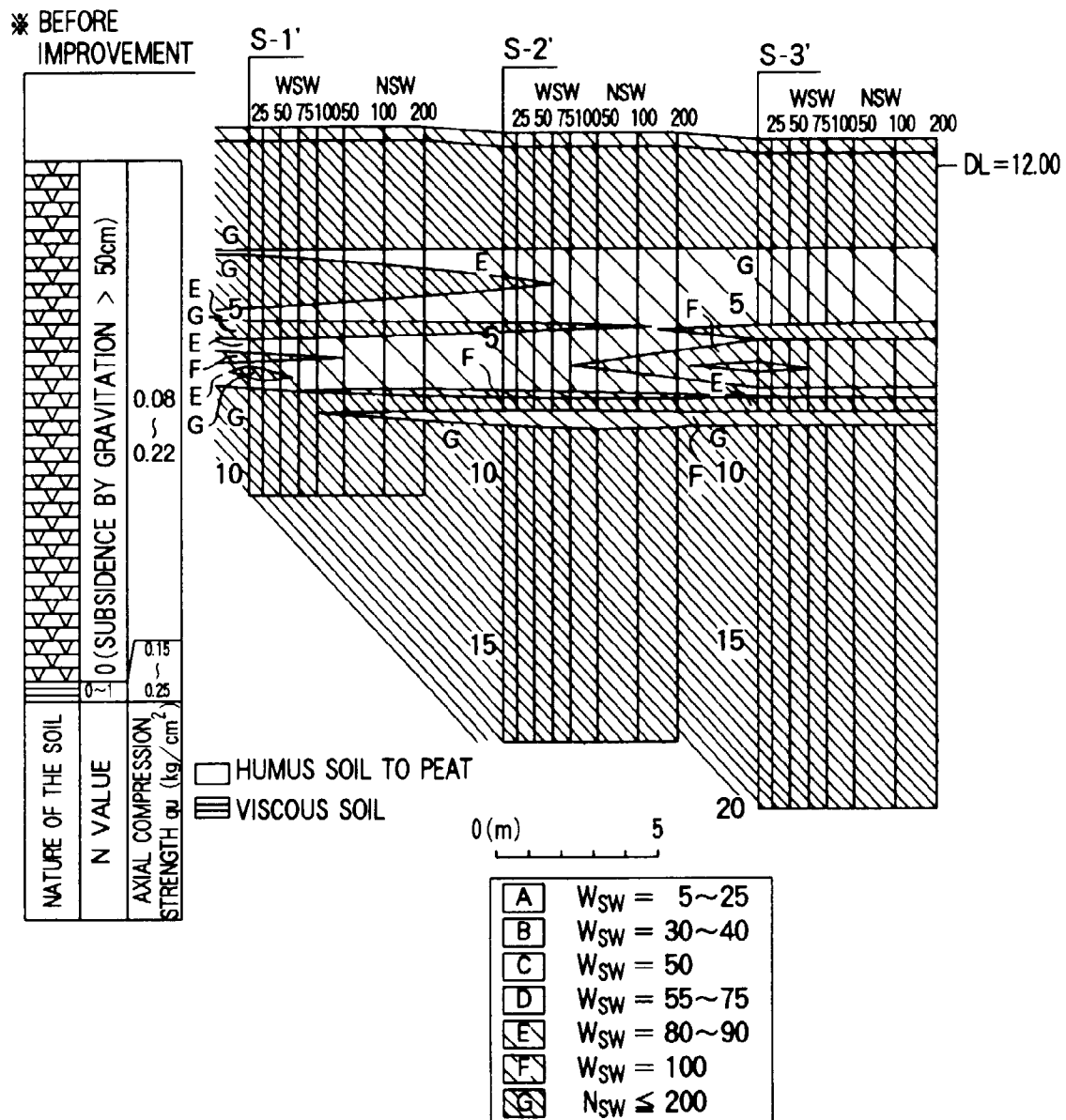


FIG. 15

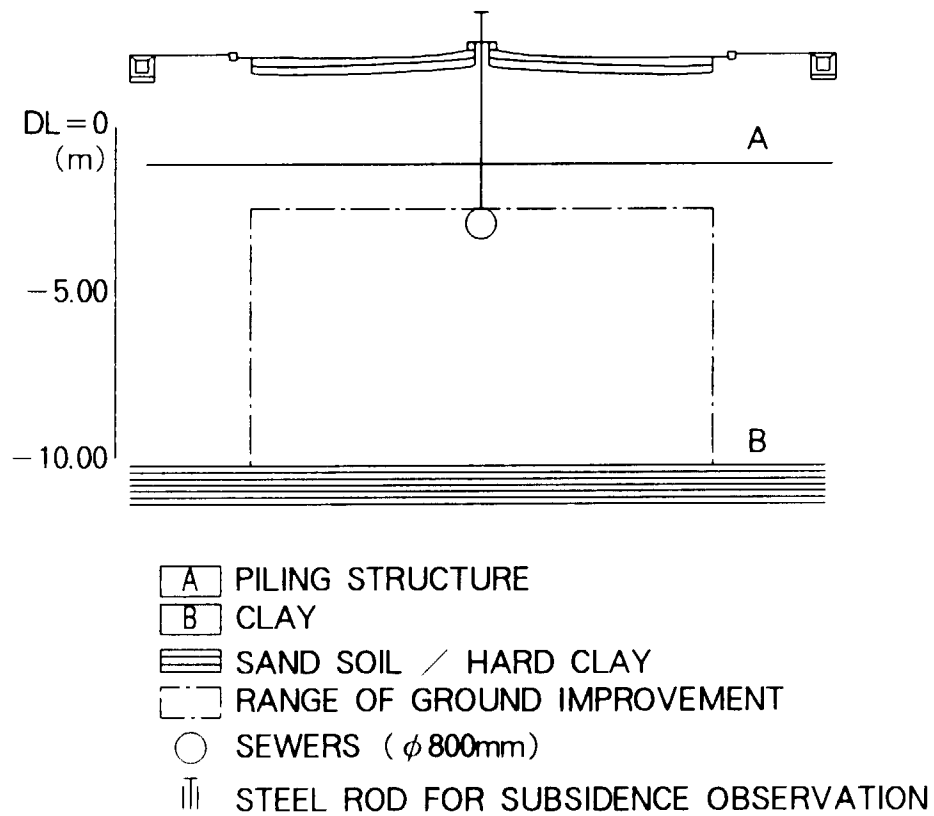
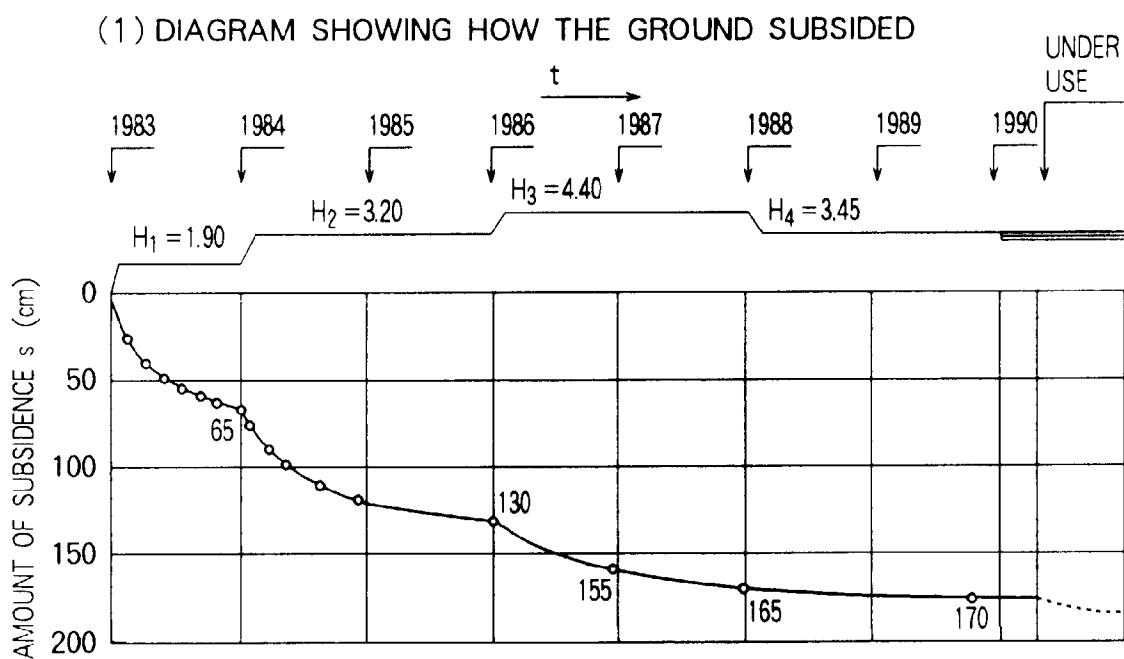


FIG. 16



(2) DIAGRAM SHOWING HOW SEWERS SUBSIDED

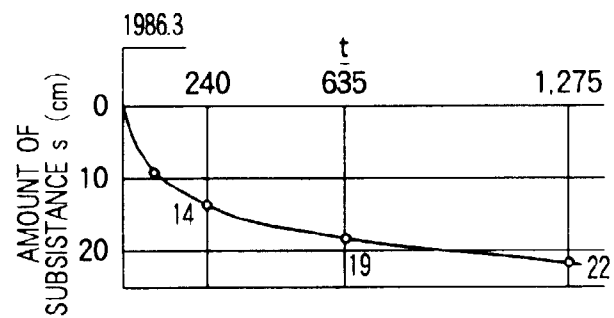
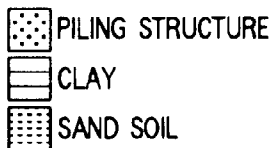
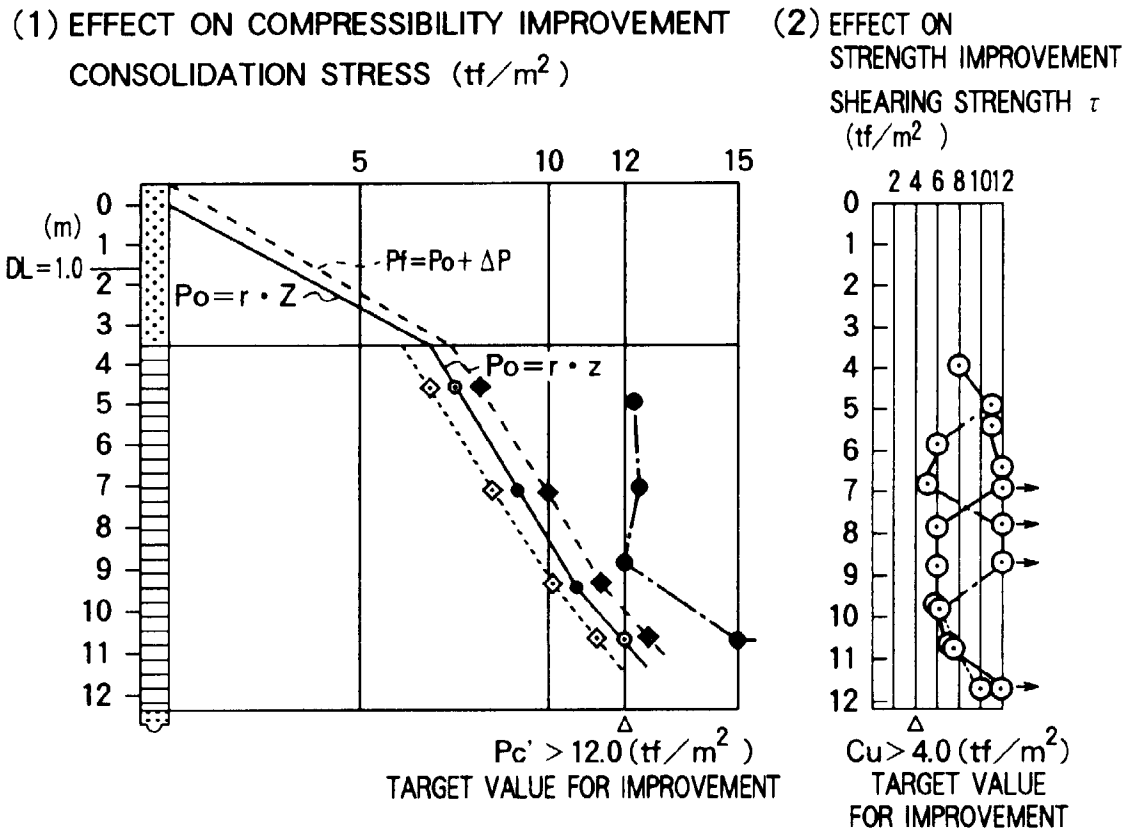
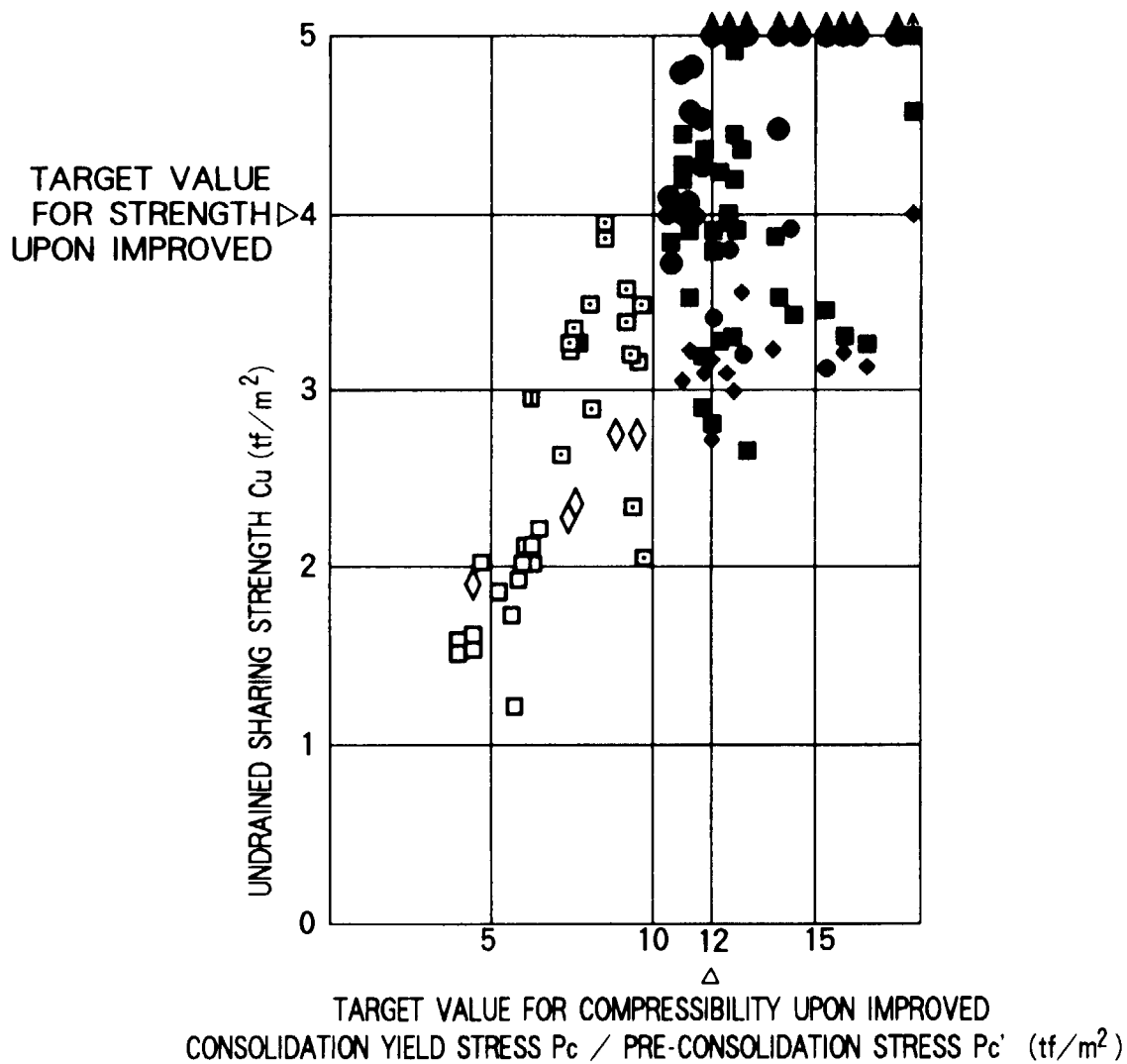


FIG. 17



- ◇ CONSOLIDATION YIELD STRESS BEFORE PILING P_c
 ○ EFFECTIVE SOIL COVERING PRESSURE AFTER PILING P_o
 ◆ EFFECTIVE SOIL COVERING PRESSURE UNDER USE P_f
 ● CONSOLIDATION YIELD STRESS (PRE-CONSOLIDATION STRESS) AFTER GROUND IMPROVEMENT P_c'
 ⊙ SHEARING STRENGTH BY VANE SHEAR TEST

FIG. 18



ORIGINAL GROUND	PILING METHOD	SAND DRAINAGE METHOD	INSTANTANEOUS CONSOLIDATION METHOD BY IMPREGNATION OF GROUND	SOIL CONSTANT
□	□	▣	■	UNIAXIAL COMPRESSION TEST ($C = \frac{q_u}{2}$)
◇			●	UNIFACE SHEAR TEST (UU)
			◆	TRIAXIAL COMPRESSION TEST (UU)
			●	VANE SHEAR TEST (τ)

FIG. 19

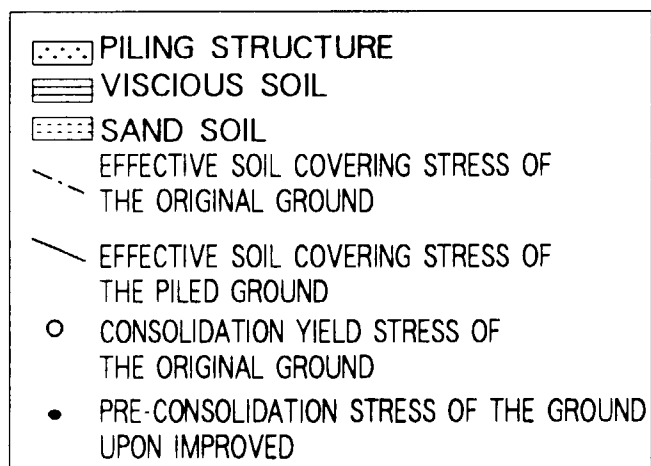
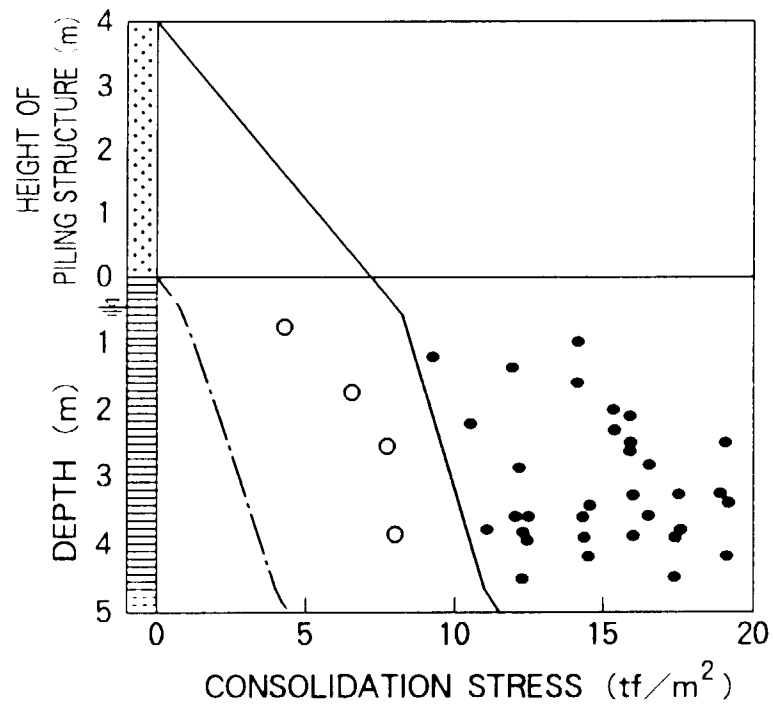
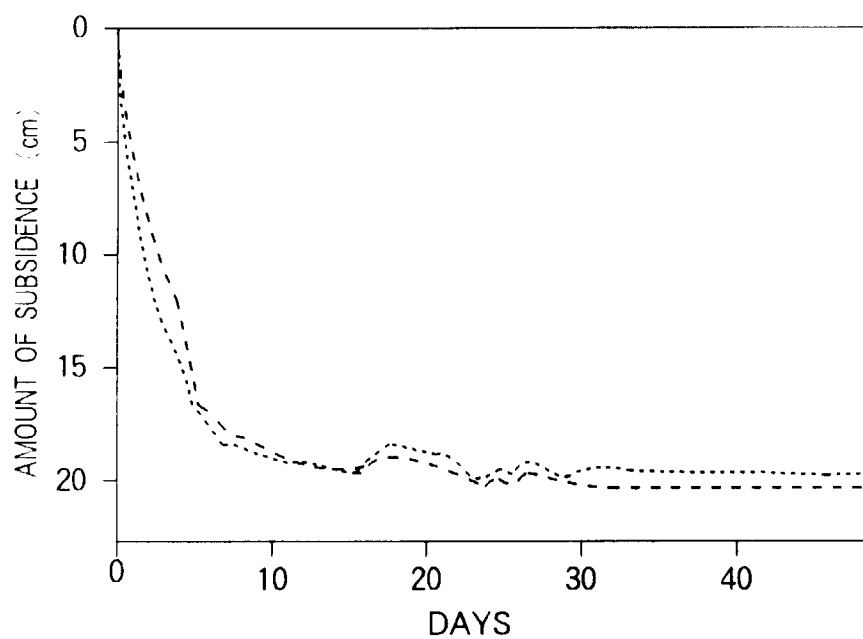
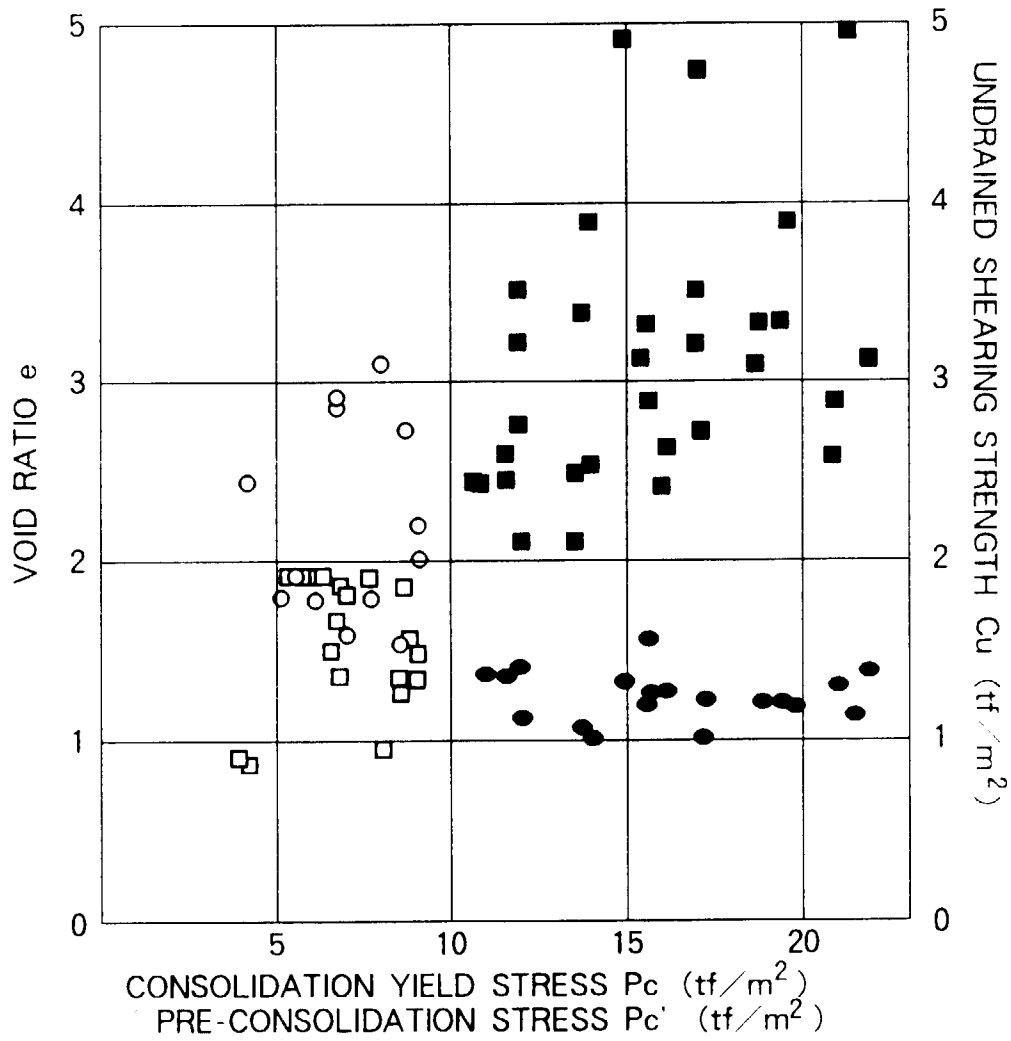


FIG. 20



HISTORY	FIRST PILING 1.5m
	PERIOD FOR WHICH THE GROUND WAS ALLOWED TO STAND
	IMPREGNATION OF GROUND
	PERIOD FOR WHICH THE GROUND WAS LET ALONE
	SECOND PILING 2.5m
PERIOD FOR OBSERVATION	

FIG. 21



- VOID RATIO OF THE ORIGINAL GROUND
- VOID RATIO OF THE GROUND UPON IMPROVED
- UNDRAINED SHEARING STRENGTH OF THE ORIGINAL GROUND BY UNIAXIAL COMPRESSION TEST
- UNDRAINED SHEARING STRENGTH BY UNIAXIAL COMPRESSION TEST OF THE GROUND UPON IMPROVED



European Patent
Office

EUROPEAN SEARCH REPORT

Application Number
EP 96 30 8190

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
Y	US 4 540 316 A (TAKAHASHI YUICHIRO) 10 September 1985	1	E02D3/12
A	* column 3, line 54 - column 7, line 27; figures 1-4 *	2-5	

Y	GB 2 258 670 A (NIT CO LTD ; NAKASHIMA SHIRO (JP)) 17 February 1993	1	
A	* column 3, line 61 - column 9, line 37; figures 1-9 *	2-5	

A	CIVIL ENGINEERING, no. 12, December 1987, NEW YORK, USA, pages 66-68, XP002025905 JASPERSE & RYAN: "geotech import : deep soil mixing"	1-4	

			TECHNICAL FIELDS SEARCHED (Int.Cl.6)
			E02D
The present search report has been drawn up for all claims			
Place of search		Date of completion of the search	Examiner
THE HAGUE		21 February 1997	Tellefsen, J
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