Pressurized clay injection method using kaolinite for controlling groundwater of a saturated sand layer

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Abstract. In tunnel construction in the city area, NATM method is adopted for construction by the limitation of the construction condition. When classifies roughly in supporting method of construction, there are against the spring water, face stability, ground surface subsidence, cement, water glass and urethane are usually used for grouting material against the spring water, but there is the concern, such as expensive and high load on the environment because of artificial materials. On the other hand, Kaolinite is a natural material, there is less load on the environment, and many merits in the processing of the excavated muck. Therefore, we focused a pressurized clay injection method by using the above-mentioned characteristics and applied this to the construction of the underground. In this paper, the availability of the injection a fluid with a dispersion of kaolinite was discussed to summarize the applicability for controlling groundwater of the saturated sand layer. Specifically, a one-dimensional column test was conducted under the high hydraulic gradient. As a result, it was shown the possibility of effecting of decreasing hydraulic conductivity at less than one-order. Consequently, it is concluded hydraulic conductivity of sand layer was able to be reduced by Kaoline clay suspension.

1. Introduction

For tunnel construction on the ground in the city area, the NATM (New Austrian Tunneling Method) is adopted by the limitation of the construction condition [1]. However, like the Hakata station square cave-in accident, which occurred on November 8, 2016, there is a concern to influence the surface of the ground with the progress of the construction. Therefore, several supporting methods of the construction based on the engineering-like approach should be chosen to prevent a similar accident. Spring, face stability, and ground surface subsidence measurements affect the selection of the supporting methods in each particular case. Water glass and urethane are usually used as the grouting material, but there are the concerns about high cost and high load on the environment of artificial materials. However, cement (e.g., portland, micro–fine) or clay (e.g., bentonite) suspension grout technologies were developed for fractured rock and porous media. Laboratory experiments were carried out to investigate the hydrodynamic properties of grouts, pressure gradient at the onset of the flow, and subsequent process of permeation [2]. Ultrafine cement grains agglomerated easily in suspension grout and formed many grains with larger size than the maximum cement size of 0.0012 mm, and this would be the main reason why the grout tends to be injected unsatisfactorily into the fine sand [3]. Bentonite grouts were also injected into sand columns prepared under various experimental conditions to evaluate the effect of each
experimental parameter on their penetration lengths, and the results show that the penetration length of bentonite grouts decreases with the decrease in the water–bentonite ratio and the increase in the yield stress and apparent viscosity [4].

Kaolinite is a natural material, causing smaller load on the environment and with many advantages in the processing of the excavated muck. A non–pressurized kaolin clay grouting method by using non–hardening and non–swelling characteristics was applied to the construction of underground oil storage caverns [4]. This study did not use pressurized injection with a grouting pump, because of clay weakness and instability as a grouting material. It took long time to reduce the permeability of the extensive rock mass by pouring diluted clayey water into the rock. Therefore, we focused on a pressurized clay injection method by using the above–mentioned characteristics and applied it to the construction of the underground. In this paper, the availability of the injection of a fluid with dispersed kaolinite was discussed to summarize the method applicability to controlling groundwater of a saturated sand layer. Specifically, a one-dimensional column test with a diameter of 10 cm and a length of 50 cm using river sand was conducted in the laboratory and a three-dimensional spherical domain under a high hydraulic gradient. This experimental study aims to estimate the optimal clay–water compounding weight (c/w) ratio maximum to reduce the hydraulic conductivity of sand with suspension injection.

2. Method

2.1. Test equipment and procedures
The schematic diagram of the experimental apparatus are shown in figure 1. The test specimen was set up into a column made of acrylic with a diameter of 10 cm and a length 50 cm with a stainless steel mesh (109 μm) and a porous plate at both ends using the waterfall method. The relative density of specimen was increased by hitting it around the column by hand. The water head acted on the specimen, and the passing water flow quantity was measured by a differential pressure gauge at the head difference in the cap of the inflow/outflow, using a flow meter installed at the outflow side of the test specimen. The injection pipe with opening rate 45% is 1 cm in diameter and 5 cm in length, stainless steel mesh (109 μm) was wound around it. It was installed in the central location of the test specimen.

![Figure 1. Schematic diagram of the experimental apparatus.](image-url)
Figure 2. Grain size accumulation curve.

Table 1. Physical properties of the samples.

| Physical properties | Clay | Sand |
|---------------------|------|------|
|                     | c3   | c5   | c7   |      |
| Soil grain density, $\rho_s$ (g/cm$^3$) | 2.748 | 2.736 | 2.713 | 2.682 |
| 15% grain size, $D_{85}$ (μm) | 7.49  | 7.48  | 12.36 | 610   |
| 50% grain size, $D_{50}$ (μm) | 6.14  | 6.33  | 10.95 | 326   |
| 85% grain size, $D_{15}$ (μm) | 3.16  | 3.27  | 4.53  | 155   |
| Uniformity coefficient, $U_c$ | 1.02  | 1.02  | 1.02  | 2.75  |
| Curvature coefficient $U_c'$ | 1.94  | 1.90  | 2.12  | 0.92  |
| Mean grain diameter (μm) | 4.93  | 5.03  | 7.48  | 292   |

2.2. Materials

Figure 2 illustrates the grain size accumulation curve of the sample used in this experiment. The sand sample is from the river of Okayama. The residues were flushed in a mesh with a size of 106 μm to prevent clogging. Three types of clays (c3, c5, and c7) with various mean grain diameters (M.P.D.s) were prepared (c3:M.P.D. = 4.93 μm, c5:M.P.D. = 5.03 μm, and c7:M.P.D. = 7.48 μm). The soil grain density ($\rho_s$), grain size, uniformity coefficient, and curvature coefficient of each sample are listed in table 1. Figure 3 illustrates the viscosity of clay suspensions for various clay–water weight (c/w) ratios. Then rotational viscometer tests were carried out for each suspension. The grain size of c5-type clay is approximately the same as that of c3, and that of c7 is the largest. In addition, c3 and c5 resemble the viscosity coefficient, but c7 shows that the viscosity does not increase even if the c/w ratios are increased.

2.3. Flow condition before the injection

Based on the construction example [1] of the tunnel, the largest hydraulic gradient and velocity acting in front of the working face were calculated by using the numerical seepage analysis. As a result, the water level of the inflow/outflow difference condition before the injection of clay suspension was set so that the hydraulic gradient is $i = 2.7$ when the largest Darcy velocity acting in front of the working face is $v_d = 2.55E-1$ cm/s.

2.4. Experiment condition setting

Table 2 lists the experimental cases and the physical properties of single clay suspensions. Based on
Table 2. Experimental cases and physical properties of single clay suspensions.

| Case | Clay suspension | Coefficient of viscosity η (dPa·s) | Dry density ρd (g/cm³) | Porosity n (%) | Darcy velocity νd (cm/s) | Hydraulic conductivity k (cm/s) |
|------|-----------------|-------------------------------------|-------------------------|----------------|--------------------------|-------------------------------|
| c3   |                 |                                     |                         |                |                          |                               |
| 1    | 0.130           | 0.15                                | 1.665                   | 0.382          | 3.25E-1                  | 1.28E-1                       |
| 2    | 0.250           | 1.46                                | 1.667                   | 0.381          | 3.20E-1                  | 1.18E-1                       |
| 3    | 0.300           | 2.52                                | 1.655                   | 0.385          | 3.65E-1                  | 1.40E-1                       |
| 4    | 0.400           | 5.70                                | 1.720                   | 0.361          | 2.41E-1                  | 9.09E-2                       |
| c5   |                 |                                     |                         |                |                          |                               |
| 1    | 0.100           | 0.17                                | 1.721                   | 0.361          | 2.56E-1                  | 9.57E-2                       |
| 2    | 0.210           | 2.51                                | 1.718                   | 0.362          | 2.25E-1                  | 8.50E-2                       |
| 3    | 0.250           | 4.60                                | 1.714                   | 0.363          | 2.73E-1                  | 9.97E-2                       |
| 4    | 0.350           | 12.90                               | 1.707                   | 0.366          | 2.79E-1                  | 1.03E-1                       |
| c7   |                 |                                     |                         |                |                          |                               |
| 1    | 0.100           | 0.03                                | 1.719                   | 0.361          | 2.27E-1                  | 8.37E-2                       |
| 2    | 0.300           | 0.10                                | 1.656                   | 0.385          | 3.15E-1                  | 1.19E-1                       |
| 3    | 0.350           | 0.10                                | 1.731                   | 0.357          | 2.74E-1                  | 1.04E-1                       |
| 4    | 0.450           | 0.29                                | 1.702                   | 0.368          | 2.52E-1                  | 9.80E-2                       |
| 5    | 0.500           | 0.43                                | 1.698                   | 0.369          | 2.73E-1                  | 1.00E-1                       |
| 6    | 0.520           | 1.10                                | 1.700                   | 0.369          | 2.67E-1                  | 1.04E-1                       |
| 7    | 0.560           | 1.68                                | 1.738                   | 0.354          | 2.71E-1                  | 9.84E-2                       |
| 8    | 0.640           | 3.06                                | 1.676                   | 0.378          | 3.63E-1                  | 1.40E-1                       |
| 9    | 0.730           | 5.11                                | 1.655                   | 0.385          | 3.25E-1                  | 1.23E-1                       |
| 10   | 0.800           | 7.58                                | 1.698                   | 0.369          | 2.98E-1                  | 1.15E-1                       |

Table 3. Experimental cases and physical properties of mixed clay suspensions.

| Case | Clay suspension | Coefficient of viscosity η (dPa·s) | Dry density ρd (g/cm³) | Porosity n (%) | Darcy velocity νd (cm/s) | Hydraulic conductivity k (cm/s) |
|------|-----------------|-------------------------------------|-------------------------|----------------|--------------------------|-------------------------------|
| c3:c7 =1:1 |                 |                                     |                         |                |                          |                               |
| 1    | 0.167           | 0.14                                | 1.684                   | 0.374          | 2.95E-1                  | 1.14E-1                       |
| 2    | 0.260           | 0.44                                | 1.707                   | 0.366          | 2.45E-1                  | 9.03E-2                       |
| 3    | 0.270           | 0.80                                | 1.734                   | 0.356          | 2.47E-1                  | 9.33E-2                       |
| 4    | 0.300           | 1.31                                | 1.721                   | 0.361          | 2.43E-1                  | 8.95E-2                       |
| 5    | 0.350           | 1.86                                | 1.727                   | 0.358          | 2.33E-1                  | 8.59E-2                       |
| 6    | 0.400           | 2.83                                | 1.709                   | 0.365          | 2.47E-1                  | 9.57E-2                       |
| 7    | 0.500           | 5.67                                | 1.702                   | 0.368          | 2.74E-1                  | 1.01E-1                       |
| c3:c7 =1:2 |                 |                                     |                         |                |                          |                               |
| 1    | 0.200           | 0.13                                | 1.731                   | 0.357          | 2.28E-1                  | 8.41E-2                       |
| 2    | 0.325           | 1.11                                | 1.727                   | 0.358          | 2.03E-1                  | 7.68E-2                       |
| 3    | 0.340           | 1.18                                | 1.714                   | 0.363          | 2.50E-1                  | 9.69E-2                       |
| 4    | 0.600           | 8.23                                | 1.733                   | 0.356          | 2.84E-1                  | 1.07E-1                       |
| c3:c7 =2:1 |                 |                                     |                         |                |                          |                               |
| 1    | 0.200           | 0.27                                | 1.719                   | 0.361          | 2.48E-1                  | 9.13E-2                       |
| 2    | 0.270           | 1.06                                | 1.698                   | 0.369          | 2.56E-1                  | 9.94E-2                       |
| 3    | 0.340           | 2.11                                | 1.709                   | 0.365          | 2.19E-1                  | 8.52E-2                       |
the relationships between the c/w ratio and the viscosity shown in figure 3, the cases of c3 and c5 enforced four cases in the ranges of c/w = 0.13–0.4 and 0.1–0.35, respectively. The case of c7 enforced ten cases in the range of c/w = 0.1–0.8. Non-uniformity is recognized by the dry density under the condition of the test specimen shown in table 2, but the Darcy velocities are shown almost near the set value (v_d = 2.55E-1 cm/s).

Table 3 lists the experimental cases and the physical properties of mixed clay suspensions. Here, c3 and c7 with significantly different grain sizes and viscosities are chosen and combined by the dry weight. The case of c3:c7 = 1:1 enforced seven cases in the range of c/w = 0.167–0.5, c3:c7 = 1:2 and c3:c7 = 2:1 enforced each four cases in the range of c/w = 0.2–0.6.

3. Results and discussion

3.1. Results for single clay suspensions

Figure 4 illustrates the hydraulic conductivity before the injection (k_0) and after the injection (k). The values of c/w = 0.25 and 0.21 of c3 and c5, respectively, show the lowest k. However, c7 has a small decrease rate, as compared to c3 and c5, and the ranges of c/w = 0.45, 0.55, 0.73 show lower values. Based on figure 4, the ratio of the hydraulic conductivity (k/k_0) is shown in figure 5. The value smaller than k/k_0 = 0.1 shows that the hydraulic conductivity after the injection of the clay suspension decreases more than by one order. It is intended that there is the optimal c/w ratio value of c3 and c5 and the range of c7 to reduce the hydraulic conductivity.
Figure 6. Quantity of suspension injection ($V_c$).

Figure 6 and figure 7 illustrate the quantity of suspension injection ($V_c$) and the clay injection mass ($m_c$). Although in this result, $V_c$ is larger, so that the c/w becomes low, $m_c$ shows the peak value at c/w = 0.25 and 0.21 of c3 and c5, c/w = 0.64 of c7, except for the range of c/w = 0.35–0.50. In other words, if the c/w ratio is small, the quantity of injection is large, but the mass of the clay included in the suspension is small. However, the mass of the clay decreases when the c/w ratio becomes large because of small injection quantity.

3.2. Results for mixed clay suspensions

The results in the case of mixed clays are shown in figures 8–10 in the same way as the results of the single clays in figures 4–7. Figure 8 shows that the graphical shape of c3:c7 = 1:1 is similar to that of c3, but with a slight shift forward to a large c/w; c/w = 0.3 shows the lowest $k$. Although the characteristic of c3 is mostly appeared, the reason is attributed to the action of c7 when the viscosity decreased. It is shown that the graphical shape of c/w = 0.35–0.40 is similar to c7 in figures 9–11.

When c3:c7 = 1:2 and c3:c7 = 2:1 are compared with c3:c7 = 1:1 for the same c/w, the decrease rate of $k/k_0$ is approximately the same as that of c3:c7 = 1:1 at c3:c7 = 1:2, but the quantity of injection becomes near that of c3:c7 = 1:1, whose value becomes near that of c3 at c3:c7 = 2:1. Therefore, because the viscosity decreases by the characteristic of c7 in comparison to that of c3:c7 = 1:1 at c3:c7 = 1:2, the quantity of injection becomes large. Nevertheless because the viscosity increases at c3:c7 = 2:1 when $k/k_0$ decreases as compared to that of c3:c7 = 1:1, the injection quantity increases, and it is suggested that the c3–like effect is provided by the action of c3.

Figure 8. Hydraulic conductivity before the injection ($k_0$) and after the injection ($k$).

Figure 9. Ratio of the hydraulic conductivity ($k/k_0$).
3.3. Discussions

The specimens were dismantled after the experiments, and sand and clay were separated using a mesh with a size of 106 μm. The results of the measurement of the clay mass that resided in the specimens by oven drying for the single and mixed clay suspensions are shown in figure 12 and figure 13, respectively. These results show that there was the optimal value of c/w (c3: 0.25, c5: 0.21, c7: 0.55, c3:c7 = 1:1; 0.30, c3:c7 = 1:2; 0.34, c3:c7 = 2:1; 0.27) to let most clays remain in the specimens.

Based on these results in figure 7 and figure 11, the results of residual clay ratio are shown in figures 14 and 15, respectively. Except for c/w = 0.56–0.73 for c7, as the c/w ratio becomes low, the residual clay ratio becomes small, and it is known that clay is easy to remain in the specimen so that the c/w ratio is high. It is shown in the remaining rate of the single c7 substance for c/w = 0.63 that most of the suspension injected at a small amount leaks through the specimen.

In addition, the relationships between the residual clay mass (mₗ') and the ratio of the hydraulic conductivity (k/k₀) are shown in figure 16. It is clear that the hydraulic conductivity lowered after the injection so that a large amount of mass remained in the test specimens. Figure 17 illustrates the relationships between the residual clay ratio (mₗ'/mₗ) and the ratio of the hydraulic conductivity (k/k₀). It is known that around 50–60% of c7, and 20–40% of c3, c5, c3:c7 = 1:1, c3:c7 = 1:2 and c3:c7 = 2:1 leak by the c/w ratio that can lower the hydraulic conductivity after the injection. From these results, it was suggested that the most suitable combination ratio existed for the hydraulic conductivity decrease.
Figure 14. Residual clay ratio ($m_c'/m_c$) of the single clay suspensions.

Figure 15. Residual clay ratio ($m_c'/m_c$) of the mixed clay suspensions.

Figure 16. Relationships between the residual clay mass ($m_c'$) and the ratio of the hydraulic conductivity ($k/k_0$).

Figure 17. Relationships between the residual clay ratio ($m_c'/m_c$) and the ratio of the hydraulic conductivity ($k/k_0$).

4. Summary and conclusions

In this paper, the availability of the injection of a fluid with a dispersed kaolinite was discussed to summarize its applicability to controlling groundwater of a saturated sand layer. Specifically, a one-dimensional column test with a diameter of 10 cm and a length of 50 cm using river sand was conducted in the laboratory and a three-dimensional spherical domain under a high hydraulic gradient ($i = 2.7$). From this experimental results, it was suggested that the most suitable combination (optimal) clay–water weight (c/w) ratio existed for maximum to reduce the hydraulic conductivity (near or less than by one–order) of sand with suspension injection.

References

[1] Takahashi K, Mitsumasu T, Yoshimoto H, Oogane T and Komatsu M 2018 Adoption Example of the Tunnel Auxiliary Construction Method for Soft Unconsolidated Ground in Urban Area Using the Mountain Tunneling Method, NATM Ground Engineering 35(1) 153-60 (Chugoku Branch of Japanese Geotechnical Society) (in Japanese)

[2] Honma S and Kamash W El 2011 Method for estimating the maximum permeation range of suspension grout in soils Proc. Schl. Eng. Tokai Univ., Ser. E  36 p 15-20

[3] Miyanaga Y, Makita T, Ebara M and Hatano T 1994 A Non-Pressurized Grouting Method using Clay for Controlling Groundwater - A Theory of Clay Grouting and the Construction Record of Kuji Underground Oil Storage Plant J. of the Japan Society of Engineering Geology 35(4) 23-35 (in Japanese with English abstract)

[4] Mohtar C S E, Yoon J and El-Khattab M 2015 Experimental study on penetration of bentonite grout through granular soils Can. Geotech. J. 52 1850-60