# United States Patent [19]

**Menard**

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[54] **METHOD OF COMPACTING MADE-UP GROUND AND NATURAL SOIL OF MEDIOCRE QUALITY**


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**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 183,397, Sept. 24, 1971, abandoned.

[52] **U.S. Cl.** ..... **61/35;** 404/75; 404/115

[51] **Int. Cl.**[2] ..... **E02D 3/04**

[58] **Field of Search** ..... 61/35, 36, 63, 50; 404/133, 75, 115



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[57] **ABSTRACT**

A method of consolidating damp foundation soil, e.g., natural or synthetic clay or silt alone or mixed with sand, includes a number of cycles each including a dynamic force phase in which dynamic superimposed loads of at least 500 to 10,000 tons are applied to the soil to fluidize it, and a rest phase, possibly several days, during which the interstitial water escapes and the soil is restructured. Optimum parameters are ascertained by the use of a model testing rig comprising an expansible chamber to contain a sample of the soil, and means for applying static and dynamic pressure to the contents and measuring the relevant parameters.


**7 Claims, 4 Drawing Figures**

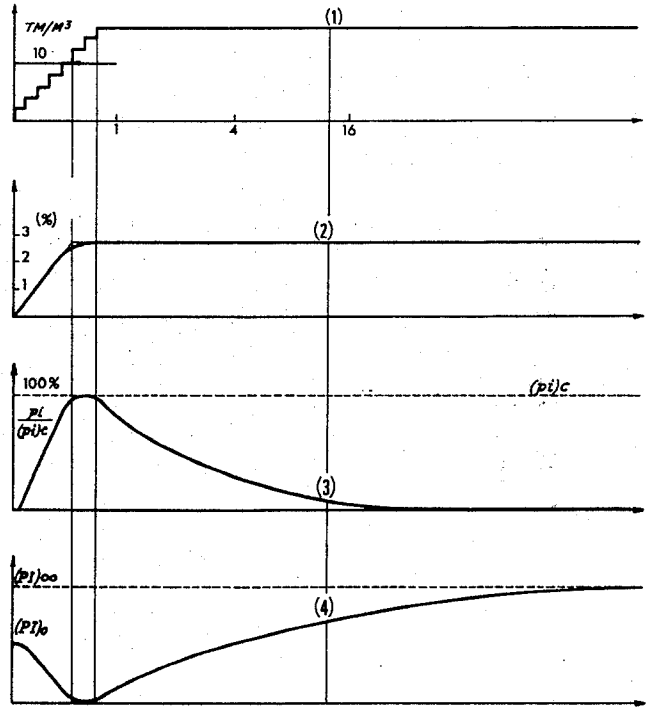


FIG. 1

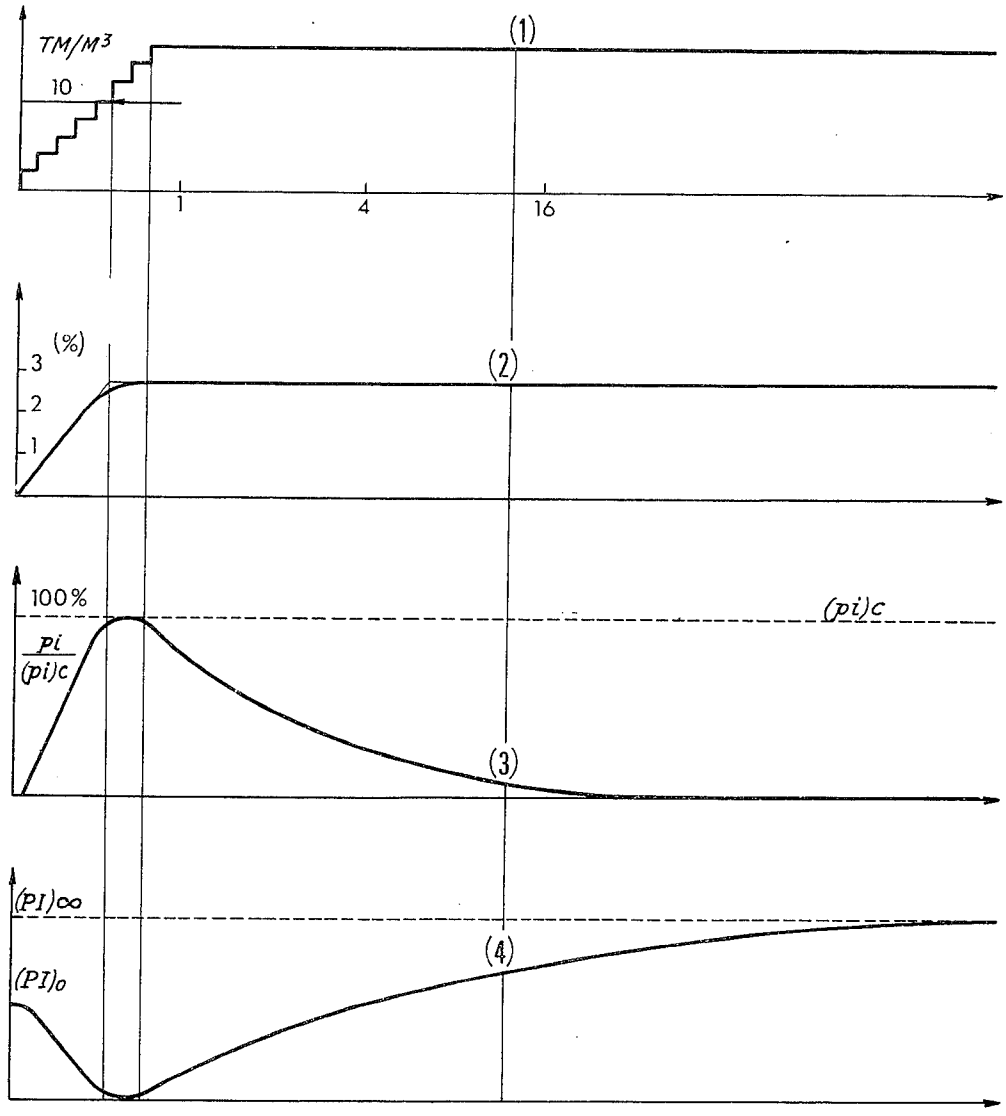


FIG. 2

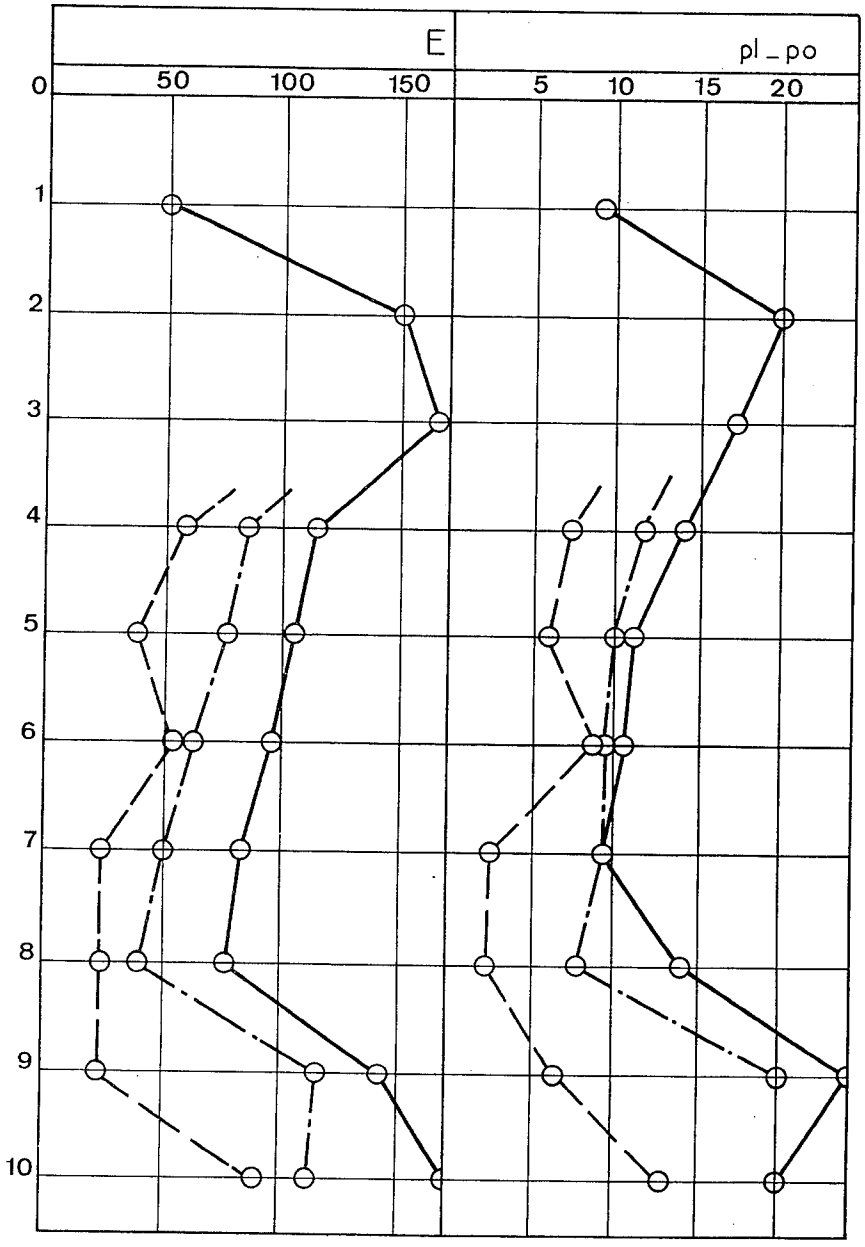
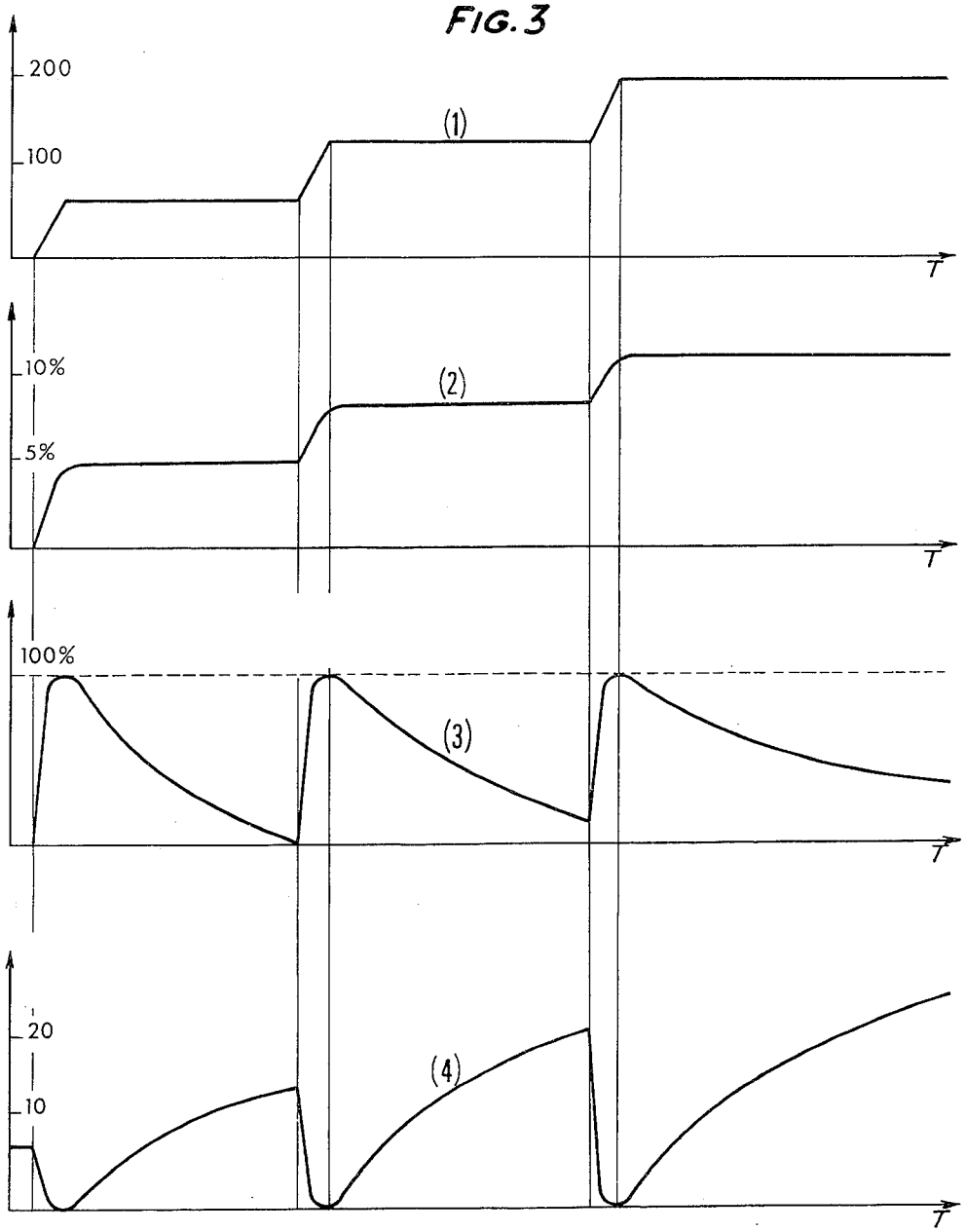


FIG. 3



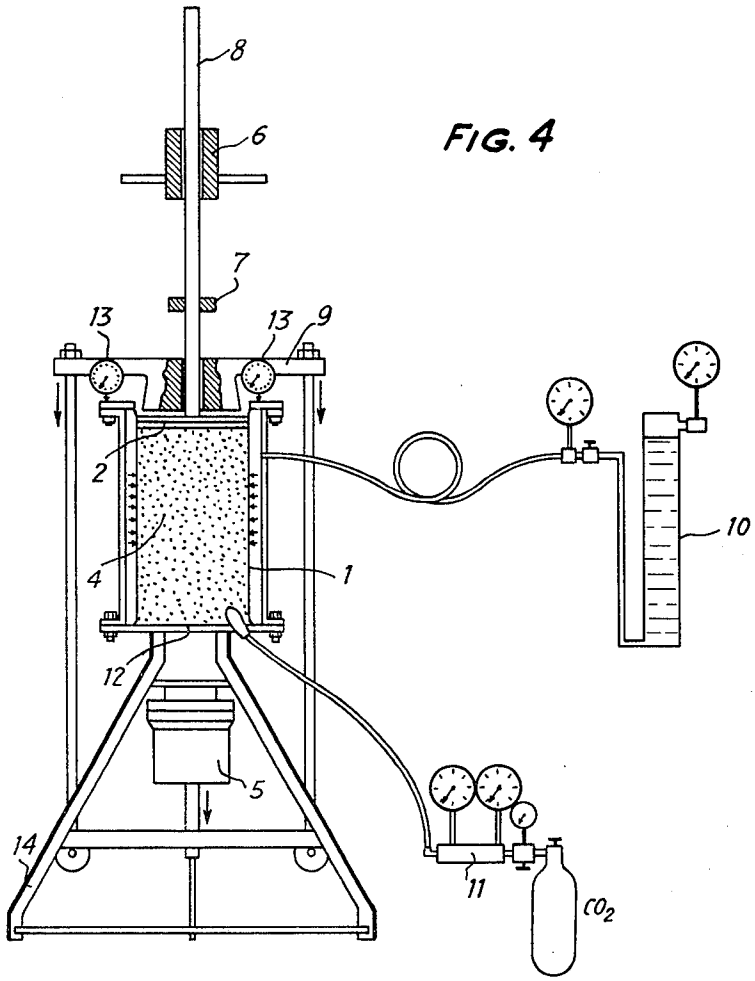



FIG. 4

# METHOD OF COMPACTING MADE-UP GROUND AND NATURAL SOIL OF MEDIOCRE QUALITY

This application is a continuation-in-part of copending application Ser. No. 183,397, filed Sept. 24, 1971, now abandoned.

The invention relates to the consolidation of soil to a great depth, so that it can be used as foundation soil.

An object of the invention is to provide a method for very considerably increasing the density and bearing capacity of a foundation soil, the method being particularly applicable to the consolidation of soil which it is thought impossible to compact, e.g., clay or clay and sand or silt, the consolidation being to a great depth, which is particularly important for virgin soil and under-water embankments.

When the soil is soft, the foundations are generally constructed on piles, allowing for super-imposed loads due to negative friction (the action of the embankment on the pile shaft). These methods are relatively expensive for relatively light structures (buildings less than five stories high) or widely distributed structures such as factories. They are also difficult (e.g. the junction between the structure on piles and any slabbing borne by the embankment).

In many cases, the embankment is made of materials having good intrinsic properties (e.g., broken stones, sand, etc.) and their unfavorable behavior (e.g., high compressibility and low bearing capacity) is due mainly to a lack of density and to the presence of voids.

The quality of an existing embankment can be improved in known manner by moving static or vibrating compaction rollers or heavy excavating machinery over the embankment. Unfortunately, owing to the small weight of the roller (10 to 50 tons), compaction is negligible beyond a depth of 50 to 90 cm, and, in order to obtain appropriate results, the embankment has to be completely excavated and replaced in **30** to **90** cm layers, each of which is compacted successively (a method used in road construction or earth dams). This method is unsuitable for existing embankments or for embankments in process of construction by dumping into water (e.g., blocking up a sand-pit after use, or embankments for rivers and more particularly seas).

The invention is based on the efficient use of a complex phenomenon, and comprises simultaneously fluidizing the soil in the mass and exerting very considerable dynamic forces at its surface.

A soil is fluidized when its solid structure is so destroyed that the material behaves like a suspension of particles in a liquid phase (water). Hitherto, this phenomenon has resulted from chance natural causes (e.g., earthquakes) or artificial causes (e.g., building operations) and has been considered completely undesirable, with the result that the soil would be abandoned and considered unsuitable for any subsequent use as a foundation soil.

After systematic research and tests, it has now been discovered on the contrary that fluidization, if brought about efficiently and in controlled manner, may provide a very effective method of consolidating soil, more particularly clay, clay and sand, or silt and sand.

The method has two characteristic features, the first relating to the energies used during the method and the second relating to the sequence of the operations in the method.

According to the invention, fluidization is brought about by subjecting a great thickness of soil to considerable dynamic pressures adapted to break the solid structure thereof, i.e., usually pressures of 3 to 40 bars, which can be achieved by dynamic forces reaching values of at least 500 to 10,000 tons.



The method may comprise successive cycles, each cycle comprising an initial phase corresponding to the application of a dynamic fluidizing pressure and a subsequent rest phase for removing pore water and enabling the material to be restructured, forming a new soil which is denser and stronger than the original soil. The new soil can be either used as foundation soil after a single cycle or subjected to further cycles.

The method can produce much more rapidly a settlement which is at least equal to the settlement obtained over a long period under a static superimposed load of several bars.

In a typical embodiment of the method according to the invention, the surface of the soil to be compacted is subjected to dynamic pressures of the order of 3 to 40 bars, i.e., usually of several tens of bars, on an area of at least 1 to 10 $m^2$, so as to produce dynamic stresses of several bars, e.g., at least 2 to 5 bars, at a great depth (say 3 to 10 m) over large areas (say 10 to 40 $m^2$) and a very large volume (say 100 to 1,000 $m^3$). This corresponds to dynamic forces of 500 to 10,000 tonnes.

In each case, the skilled technician will determine the amount of pressure and the areas involved, depending on the characteristics of the soil before and during processing, and on the desired results.

To this end, a device may be used which will be described hereinafter and which also forms part of the invention.

The method, i.e., basically the production of dynamic fluidization pressures, can be worked by any appropriate means, e.g., by dropping weights on to the soil or by the use of explosives.

In the first case the weights may for example be from 6 to 50 tons and may be dropped from 6 to 20 meters.

Under these conditions, the thickness of material which can be compacted in a single layer reaches 10 to 20 meters, which is incomparably superior to known methods, which are limited to a fraction of a metre or at most to 2 meters if the largest existing static or vibrating machines are used.

In some cases the methods can be made more efficient (i.e., quicker and yielding a better result) if the top meter of soil is made of high-quality material, i.e., draining material having a high angle of internal friction, before the first cycle or during the cycles. The original soil may be used or material may be added.

One specific embodiment of the method will now be described by way of example with reference to the accompanying drawings in which:

FIGS. **1** and **2** are graphs showing the changes in material subjected to a cycle according to the method;

FIG. **3** is a graph showing changes in a soil subjected to a number of cycles according to the method; and

FIG. **4** is a diagram of a device facilitating the process according to the invention.

As indicated in FIG. **1** the method comprises one or more cycles which, or each of which, includes a dynamic force phase and a rest phase. During the dynamic force phase a number of heavy impacts are delivered to the soil to be consolidated, either by means of explosives, or by dropping a weight of between 6 and 50 tons from a height of from 6 to 20 meters. FIG. **1** shows eight such impacts, distributed over part of a

day. This phase has the effect of closing the voids until the soil is saturated with water (after five impacts in the example shown) and thereby fluidized or liquefied.

Thereafter the rest phase, which may last for several days or weeks (e.g., 2 weeks), provides an opportunity for the water to escape, allowing restructuring and consolidation of the soil.

During fluidization, the structure of the material is broken; all the intergranular stresses are taken up by the interstitial liquid, the pressure of which becomes equal to the weight of the soil above, which is usually more than double the hydrostatic value.

Fluidization occurs simultaneously with an instantaneous settlement, which depends on the particle size of the soil and its initial void ratio, but which is rarely less than 3 percent of the total thickness of the compressible layer. The settlement is particularly spectacular in peat and silty soil containing an appreciable percentage of organic matter. The explanation is fairly simple: the soils always contain some gas (air, methane, etc.) and consequently behave like a solid-liquid-gas complex or stack of "hydropneumatic capacities." The dynamic stress reduces the volume of the gas phase, producing an instantaneous and very appreciable total settlement.

The interstitial water, when suddenly subjected to a considerable pressure gradient, has no difficulty in opening the structure formed by the solid particles and previously fluidized by the shock waves, resulting in an internal breakdown and a multiple branching drainage network.

As the interstitial pressure dissipates, the network of intergranular stresses reforms and the material is restructured; the mechanical strength increases rapidly during the entire period of dissipation of water pressure, and then increases more slowly under the effect of subsequent thixotropic phenomena.

The energy used per $m^3$ and the corresponding reduction in volume are shown by curves **1** and **2** respectively; the interstitial pressure, as a percentage of the fluidization pressure, and the bearing capacity (e.g., the limiting pressure measured by the pressure gauge) are shown by curves **3** and **4.** As can be seen, therefore, the reduction in volume increases substantially proportionally to the energy applied, whereas the interstitial pressure remains below the fluidization pressure, so that the saturation energy can be thus defined; subsequently, the interstitial pressure decreases rapidly with time, from the maximum reached during the application of dynamic pressure. The bearing capacity, which is characterized by an initial value $(P1)_o$, becomes very small during the fluidization phase, and then rapidly increases during the dissipation of the interstitial pressure and reaches a final value $(P1)_{oo}$ considerably above the initial value.

Energy may be applied in a single cycle in dry or very permeable soil. In other cases it is more usual to have a number of cycles, the results of which are shown in FIG. 3. A second cycle does not begin until after the dissipation of the interstitial pressure produced during the preceding cycle; so that, for example in the case of saturated silty soil the process may take a total of several months.

Clearly, the required number of cycles increases as the material becomes less permeable, which limits the practical utility of the method in the case of very impermeable clayey layers.

In order to obtain the best results, according to the invention the dimensions and shape of the tamping weight are selected in dependence on the characteristics of the soil treated. The optimum efficiency is obtained when the tamper is driven in about 10 to 20 percent of its diameter or equivalent dimension at each blow.

The tamper should also be slightly frustoconical so as to reduce lateral friction and suction when it is withdrawn from the soil.

With regard to the plan distribution of energy, it may be advantageous, depending on the desired result, to finish tamping at a single place before moving to the next place, or, on the contrary, to tamp each point on the elementary soil square (e.g., $4 \times 4$) at least once before the second or third series of tamping operations.

The method is also very advantageous in the case of underwater or dry coarse rocks (sea or river dykes or dams), sand and gravel, dry or underwater coarse sand, moraine soil, or fine "Fontainebleu" sand (dry).

It is relatively advantageous in the case of silt containing a small proportion of water, loess and relatively dry sandy clay.

The method according to the invention can be facilitated by using a device adapted to simulate the fluidization operation on a sample of soil and thus to determine the saturation energy (fluidization threshold), the time taken for the interstitial pressure to dissipate, and the increase in settlement in dependence on the energy applied. Such an apparatus is shown in FIG. 4.

## DESCRIPTION OF THE TESTING APPARATUS

The apparatus comprises a closed chamber **1,** e.g., a cylindrical tank of about 30 liters capacity, having deformable side walls made for example of reinforced rubber or synthetic elastomer so that lateral pressure can be measured during the different operations. The chamber is closed at the top by a piston in the form of a plate **2** for applying static or dynamic pressure to the contents of the chamber, and a disc **3** is disposed between plate **2** and chamber contents **4** in order to dry the contents. The piston has a horizontal cross-section corresponding to the cross-section of the sample of soil contained in the chamber.

The chamber forms an expansible jacket, in which the soil sample is disposed in successive layers statically consolidated at a pressure which is a function of the resistance of the soil in situ. The content of water introduced corresponds to the actual water content of the material.

The disc **3,** which is used for draining, is made, for example, of porous bronze or, better, of coarse sand.

If required, the disc can also form the piston **2,** used for transmitting adequate static or dynamic pressures to the material in the chamber. The pressures are supplied by any suitable means, e.g., by a jack **5** and a tup or hammer **6** striking an anvil **7** secured to a rod **8** fixed to the piston **2.**

In the drawing, the jack acts on the piston **2** via a stirrup **9** which it pushes downwards, while the rod **8** extends through the stirrup **9.**

The apparatus comprises measuring devices, including a detector **10** (or pressure gauge) for measuring the pressure exerted by the chamber contents on the deformable side wall, a detector **11** connected to the bottom end **12** of the chamber in order to measure the interstitial pressure, i.e., the degree of fluidization of the

material in the chamber during the different stages of the operation, and comparators or dial gauges **13** for measuring the change in volume of the sample in the chamber, depending on the depth to which the piston plate **2** is driven in.

An example of the use of the device will now be described.

II. Measurement Parameters

| | |
|---|---|
| Initial height of sample: | $ho \sim 20$ to 50 cm. |
| Variation in height of sample: | $\Delta h$ |
| Initial volume of sample: | $Vo \sim 1000$ to 3000 cm$^3$ |
| Static pressure maintained on head of sample: | $Pv_o$ (= 0.5 bar for standard test) |

Energy transmitted to sample in meter-tones/m$^3$ Lateral pressure exerted by sample on wall of mould at base of sample: Ph Interstitial pressure at base of sample, minus the height of water kept in the tank (since the test is performed under saturation): $P_i$

III. Performance of Test

A. Preparation of sample:

The sample is taken from a boring, taking care to avoid any change in the water content. It is placed in the tank in 10-cm layers, each of which is maintained at a pressure $p$ equal to the limiting pressure measured in situ (with the pressure gauge).

A draining layer of coarse sand and the piston are positioned at the top of the sample. The following recommended static load should be kept constant during the entire test:

$p_c = (\gamma - 1)(h - hl) + h\,l$

$h$ = depth of middle of layer to be compacted,

$hl$ = depth of water table,

$\gamma$ = density of soil on saturation.

Usually, the average value:

$p_c$ = **0.5** bar

is used in calculation.

It may be desirable to perform a first lateral confinement test at this stage of preparation, and to measure the consolidation modulus of the soil before compaction. In all cases, the dynamic consolidation phase does not start until the interstitial pressure produced by the static load has dissipated and been reduced to the height of water in the apparatus ($p_i = ho$).

B. Dynamic consolidation test:

Energy is applied to the sample by dropping the hammer on the anvil placed at the top of the apparatus. The energy is applied in fractions of 3 meter-tons/m$^3$ (3 meter-tons/m$^3$ starting energy which may be variously modified depending on the problems under study).

| | | | |
|---|---|---|---|
| 1st Phase: | | | |
| Total energy applied: | (3) | (3+3) | (3+3+4) |
| Measurement of $\Delta h$ | — | — | — |
| Measurement of $p_h$ | — | — | — |
| Measurement of $p_i$ | — | — | — |
| 2nd Phase: | | | |
| Rest phase. | | | |

$\Delta h$, $p_h$, $p_i$ are measured until the interstitial pressure conditions have returned substantially to their initial value, or at least until:

$p_i < 2\ h_o$

| | | | |
|---|---|---|---|
| 3rd and 4th Phases: | | | |
| Energy applied during phase: | 3 | 3+3 | (3+3+4) |
| Total energy applied since the beginning of test: | 13 | 16 | 20 metre-tonnes/m$^3$ |

Measurement of $\Delta h$, $p_h$, $p_i$, etc., in dependence on the known energy for the initial phase and the time during the rest phase.

5th and 6th Phases:

Identical with the preceding. At the end of the test, a second lateral confinement test is made, doubling the number of levels and using the same pressure variations.

C. Use of results:

Determination of saturation energy:

This is the energy corresponding to the total fluidization of the soil. Any further application of energy produces very little settlement and the increase of compaction is insignificant.

Determination of the settlement curve in dependence on the applied energy:

a. initial settlement curve for each phase:

$\Delta h_i$ = instantaneous variation in height of sample after application of energy during phases 1, 3, 5.

$\Sigma\Delta h$ is plotted against the total energy applied to the sample (i.e., 3, 3+3, or 3+3+3 meter tons/m$^3$).

b. total settlement curve:

This is the variation in the height of the sample, measured at the end of phase 2, 4 and 6 and plotted against the total energy applied. In the case of a draining soil, the total settlement curve is identical with the initial settlement curve.

D. Application to tamping work

The laboratory results can be used to determine the characteristics of the dynamic consolidation to be performed in situ. The most important characteristics are:

the dissipation time,

the saturation energy,

the settlement.

The times $T$ to be allowed between each phase in situ should be proportional to the dissipation time $t$ measured in the laboratory, at least if one neglects the breakdown of the soil produced by the interstitial pressure:

$$\frac{\text{time between phases (in situ)}}{\text{dissipation time (in laboratory)}}$$

$$\frac{T}{t} = \frac{(H_o)^2}{h_o}$$

$H_o$ = half the thickness of the compressible layer to be compacted. The above value is in fact an upper limit of $T$.

The energy for each phase should in no case be greater than the saturation energy measured in the laboratory.

The settlement $\Delta H$ of the soil is substantially proportional to the variation in the volume of the sample for each compaction stage.

$$\frac{\Delta H}{H_o} = \frac{\Delta h}{h_o} = \frac{\Delta V}{V_o}$$

When a consolidation operation is being planned, the first value to be estimated is the minimum required set-

tlement. This can be estimated as a function of the measured resistance of the soil before tamping, and as a function of the required resistance.

As a first approximation, each doubling of the initial resistance of the soil should correspond to an increase $d(ds)$ of 4 to 5 percent in the density $ds$ of the same soil.

Thus, if the bearing capacity measured with the pressure gauge is $pl = 3$ bars, and if it is required to obtain 10–12 bars at the end of the operation, the density of the material must be increased by at least 8 to 10 percent during the compaction operation:

When the increase in density

$$\frac{d(ds)}{ds} = \frac{\Delta h}{h_o}$$

has been determined, it is necessary to decide on the most economic compaction process for obtaining the desired increase within an acceptable time. Preferably the energy chosen is the saturation energy, and the corresponding settlements produced in the sample are noted.

$$\frac{\Delta h\,1}{h_o} \quad \frac{\Delta h\,2}{h_o} \quad \cdots \quad \frac{\Delta h\,n}{h_o}$$

The number $n$ of phases is determined by the relation:

$$\frac{\Delta h\,1}{h_o} + \frac{\Delta h\,2}{h_o} + \ldots \frac{\Delta h\,n}{h_o} > \frac{\Delta h}{h_o}$$

i.e.,

$\Delta h_1 + \Delta h2 + \ldots \Delta hn > \Delta h$

The maximum time $T_i$ between phases in situ is automatically given by the dissipation time in the laboratory:

$$T_i = t_i \left(\frac{H_o}{h_o}\right)^2$$

Consequently the total duration of operation is:

$T = T1 + T2 + \ldots . Tn$

$$T = \left(\frac{H}{h_o}\right)^2 (t1 + t2 + \ldots tn)$$

Advantageously, in order to economise energy, the number of phases may be made greater than that given by the preceding equation, since the effect on efficiency can only be favourable, although the total duration of the operation increases. The same applies if the times $T1$, $T2$ between phases are increased.

If, on the other hand, time is the most important consideration in the project, the number of phases or the time between phases can be reduced, though this substantially increases the energy required for compaction.

FIG. 4 shows a device wherein the chamber and the jack controlling static pressure are borne by a single support **14**; it will be understood, however, that this is not essential.

By way of example, FIG. 2 of the accompanying drawings shows a "pressure profile or cross-section" for a clayey silt soil. Curves are shown on the left for the deformation modulus and on the right for limiting pressures plotted against the depth in metres, shown as the ordinate.

The chain-line curves show values measured before compaction, the chain-dotted curves show results obtained after compaction after the interstitial pressure has dissipated, and the continuous curves show the results measured after 9 months.

In the claims, the word "soil" covers any kind of soil as stated above and specially natural or synthetic, moist or saturated, clay, clay-sand, silt or sand soil.

What I claim as my invention and desire to secure by Letters Patent is:

**1.** A method of consolidating damp unfluidized soil, said method comprising the steps of: applying a dynamic load to the soil until the voids in the soil are reduced to bring the soil to fluidization; discontinuing the application of the dynamic load after the soil has been compacted to fluidization; and allowing the water to drain from the soil, during a rest phase.

**2.** A method according to claim **1**, which includes determining the value of the dynamic loads to be applied, the duration of the rest phase, and the extent of settlement by simulating the fluidizing operation on a sample of soil prior to compacting the soil in situ.

**3.** A method according to claim **1**, which includes an operation introducing dynamic stress cycles of at least 2 to 5 bars at a depth of at least 5 to 20 m over an area of at least 10 to 40 $m^2$ and a volume of at least 100 to 1,000 $m^3$.

**4.** A method according to claim **3**, in which the said operation comprises a plurality of cycles in each of which dynamic forces of at least 500 to 10,000 tons are applied to the surface.

**5.** A method according to claim **1** in which the load is applied by a tamper which is driven in about 10 to 20 percent of its equivalent diameter at each impact.

**6.** A method according to claim **1**, which includes at least two successive cycles each comprising a dynamic pressure phase, followed by a rest phase.

**7.** A method according to claim **1**, which includes an operation wherein draining materials are used to form the top part of the soil.

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