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(54) Method for consolidating soils or lifting structures with pressures larger than 500 kPa

(57) A method for consolidating foundation soils or for lifting very heavy or very large structures requiring the application of a pressure of more than 500 kPa, which consists in injecting into the soil to be consolidated or into the soil below the foundations of the structure to be lifted substances which expand as a consequence of a chemical reaction and are suitable to generate, during expansion, a pressure of more than 500 kPa.

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Description

[0001] The present invention relates to a method for consolidating foundation soils or for lifting very heavy or large structures requiring the application of a pressure of more than 500 kPa.

[0002] In the field of interventions for consolidating foundation soils for buildings, aimed at increasing the bearing capacity of the soil before and after building a structure, and in the field of interventions for obviating the subsidence of flooring or paving, it is known to use substances which expand as a consequence of a chemical reaction, of the type comprising a mixture of polyols and an MDI isocyanate, or a similar expandable substance, which after expansion solidifies and makes said expansion permanent.

[0003] European Patent no. 851,064 by same Applicant discloses a method for increasing the bearing capacity of foundation soils that substantially consists in forming a plurality of spaced deep holes in the soil and in injecting through these holes an expandable substance of this type, which expands as a consequence of a chemical reaction of its components, utilizing an expansion power which, at atmospheric pressure, causes a volume increase of at least five times its initial volume. The expansion of the substance produces a compaction of the contiguous soil until it reaches the intended bearing capacity. The level of the soil or of the structure overlying the region of the soil that is subjected to intervention is monitored constantly in order to detect the beginning of its lifting, which means that the foundation soil has achieved a bearing capacity suitable to support the overlying structure or simply, if there is no structure, that the layer of soil between the ground and the injection region has been compacted.

[0004] Clearly, the structure can be lifted only if the pressure generated by the expansion of the substances involved is greater than the pressure applied to the soil affected by the expansion, by the static and dynamic weight of the structure plus the weight of any soil overlying the injection point and the friction forces within the soil.

[0005] The maximum pressure that can be generated by the expansion of these substances has always been assessed as being at the most of approximately 500 kPa. For this reason, this method has never been deemed suitable and used to perform consolidation of foundations of very large or very heavy buildings or structures or to try to lift such structures, since they generally apply to the soil a pressure of more than 500 kPa; this happens because it was thought that the expansion of said substances under said structures would not be able to improve soil compaction or produce lifting of the structure. Moreover, no attempt was made to further consolidate soils that were already well-compacted and offered a breaking strength of more than 500 kPa.

[0006] Sometimes it might be convenient or indispensable to produce a soil compression of more than 500 kPa also under low-weight structures or in non-loaded soil. It is in fact important to stress the distinction between subsidences caused by low bearing capacity of the soil (which, if the load of the structure is lower than 500 kPa, were solved effectively with the method disclosed in the above-cited Patent by same Applicant) and consolidation subsidences that can occur in fine-grain soil even when it has sufficient bearing capacity. Actually, relatively light structures often subside although being built on soils with a capacity that exceeds the overlying load. This occurs simply because a consolidation process is in progress which causes a reduction in volume, with consequent subsidence over time due to water migration.

[0007] Sometimes in similar conditions it is important to prevent from the start the onset of these subsidences, in order to avoid damage to the structure. In such cases one normally provides, directly during design, foundations and structures that can tolerate a certain degree of subsidence. However, for existing structures, where this was not done or where the expected extent of the subsidence turns out to be incorrect, in view of the extreme difficulty of formulating exact subsidence predictions, even with in-depth geotechnical studies, or also where it is important to prevent from the start the onset of these subsidences, in order to prevent for example even minimal level oscillations of instruments or machines, it is necessary to intervene to remedy or prevent the phenomenon, since a large increase in the compression of the soil (even much higher than the compression required for bearing capacity alone) leads to the development of consolidation and therefore prevents subsidence.

[0008] The edometric modulus of a soil is in fact inversely proportional to the subsidence. A high compression of the soil (above 500 kPa) would increase the edometric module and accordingly reduce subsidence even in these kinds of soil.

[0009] Finally, standards in general require a safety coefficient of three on surface foundations. Accordingly, in order to comply with the standards any foundation soil must have a bearing capacity that is at least three times the tension induced by the overlying structure.

[0010] In summary, all the problems that, like the ones described above, required an expansion pressure of the expandable substance of more than 500 kPa were not handled with the above-described method, since its was thought that expandable substances of the above-cited type could not generate an expansion force above this value.

[0011] Surprisingly, during interventions on high-density soils performed by the Applicant, results were obtained which questioned this conviction and led to think that the pressure generated by the substances used could be higher than hypothesized.

[0012] For this reason, Applicant performed a plurality of tests aimed at identifying the actual maximum pressure

that can be obtained from the expansion of substances that expand as a consequence of a chemical reaction.

[0013] The outcome of these tests was equally surprising, since it was found that the maximum pressure that can be generated by substances of the above-cited type in certain conditions is considerably higher than the hypothesized pressure, and on the basis of these results it has been thought to use said expandable substances for interventions hitherto believed impossible.

[0014] The aim of the present invention is to provide a method that allows to utilize the force generated by the expansion of these substances to consolidate foundation soils and to lift, particularly for repair after subsidence, very large or very heavy structures, such as for example skyscrapers, large monumental buildings, bridges, highway structures, silos, dams, large infrastructures etcetera, which can be lifted only by overcoming a pressure thereof on the soil of far more than 500 kPa, i.e., for interventions that up to now were not even imaginable by using substances that expand as a consequence of a chemical reaction, or in any case to obtain effects of overconsolidation in some kinds of soil underlying even not very heavy structures, since sometimes this is the only way to prevent subsidences and ensure, over time, the stability of the structure.

[0015] Within this aim, an object of the present invention is to provide a method that allows to perform prevention or repair after subsidences of very large or very heavy structures with considerably lower costs than required by known kinds of intervention.

[0016] This aim and this and other objects that will become better apparent hereinafter are achieved by a method for consolidating foundation soils or for lifting very heavy or very large structures requiring the application of a pressure of more than 500 kPa, characterized in that it consists in injecting into the soil to be consolidated or into the soil below the foundations of the structure to be lifted substances which expand as a consequence of a chemical reaction and are suitable to generate, during expansion, a pressure of more than 500 kPa.

[0017] Preferably, the method according to the invention consists in:

- producing a plurality of holes in the soil, said holes being mutually spaced and lying below the lower front or underside of the foundations of the structure;
- injecting into the soil, through said holes, a substance which expands as a consequence of a chemical reaction and comprises a mixture of polyols and an MDI isocyanate, or a similar expandable substance, with an expansion start time substantially between 2 and 25 seconds and with a potential volume increase, as a consequence of expansion, of more than five times the volume of the expandable substance before expansion;
- determining when the intended degree of consolidation of the soil or the intended degree of lifting of the structure is reached;
- ending the injection of said expandable substance when the intended degree of consolidation of the soil is reached or when the intended degree of lifting of the structure is reached.

[0018] Further characteristics and advantages of the present invention will become better apparent from the following detailed description and the accompanying drawings of a preferred but not exclusive embodiment thereof, which are given only by way of non-limitative example hereafter.

[0019] Figures 1-3, are graphs which show the swelling pressure variation as a function of several injection factors;

[0020] Figures 4 and 5, are comparative diagrams showing results of penetrometric tests carried out on treated foundation soils, under heavy structures.

[0021] The method according to the invention conveniently comprises a first step of producing a plurality of holes in the soil, said holes being mutually spaced and lying below the lower front or underside of the foundations of the structure.

[0022] The number of holes to be produced, their dimensions and their mutual distance are calculated according to the force to be overcome in order to lift the structure, i.e., according to the weight of the structure and to the distribution of said weight on the soil being treated.

[0023] The holes can run vertically or can be inclined with respect to the vertical, according to requirements.

[0024] Through these holes, with the aid of tubes inserted beforehand in said holes, a substance which expands as a consequence of a chemical reaction among its components is injected into the soil, said substance comprising a mixture of polyols and an MDI isocyanate, or a similar expandable substance, with an expansion start time between 2 and 25 sec, preferably between 2 and 7 sec, and with a potential volume increase of at least five times the volume of the substance before expansion. The expression "potential volume increase" relates to the volume increase of the substance as a consequence of an expansion occurring unhindered at atmospheric pressure.

[0025] In the case of structures having rather wide foundations, such as for example raft foundations, where it is not strictly necessary to localize the region of action of the expandable substance, it is possible to use an expandable substance with an expansion start time of more than 7 seconds.

[0026] If instead high precision in the localization of the region of action of the expandable substance is required, preference is given to substances with an expansion start time between 2 and 7 seconds.

[0027] Said substance is constituted by a closed-cell polyurethane foam which, after expansion, gradually hardens

and permanently maintains its expansion.

[0028] The components of the expandable substance are mixed inside a mixing apparatus with a pump, which is connected to the tubes inserted in the holes formed in the soil.

[0029] The expandable substance is preferably constituted by two components, respectively a first component constituted by a mixture of polyols comprising a polyether polyol and/or a polyester polyol, a catalyst and water, for example such as URETEK GEOPLUS A produced by the Dutch company Resina Chemie, and a second composed constituted by an MDI isocyanate, for example such as URETEK GEOPLUS B produced by the same company, which has an expansion start time of approximately 3 seconds and in particular can generate the maximum measured expansion force, as described in greater detail hereinafter.

[0030] The mixing of these two components produces an expanding polyurethane foam whose density, at the end of the expansion, varies according to the resistance opposed to the expansion, i.e., in the case being considered, the resistance opposed by the soil adjacent to the injection region.

[0031] The pressure that the substance transmits to the adjacent soil is also proportional to the density and therefore to the resistance opposed by the soil into which the substance is injected.

[0032] Vertical expansion tests, carried out in endometric conditions, with the URETEK GEOPLUS A+B mix, catalyst and water, in metered amounts have provided the results reported in the following table

test sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
P (g)	138.8	316.1	138.3	171.5	490.6	313.2	358.4	363.2	190.4	471.8	396.6	431.9	551	401	548.3
D (cm)	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
H (cm)	11.65	11.88	6.51	6.01	10.14	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
V (cm^3)	585.59	597.15	327.23	302.10	509.69	532.5	532.5	532.5	532.5	532.5	532.5	532.5	532.5	532.5	532.5
$\gamma(kN/m^3)$	2.33	5.19	4.15	5.57	9.44	5.77	6.60	6.69	3.51	8.69	7.31	7.96	10.15	7.39	10.1

t(sec.)	Swelling pressure σ (KPa)														
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	196	1275	883	1275	1962	1668	2453	2551	834	4120	2747	3630	6475	3139	5886
20	294	1373	1030	1422	3728	1913	2698	2747	883	4513	3139	4022	7848	3434	7358
30	343	1521	1079	1472	4415	2011	2645	2894	981	4807	3237	4316	8339	3630	8044
60					5690	2158	3041	3139	981	5199	3630	4611	9418	3924	9123
90	412	1687	1158	1619	6180	2305	3139	3286		5396	3826	4905	9908	4120	9516
120	412	1766	1177	1697	6377	2305	3139	3286		5494	3875	4905	10055	4120	9810
150		1766	1177	1697	6377					5592	3875		10202		9810
180										5592			10202		

σmax(kPa)	412	1766	1177	1697	6377	2305	3139	3286	981	5592	3875	4905	10202	4120	9810

in which, the abbreviation signs are P (weight), D (diameter), H (height), V (volume), σ (swelling pressure), t (testing time), and represent features of the tests samples.

[0033] The tests were carried out at, and with an instrumentation available at the specialized Laboratory of the University of Padova, based substantially on creating in controlled pressure environments pressure conditions similar to those at which the expanding substance is subjected during injection/expansion in heavy loaded foundation soils, and eventually measuring the swelling pressure of the various test samples obtained.

[0034] The accompanying figures 1-3 plot, respectively, the pressure generated by the expansion of said substance as a function of the density of the substance at the end of expansion, which as mentioned is proportional to the density of the soil into which the injection is performed, of the swelling time, and of the volume-weight.

[0035] As can be seen, the pressure actually generated by the expansion of said substance can reach and exceed 10,000 kPa.

[0036] The pressure generated by the expansion also varies as a function of the temperature of the substance. The illustrated chart plots two curves of the pressure at two different temperatures, respectively 80 °C and 238.6 °C.

[0037] The expansion start time can be changed by varying the ratio between the two components of the substance according to requirements. More particularly, preference is given to a shorter time for injection into soils that can cause dispersions of the substance and to longer times (in any case preferably between 2 and 7 seconds) for more uniform and compact soils. Times above 7 seconds can be suitable or useful under very extensive foundations.

[0038] According to requirements, the substance can be injected into the holes formed in the soil in a single injection step, making the injection point rise gradually and therefore retracting upward the tubes inserted in the holes formed in the soil, or it can be injected in a plurality of steps by causing the intermittent rise of the injection point, i.e., by retracting upward the tubes inserted in the holes with intermediate pauses.

[0039] If it is necessary to utilize simultaneously the pressure generated by the expandable substance on a vast surface, for example in order to lift very large and heavy structures, or to provide simultaneous and uniform lifting of the structure in order to avoid damage thereto, the expandable substance is injected simultaneously into a plurality of holes, optionally using a plurality' of pumps.

[0040] The expandable substance, during injection, is very fluid and therefore penetrates more easily in the less dense regions of the soil. The subsequent expansion of the substance then compacts more intensely the less dense regions of the soil, further improving the uniformity of the density of the soil.

[0041] The swiftness of the expansion of the injected substance in any case avoids unwanted dispersions of the substance, delimiting the region affected by the expansion rather accurately and therefore obtaining an excellent effectiveness in the compaction of the soil and in the lifting of the structure. The thrust effect on the soil produced by the substance during expansion arises from the chemical reaction of its components, not from hydraulic pressure. Although the expandable substance is injected into the soil by using hydraulic pressure, said pressure is in fact used only to introduce the substance in the intended points.

[0042] As regards the depth of the holes formed in the soil, it may vary according to the method for compacting the soil beneath the structure on which one wishes to act.

[0043] It is specified in any case that the expression "foundation soil" is used to designate an area covered by the pressure bulb, i.e., the entire portion of soil, below the foundations, that dissipates almost all the tensions and stresses induced by the static and dynamic load, and calculated for each specific case; it generally corresponds to a depth, below the bottom plane, of approximately 2-3 times the width of said foundation.

[0044] To lift the structure, and also to consolidate the foundation soil in order to remedy or prevent subsidence of the underlying soil, it is possible to follow two methods depending on the situation of the soil.

[0045] A first method consists in treating the entire thickness of the pressure bulb and any further thickness of the compressible or low-bearing layers so as to perform the consolidation, to the solid horizon, of the sufficiently bearing layers, whatever their depth. The solid horizon can be identified by means of geotechnical soil analysis.

[0046] The second method instead consists in treating a layer of soil (at least equal to the pressure bulb) which, for reasons of technical and/or financial convenience, does not reach the identified solid horizon, which might be located at an excessive depth, but in any case has a thickness that is sufficient to dissipate the overlying weight on a wider surface.

[0047] If the intervention is aimed at lifting the structure located above the injection region, during the injection of the expandable substance, the level of the structure above the treated soil area is monitored constantly by means of laser levels or another system in order to detect with high accuracy the beginning of the lifting of the structure.

[0048] The beginning of the lifting of the structure means that the compaction performed on the soil in that point is sufficient to support the structure and that the further expansion of the substance will lift the structure.

[0049] If the intervention is aimed at consolidating the foundation soil without lifting the structure, for example because its rigidity or weight do not allow to lift it, or simply because this is not the effect being sought, achievement of the required degree of consolidation can be determined by measuring the amount of injected expandable substance, as an alternative to monitoring the beginning of the lifting of the structure. It is in fact possible to determine in advance,

by way of appropriate calculations, how much expandable substance to inject in order to obtain the intended consolidation. If one wishes to determine the necessary degree of consolidation during individually performed injections (a procedure that is easy to perform and besides allows to achieve maximum consolidation), it is possible to establish the amount of expandable substance to be injected by way of mathematical calculations based on the data of adequate geotechnical studies of the soil, on the degree of consolidation to be obtained, on the pressures to be applied and on the consequent densities of the expandable substance that will be obtained by applying said pressures and finally on the volumes of expandable substance required to achieve the intended result. This procedure is unquestionably more laborious and expensive and is fully justified, in the cases being considered, by the great extent of the intervention.

[0050] In soils that are scarcely loaded and in any case require overconsolidation in order to prevent subsidence, one proceeds initially as in the preceding steps and then further injections are performed, spacing them between the previously performed injections, into the soil that is already (partially) hardened, continuing to repeat the procedure in this manner until the required values, predetermined by appropriate geotechnical calculations, are obtained.

[0051] The soil, which is thus gradually rendered denser, provides further resistance to the expansion of the expandable substance, which by being gradually more strongly confined automatically generates higher expansion forces.

[0052] By performing just one injection at a time, even a rather light structure, having already been fully tensioned with load by the lifting produced by the initial injections and in the state of greater tension that it has acquired at this point, provides a contrast pressure that is far greater than the unit load above the injection point, which added to the contrast pressure opposed by the soil which has already been rendered denser allows to perform a higher compression of said soil. One might also add weight onto a soil or structure in order to obtain a higher contrast pressure.

[0053] When the structure reaches the intended degree of lifting, or when the intended degree of soil compaction is reached, injection of the substance is interrupted and the subsequent solidification of the substance stably maintains the obtained results.

[0054] As mentioned, the pressure that can be generated by the substance during expansion can reach and exceed 10,000 kPa. This means that the injection of said substance below foundations, optionally in many points simultaneously, is capable of lifting very large structures, such as skyscrapers, towers, large monuments, bridges, dams, highway structures, silos, large infrastructures, etcetera, or of consolidating foundation soils even if this requires an extremely high pressure, and it means that it is therefore possible to use the above described technique for interventions hitherto unthinkable. Likewise, it is possible to bring a soil, even if it is scarcely loaded, to a state of overconsolidation with respect to the state generated by the load of the structure, preventing or stopping consolidation subsidences deemed up to now untreatable with substances that expand as a consequence of a chemical reaction.

[0055] Penetrometric tests were carried out in foundation soils (as shown in Figures 4 and 5), treated with the method according to the present invention, under very heavy buildings located in Paris (loads generating soil pressures) well in excess of 500 kPa.

[0056] The injections were carried out at 1, 2 and 4, 5m under the foundation and the area treated had a linear extension of about 9m.

[0057] The penetrometric tests showed dynamic resistances improved up to 10 times and more with respect to the initial values, perfectly suitable to provide lifting of the structures and reliable consolidation of the foundation soil.

[0058] In practice it has been found that the method according to the invention fully achieves the intended aim and objects, since by utilizing hitherto unknown properties of expandable substances of the above cited type it allows to perform consolidation interventions for foundation soils with optional lifting, particularly for preventing or repairing subsidences, for very large or very heavy structures, and also allows a great increase in the degree of consolidation (overconsolidation) in scarcely loaded fine-grain soils.

[0059] The method thus conceived is susceptible of numerous modifications and variations, all of which are within the scope of the inventive concept; all the details may further be replaced with other technically equivalent elements.

[0060] The disclosures in Italian Patent Application No. MI2001A002496 from which this application claims priority are incorporated herein by reference.

Claims

1. A method for consolidating foundation soils or for lifting very heavy or very large structures requiring the application of a pressure of more than 500 kPa, **characterized in that** it consists in injecting into the soil to be consolidated or into the soil below the foundations of the structure to be lifted substances which expand as a consequence of a chemical reaction and are suitable to generate, during expansion, a pressure of more than 500 kPa.

2. A method for consolidating foundation soils or for lifting very heavy or very large structures requiring the application of a pressure of more than 500 kPa, **characterized in that** it consists in:

-- producing a plurality of holes in the soil, said holes being mutually spaced and lying below the lower front or underside of the foundations of the structure;
-- injecting into the soil, through said holes, a substance which expands as a consequence of a chemical reaction and comprises a mixture of polyols and an MDI isocyanate, or a similar expandable substance, with an expansion start time substantially between 2 and 25 seconds and with a potential volume increase, as a consequence of expansion, of more than 5 times the volume of the expandable substance before expansion;
-- determining when the intended degree of consolidation of the soil or the intended degree of lifting of the structure is reached;
-- ending the injection of said expandable substance when the intended degree of consolidation of the soil is reached or when the intended degree of lifting of the structure is reached.

3. The method according to claims 1 and 2, **characterized in that** the intended degree of lifting of the structure and/or the intended degree of consolidation of the soil is determined by constantly monitoring the level of the structure above the injection region.

4. The method according to claims 1 and 2, **characterized in that** the intended degree of consolidation of the soil is determined by measuring the amount of injected expandable substance.

5. The method according to one or more of the preceding claims, **characterized in that** the expansion start time of said expandable substance is substantially between 2 and 7 seconds.

6. The method according to one or more of the preceding claims, **characterized in that** said expandable substance, during expansion, generates a pressure on the surrounding soil that is proportional to the tension opposed by the soil and is higher than 500 kPa and can exceed 10,000 kPa.

7. The method according to one or more of the preceding claims, **characterized in that** said expandable substance comprises two components: a first component constituted by polyether polyol and/or polyester polyol, by a catalyst and by water, and a second component constituted by MDI isocyanate.

8. The method according to one or more of the preceding claims, **characterized in that** said holes are formed vertically.

9. The method according to one or more of the preceding claims, **characterized in that** said holes are formed at an angle with respect to the vertical.

10. The method according to one or more of the preceding claims, **characterized in that** the injection of said expandable substance in said holes is performed simultaneously in a plurality of holes.

11. The method according to one or more of the preceding claims, **characterized in that** the injection of said expandable substance in said holes is performed continuously, making the injection point rise gradually along the corresponding hole.

12. The method according to one or more of the preceding claims, **characterized in that** the injection of said expandable substance in said holes is performed in a plurality of steps, making the injection point rise intermittently along the corresponding hole.

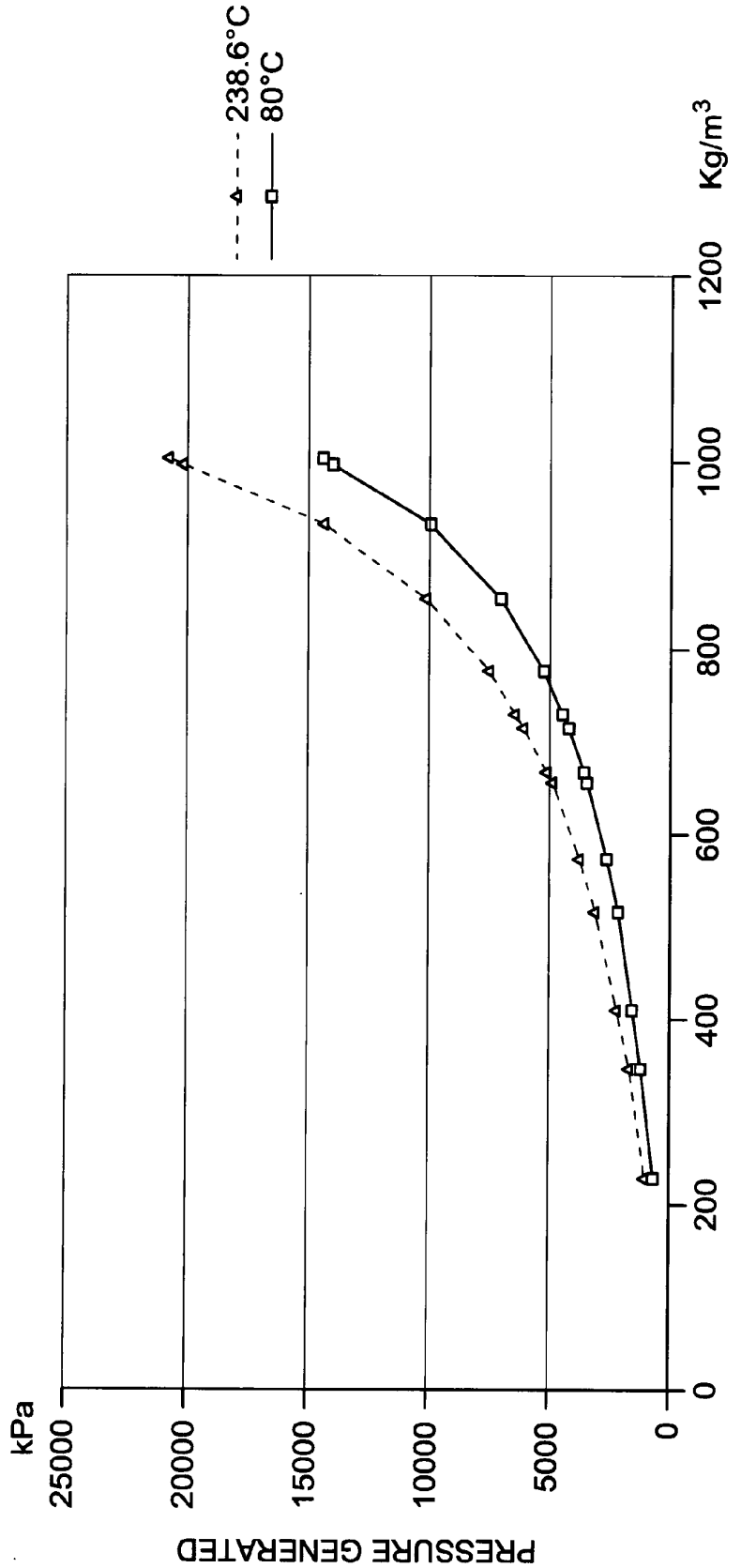
13. The method according to one or more of the preceding claims, **characterized in that** it comprises additional steps for the injection of said expandable substance in holes which are spaced between the holes already used for preceding injection steps.

14. Use of a substance that expands as a consequence of a chemical reaction, comprising a mixture of polyols and an MDI isocyanate, or a similar expandable substance, with an expansion start time substantially between 2 and 25 seconds and with a potential volume increase, as a consequence of expansion, which is more than five times the volume of the substance before expansion, in order to consolidate foundation soils or lift very heavy or very large structures that require the application of a pressure of more than 500 kPa.

15. The use according to claim 14, **characterized in that** said expandable substance comprises a mixture of two components: a first component, constituted by polyether polyol and/or polyester polyol, by a catalyst and by water,

and a second component, constituted by MDI isocyanate.

16. The use according to claim 14, **characterized in that** said expandable substance has an expansion start time that is substantially between 2 and 7 seconds.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80°C
kPa
25000
20000
15000
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5000
0
PRESSURE GENERATED
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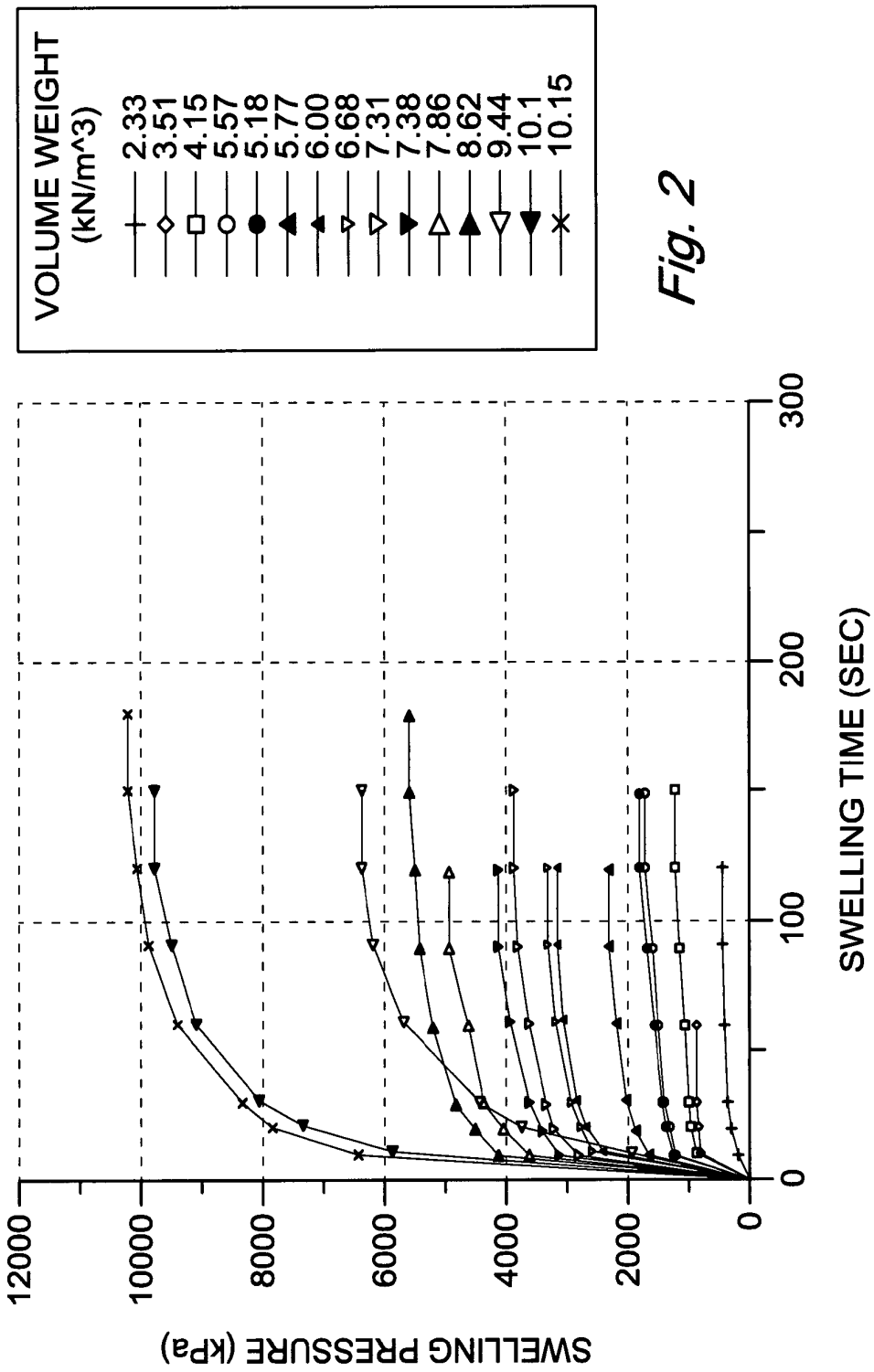
200
400
600
800
1000
1200
DENSITY
Kg/m3

Fig. 1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5.77
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7.38
7.86
8.62
9.44
10.1
10.15
SWELLING PRESSURE (kPa)
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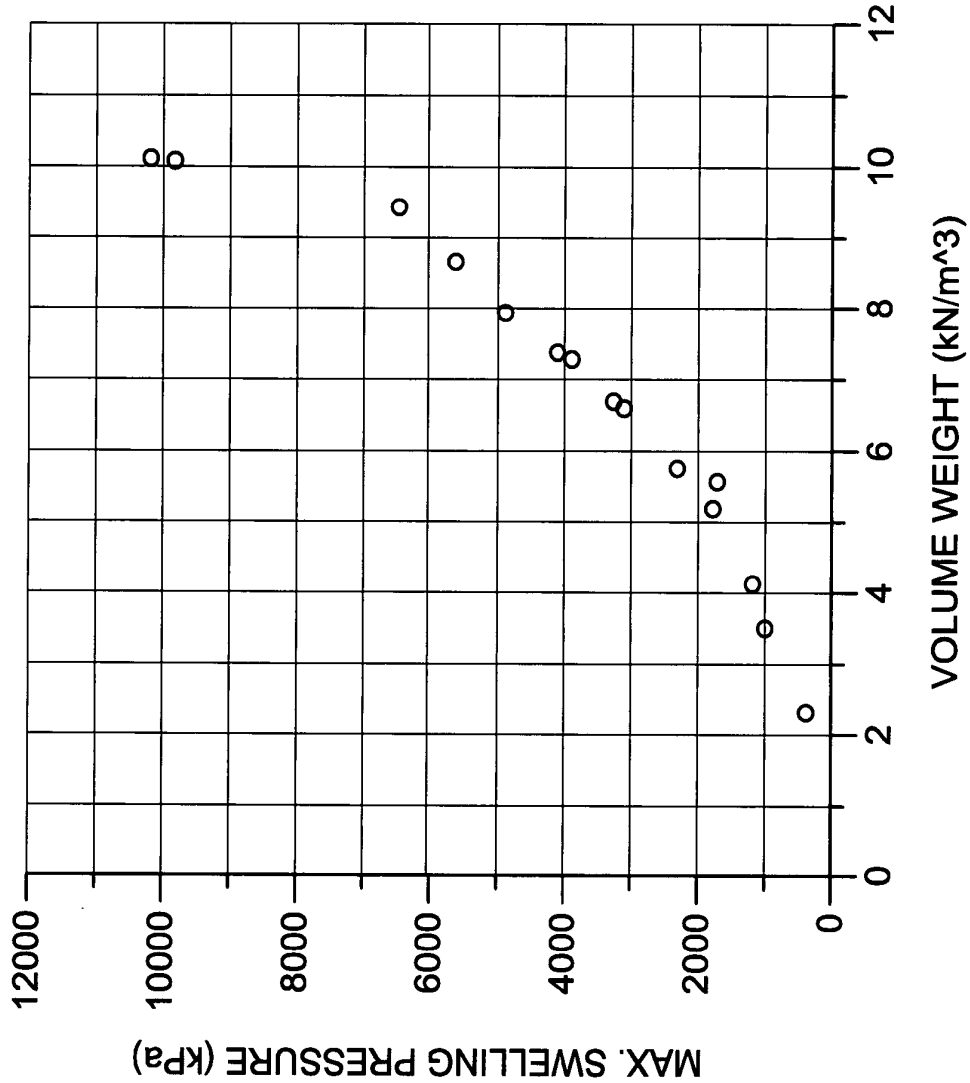
10000
8000
6000
4000
2000
0
0
100
200
300
SWELLING TIME (SEC)

Fig. 2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6000
4000
2000
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0
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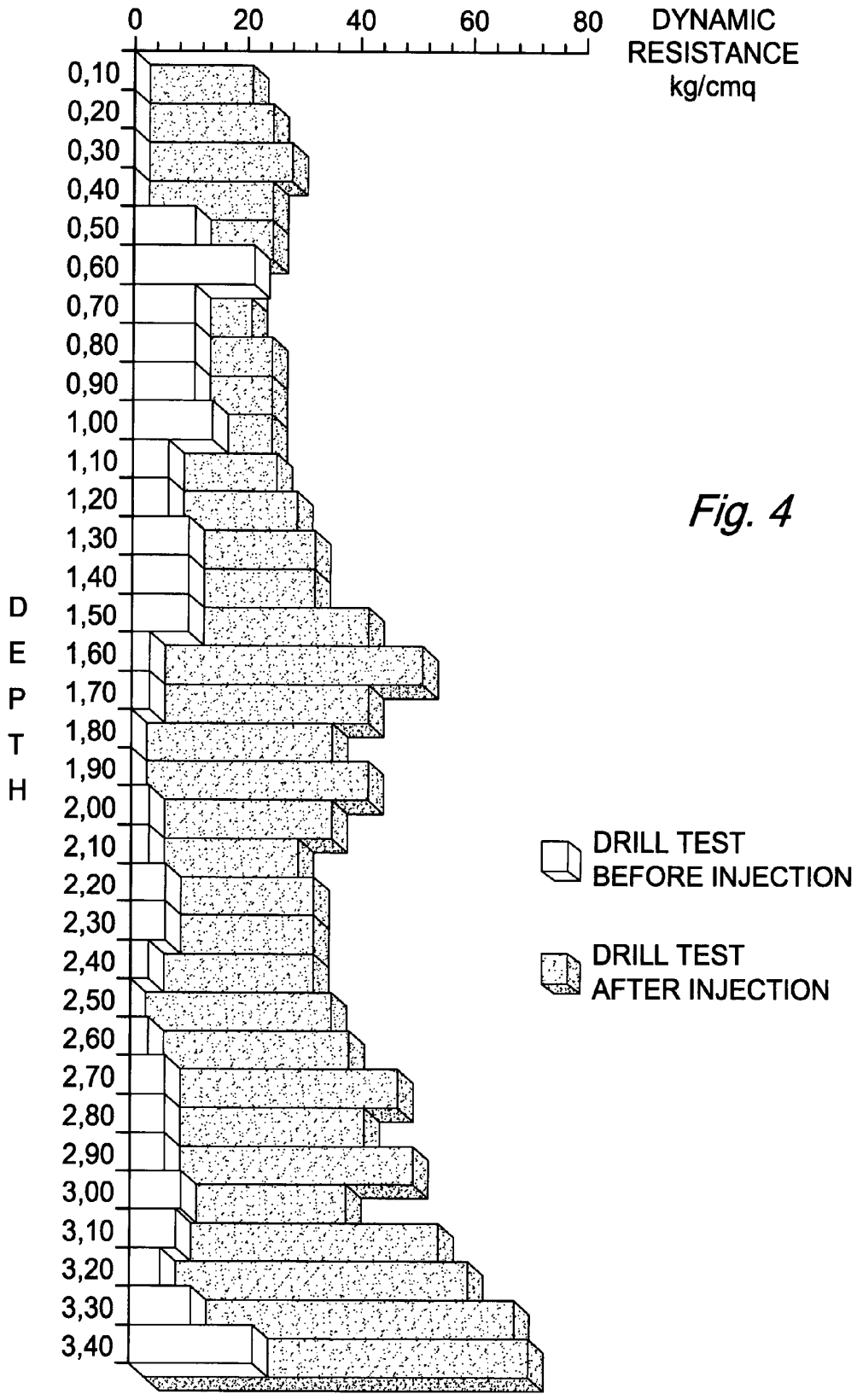
4
6
8
10
12
VOLUME WEIGHT (kN/m^3)

Fig. 3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20
40
60
80
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DEPTH
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0,20
0,30
0,40
0,50
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0,90
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2,50
2,60
2,70
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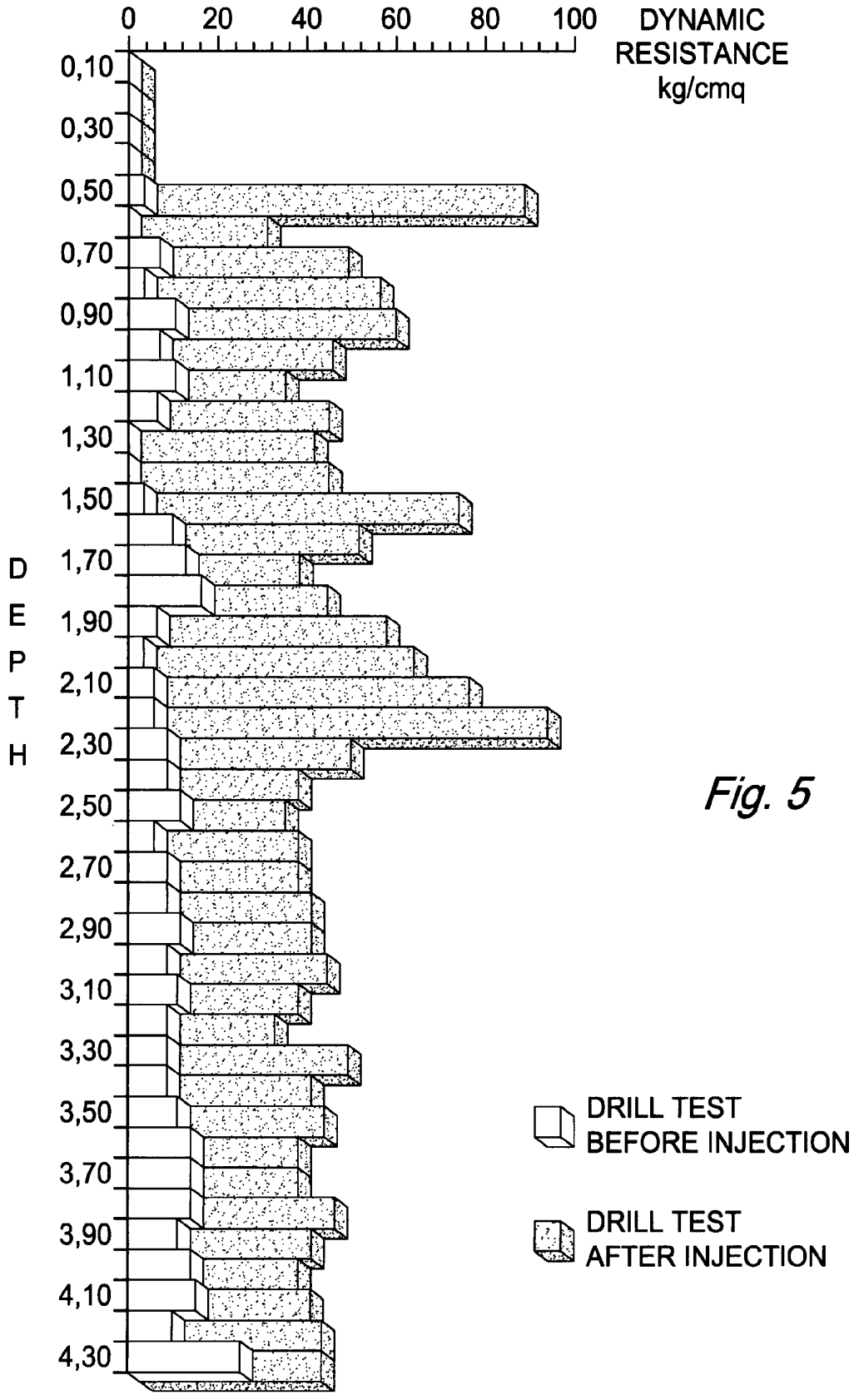
3,30
3,40
DRILL TEST BEFORE INJECTION
DRILL TEST AFTER INJECTION

Fig. 4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20
40
60
80
100
DYNAMIC RESISTANCE kg/cmq
DEPTH
0,10
0,30
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0,70
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1,10
1,30
1,50
1,70
1,90
2,10
2,30
2,50
2,70
2,90
3,10
3,30
3,50
3,70
3,90
4,10
4,30
DRILL TEST BEFORE INJECTION
DRILL TEST AFTER INJECTION

Fig. 5