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Developing Geotechnology for Permeation Grouting of Ultra Microfine Cement to Locally Countermeasure against Soil Liquefaction

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ABSTRACT

Permeation grouting by means of sodium silicate solutions has been widely used for mitigating effects of soil liquefaction on existing structures built on liquefiable soil deposits. With the recent advent of ultra microfine cement, permeation grouting using such micro-scaled cement agents has become one of the possible solutions for mitigating effects of soil liquefaction. In the present study, laboratory permeation tests are conducted to examine the effects of fines content of soils and concentration of cement solutions on the permeation of cement solutions through saturated soil specimens. Two supplementary methods are examined, which would be expected to assist in permeation of cement solutions. One method is to apply vacuum pressures at the outlet of soil specimens, in addition to applying injection pressures at the inlet of soil specimens. The other method is simply to let pure water permeate through soil specimens afterwards to let any clogged cement solutions go through. A series of field tests are also conducted at a test site in Karatsu city of Saga, Japan, to develop permeation grouting of ultra microfine cement, which is intended to be used for local soil improvement against liquefaction. The cement solutions are introduced to permeate through soil strata at one of the boreholes, and groundwater is extracted at the other bore hole, to foster permeation of cement solutions through a soil strata located in between. Some preliminary outcome of field tests is discussed in detail.

Introduction

Permeation grouting has been widely used for mitigating effects of soil liquefaction on existing structures built on liquefiable soil deposits. Most of such permeation grouting technology have been based on sodium silicate solutions, (Tsukamoto et al. 2006 & 2007). However, with the recent advent of ultra microfine cement of the order of 1 μm in particle diameter, (Kanazawa 2012), it has become possible to advance geotechnology for permeation grouting using such micro-scaled cement materials, which may be capable of producing resilient and permanent improved soil structures. In the present study, with such most liable cement grouting materials, a series of laboratory permeation tests were conducted to examine the effects of fines content of

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soils and concentration of cement on the permeation of cement solutions through saturated long soil specimens. Two supplementary methods were examined, which would be expected to assist in permeation of cement solutions through saturated long soil specimens. One supplementary method was to apply negative vacuum pressures at the outlet of saturated long soil specimens, in addition to positive injection pressures applied at the inlet of saturated long soil specimens. The other supplementary method was to let pure water permeate through soil specimens afterwards in case it was found difficult to let cement solutions permeate further in early stages of tests. A series of field tests were also conducted at a test site in Karatsu city of Saga, Japan, to examine permeation of cement solutions through some native soil deposits. In the field tests described in the present study, a borehole of extracting groundwater was supplementarily set up close to a borehole of injecting cement solutions, to examine if it would help foster permeation of cement solutions through native soil deposits.

Laboratory Permeation Tests of Cement Solutions

A series of laboratory permeation tests were conducted in the present study. Split moulds of 6 cm in inner diameter and 12 cm long were used. Soil specimens of Tohoku silica sand with different fines contents F_c were first prepared in each split mould by the method of wet tamping. The soil specimens with F_c = 0 and 20% were prepared to achieve the relative density of D_r = 80%, and those with F_c = 10 and 15% were prepared with D_r = 70% and 75%, respectively. The soil specimens prepared in the split moulds were then stacked up with one another to make up a total of 60 cm long specimen, except for one specimen of 78 cm long. Herein, the physical properties of Tohoku silica sand with different fines contents, including maximum and minimum void ratios, were determined by the testing methods stipulated by JGS (2000). Deaired water was then introduced from the bottom of the specimen and fully saturated. The cement solutions with its concentration in terms of water to cement ratios of w/c = 800% and 1200% were prepared by using some appropriate dispersing agents. The cement solutions thus prepared were then introduced from the top inlet of the long specimens with an injection pressure, p_+. In some of the tests, the vacuum pressure, p_-, was applied at the bottom outlet of the long specimens. In addition, in case it was found difficult to let the cement solutions permeate through the soil specimens, pure water was simply introduced to permeate through the soil specimens afterwards to let any clogged cement solutions go through. Figure 1(a) shows the plots of fines content of soil specimens against the travel distance of cement solutions observed in the test series. Herein, the travel distance of cement solutions is determined as the length of soil specimens solidified after some curing periods. It is found that the distance of travel tends to reduce drastically as the fines content of soil specimens increases. The concentration of cement solutions also tends to have some influence on the distance of travel, where the less concentrated cement solutions of w/c = 1200% would give longer distance of travel. The effects of application of negative vacuum pressure at the outlet of soil specimens are not clear. However, the volume of seepage water through the specimens observed throughout the tests is found larger for the specimen subjected to negative vacuum pressure than for the specimen without negative vacuum pressure, as shown in Figure 1(b). Herein, the volume of seepage water was monitored at the outlet of the saturated long specimens. On the other hand, Figure 1(a) indicates that introducing pure water afterwards would certainly tend to increase the distance of travel. For the soil specimens that the cement solutions permeated, the split moulds were dismantled 28 days after the laboratory permeation tests, and unconfined compression tests were conducted.

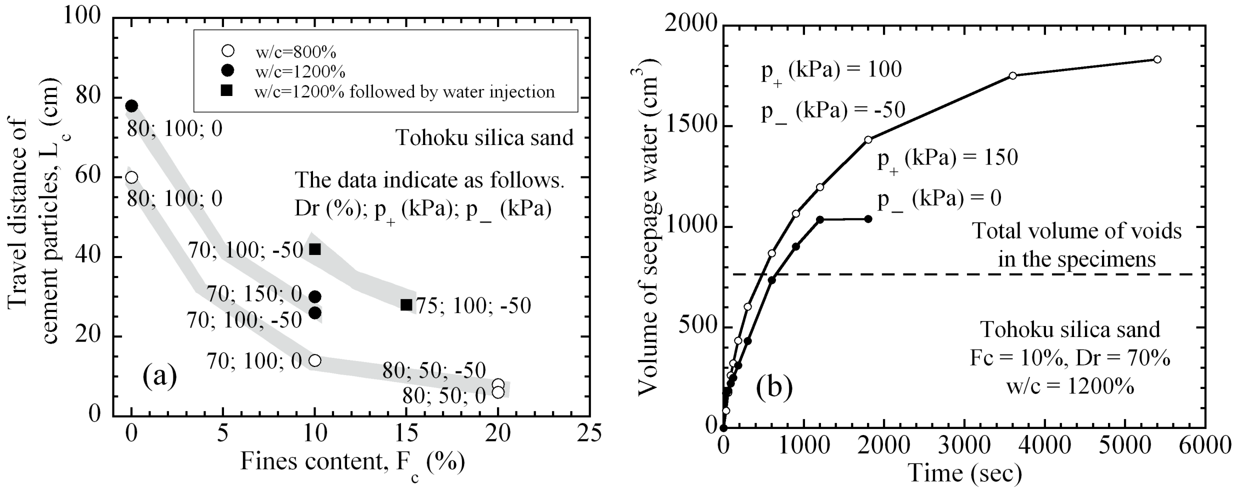

Figure 1. Plots of (a) fines content F_c of soil specimens against the travel distance of cement solutions and (b) Comparison of time history of volume of seepage water through the specimens with and without negative vacuum pressure, (F_c = 10%, D_r = 70%)

Figure 2(a) shows the data of unconfined compression strength, q_u, observed in the soil specimens of Tohoku silica sand containing no fines, plotted against the location of specimens specified as the distance from the top inlet. Quite large values of q_u are found in those tests, though such improved soils exhibiting large strength may not necessarily be useful from the viewpoint of soil liquefaction mitigations, where it would be sufficient enough for improved soils to have a q_u-value of 200 kPa for the purpose of soil liquefaction mitigations. In some of the tests, clogging of cement solutions was observed during the first phase of permeation of cement solutions. In such cases, pure water was simply introduced to permeate through the specimens to let any clogged cement particles go through.

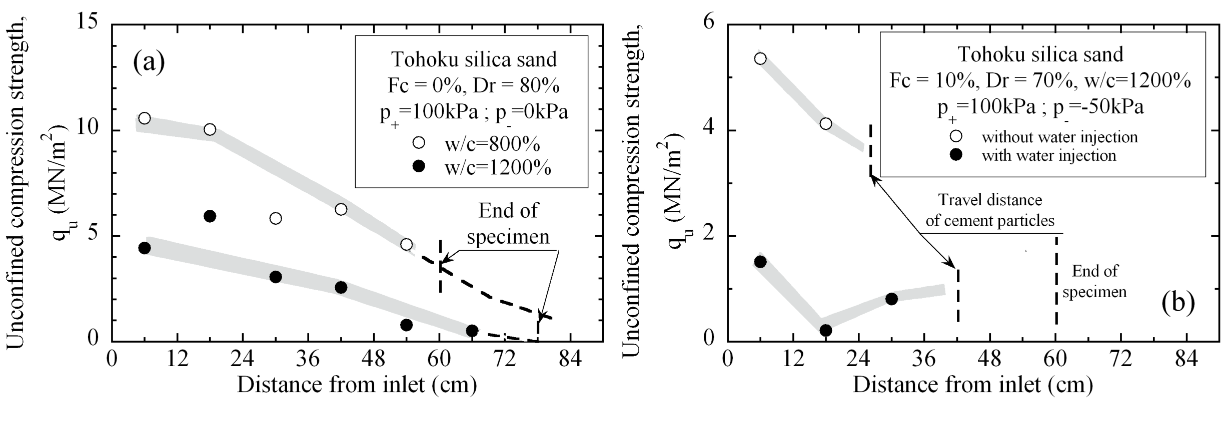

Figure 2. Plots of (a) comparison of unconfined compression strength of the specimens that cement solutions of w/c = 800% and 1200% infiltrated, (F_c = 0%, D_r = 80%, p_+ = 100kPa, p_- = 0kPa) and (b) Comparison of unconfined compression strength of the specimens with and without post-clogging pure water permeation, (F_c = 10%, D_r = 70%, w/c = 1200%, p_+ = 100kPa, p_- = -50kPa)

Figure 2(b) shows the comparison of values of q_u for the specimens which were subjected and not subjected to such permeation of pure water after clogging of cement solutions were observed. Those two tests were conducted both on the soil specimens of Tohoku silica sand containing fines of F_c = 10%. The values of q_u observed in the soil specimens having experienced permeation of pure water afterwards are found lower than those having not experienced, though would be sufficient to form improved soil structures from the viewpoint of soil liquefaction mitigations.

Field Tests on Cement Permeation Grouting

Test site and Site Condition

A series of field tests were conducted at a test site located along coastal regions in Karatsu of Saga, Japan, on December 10 and 11, 2014. The location of the test site is indicated in Figure 3. The soil profiles with SPT N-values and the physical properties of soils, mean particle diameter D_{50} and fines content F_c, are plotted against depth as shown in Figure 4. The groundwater is located at 1.5 metres below the ground surface. The top surface is certainly covered by the recent fill down to 2 metres below the ground surface, underlain by an alluvial sand layer from 2 to 5 metres below the ground surface. It is noteworthy that a thin clayey soil layer exists at a depth of about 5 metres below the ground surface, which is most likely to be less permeable. Herein, a series of field tests were conducted to let cement solutions permeate through this alluvial sand layer located from 2 to 5 metres below the ground surface. The values of fines content of this alluvial sand layer range from about F_c = 0 to 15%.

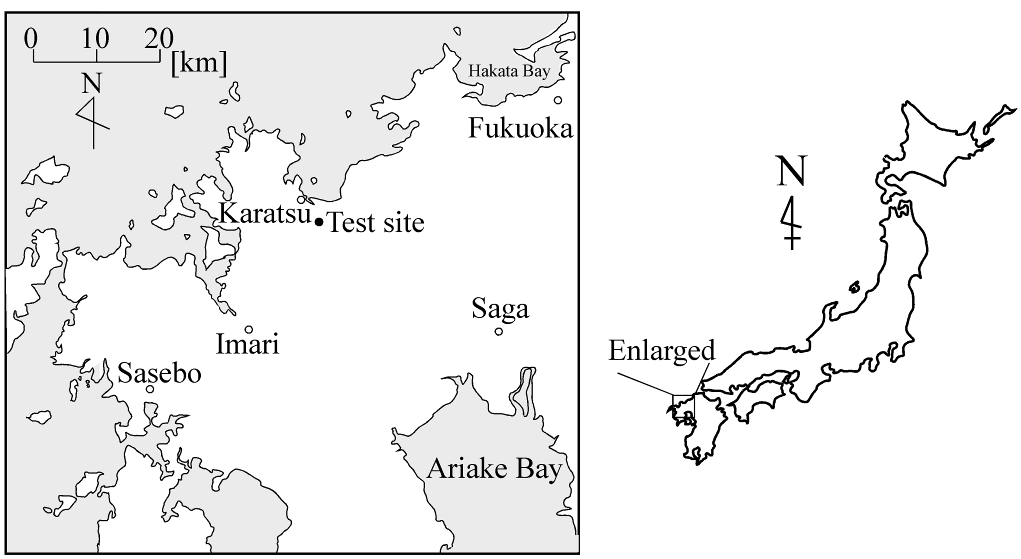

Figure 3. Location of a test site

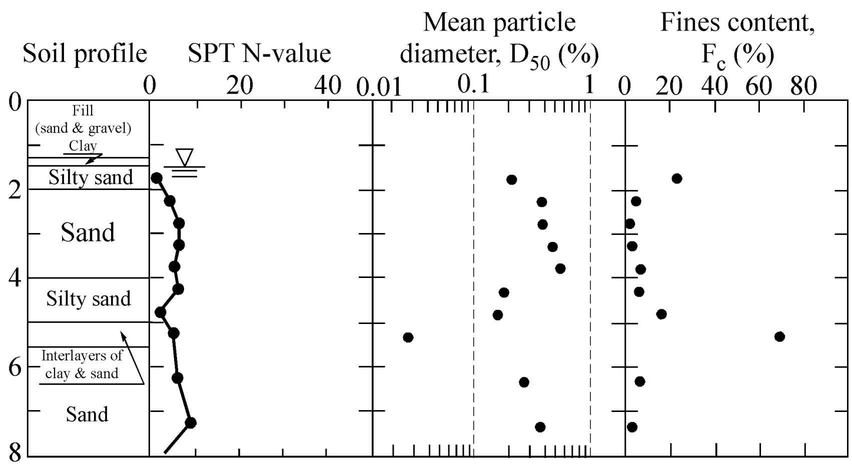

Figure 4. Soil profile and depth-wise distributions of SPT N-values and physical properties of soil deposits at a test site

Layout and Procedure of Field Tests

The layout of the test site is shown in Figure 5 in plan view. Located at the centre of four diagonally positioning testing boreholes of injecting cement solutions is a borehole of extracting groundwater. At those four testing boreholes, the injection pipes made of rigid polyvinyl chloride were installed. Those pipes were manufactured to have slit openings at depths from 2 to 5 metres below the ground surface, at which an alluvial sand layer is located. Prior to the conduct of field tests, some insitu geotechnical investigations were carried out, using Swedish weight sounding (SWS) tests. The distributions of penetration resistance N_{sw} of SWS with depth are indicated in Figure 6. It is found that the values of N_{sw} observed in these four locations vary almost from 20 to 60, and are location-dependent even at such close proximity. Figure 7(a) shows the N-values estimated from the values of N_{sw} based on the following empirical equation summarised by Tsukamoto (2015), as well as the SPT N-values shown in Figure 4.

$$N = \frac{\sqrt{e_{\max} - e_{\min}}}{10}(N_{sw} + 40) \tag{1}$$

It is possible to estimate the liquefaction resistance of soils, R_l, from the results of SWS tests, based on the empirical equation derived by Tsukamoto et al. (2015), as follows,

$$R_l = 0.016\sqrt{(N_{sw} + 40)\sqrt{\frac{98}{\sigma'_v}}} = 0.016\sqrt{N'_{sw1}} \text{ (for clean sand)} \tag{2}$$

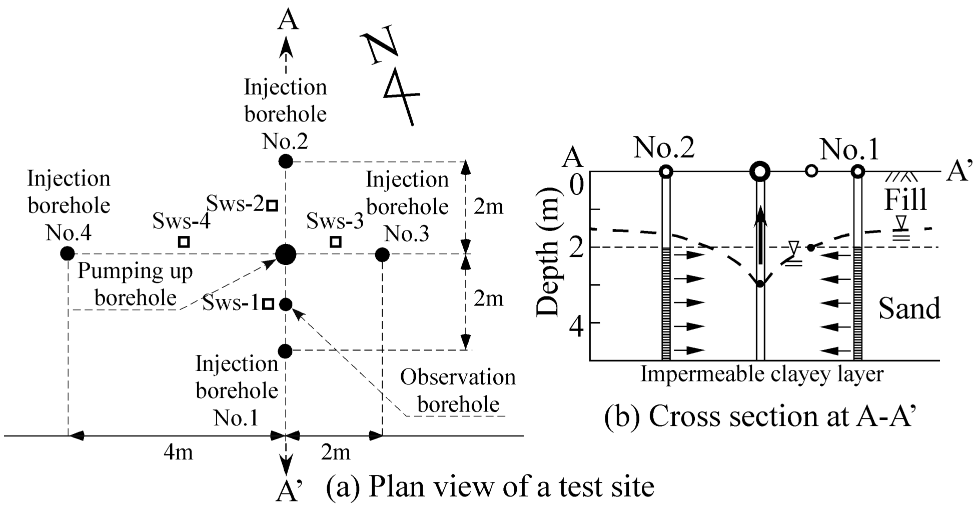

Figure 5. Layout of a test site

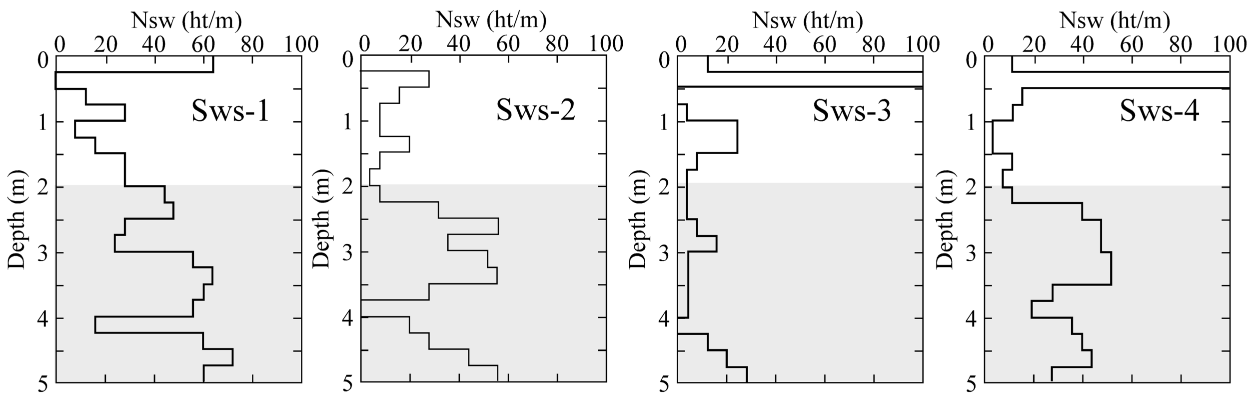

Figure 6. Results of SWS tests at a test site

It is also possible to estimate the values of R_l from the previous study by Tsukamoto (2015), in which the N-values are first estimated from the values of N_{sw}, and then the values of R_l are estimated based on the empirical expression proposed by Tatsuoka et al. (1980). The comparisons of the values of R_l estimated from the above two procedures are shown in Figure 7(b), and they are found to be relatively in good agreement. The values of the liquefaction resistance, R_l, estimated from Tsukamoto et al. (2015) are therefore plotted against depth for the locations of Sws-1 to Sws-4, as shown in Figure 7(c). The values of R_l are found low enough to induce soil liquefaction during large earthquakes.

A series of field tests were conducted on December 10 and 11, 2014. Prior to the field tests, the groundwater level at the "pumping up" borehole was lowered down 1.5 metres below the original groundwater level. At the observing borehole located in between the injection borehole and pumping up borehole, the groundwater level was found lowered down 0.5 metres below the original groundwater level. On the first day of December 10, 2014, two field tests were conducted using the testing boreholes of No.1 and No.2, where the cement solutions of w/c = 1200% were used with some appropriate dispersing agents. At those testing boreholes, it was intended that the rates of injection would have been kept constant at 20 litres/min. However, about one hour after the injection started, it rather tended to be difficult to maintain the rates of injection as the abundant cement solutions tended to overflow from the top of the boreholes fixed about 1 metre above the ground surface. Nevertheless, a total of 2200 litres of cement solutions infiltrated the testing borehole of No.1, so did 520 litres of cement solutions at the testing borehole of No.2. On the second day of December 11, 2014, the other two field tests were conducted using the testing boreholes of No.3 and No.4, where the cement solutions of w/c = 800% were used with some appropriate dispersing agents. The testing borehole of No.4 is located far from the pumping up borehole, and is intended to be free from any effects of lowering of groundwater at the pumping up borehole. Based on the difficulty of injection observed on the first day, the rates of injection were controlled and changed so as not to induce any overflow of injecting cement solutions at the testing boreholes. At the start of the tests, the rates of injection were 12 litres/min at the testing borehole of No.3 and 25 litres/min at the testing borehole of No.4. However, they gradually reduced, and about two hours and a half later, they were eventually reduced to 2 litres/min and 6.5 litres/min. A total of 960 litres of cement solutions infiltrated the testing borehole of No.3, so did 2760 litres of cement solutions at the testing borehole of No.4.

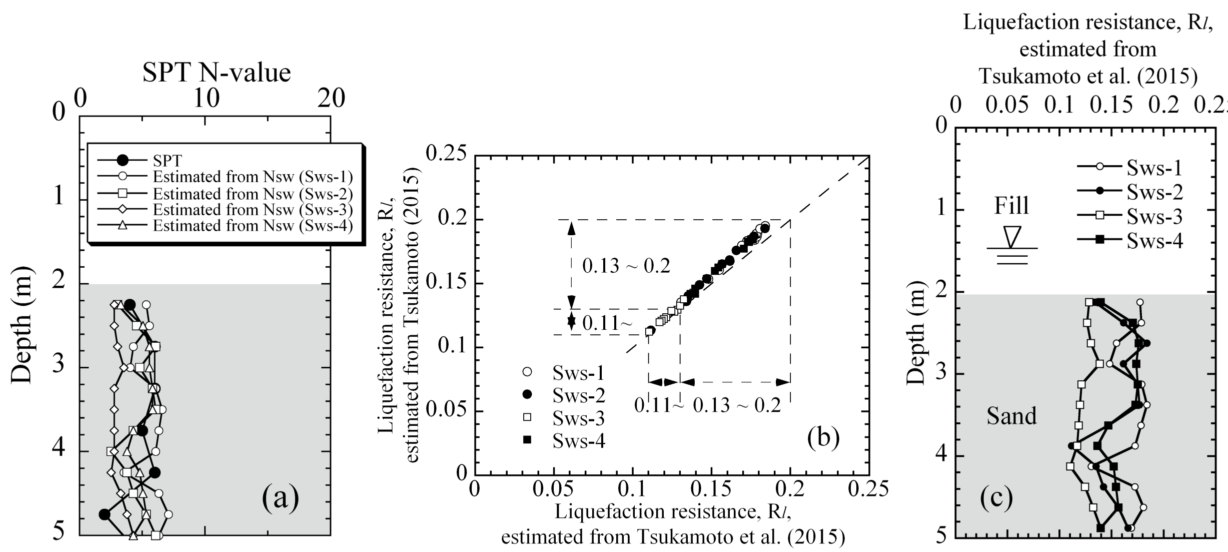

Figure 7. Plots for (a) depth-wise distributions of N-values, estimated from Tsukamoto et al. (2015) for locations of Sws-1 to Sws-4 (b) comparison of values of liquefaction resistance, R_l, estimated from Tsukamoto et al. (2015) and Tsukamoto (2015) and (c) depth-wise distributions of R_l, estimated from Tsukamoto et al. (2015) for locations of Sws-1 to Sws-4

Preliminary Outcome of Field Tests

Some preliminary field investigations were carried out to see the outcome of field cement infiltration tests about 60 days later on February 19, 2015. A series of SWS tests were carried out at the peripheries of the four injection boreholes, No.1 to 4. When the SWS testing rods hit the hard soils, it would be confirmed that cement 7tabilized soils exist, as indicated with dark grey-coloured points in Figure 8. On the other hand, when there are only soft soil layers, there would be no cement 8tabilized soils, as indicated with white-coloured points in Figure 8. All of the top surfaces of cement 8tabilized soils were found located at depths of 2.4 to 2.7 metres below a ground surface. It was found that introducing the extraction of groundwater would not have any positive effects on the cement infiltration. The injection borehole of No.4, which infiltrated the largest amount of cement, produced the largest diameter of cement 8tabilized soils.

Conclusions

Permeation grouting by means of ultra microfine cement for soil liquefaction mitigations was examined based on laboratory permeation tests as well as filed tests. Two viable assisting methods were particularly examined, which would assist in permeation of cement solutions through soils. One method is to apply vacuum pressures at the outlet of soil specimens, and the other method is to introduce pure water afterwards to let any clogged cement solutions go through. The use of those two assisting methods was found encouraging. In the field tests conducted at the test site in Karatsu city of Saga, Japan, the permeation of ultra microfine cement through some native soil deposits was tested, in which groundwater was extracted at a nearby bore hole, in order to see if permeation of cement solutions would be assisted. From the preliminary outcome of field tests, it is not largely effective to introduce the extraction of ground water for fostering cement infiltration through native soil deposits.

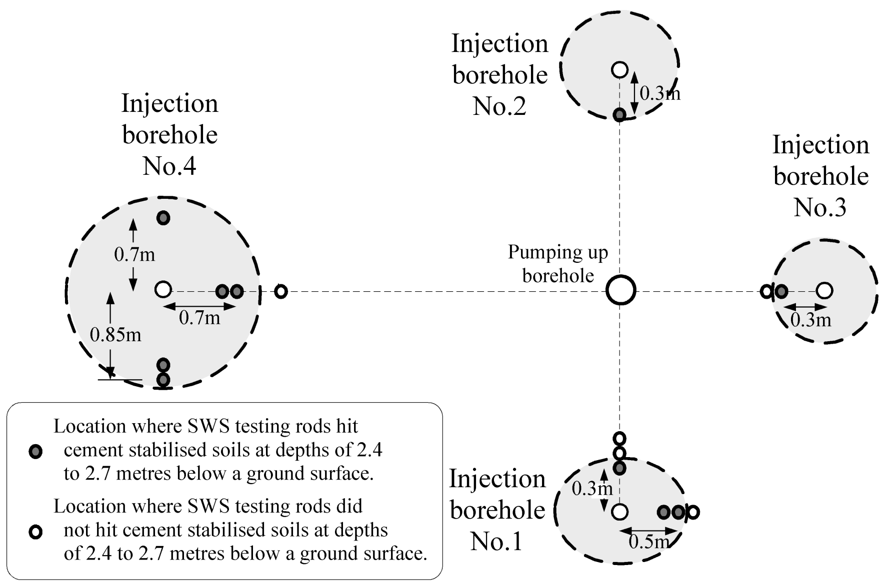

Figure 8. Areas of cement stabilised soils produced

Acknowledgments

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