Proposal Of Permeability Evaluation Method Of Suspension Grout

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ABSTRACT: Large earthquakes have occurred and caused liquefaction damage in urban areas in Japan every few years. Recently, the applicability of suspension grout has been expanded because of the development of micronized technology of particles. Permeability of suspension grout has been conventionally evaluated using groutability ratios obtained from sizes of micro-particles contained suspension grout and particle size of soil. The problem is that permeability is affected not only by grain size of micro-particles of grout but also pore structure. In this study, in order to evaluate permeability of micro-particles more accurately, the pore index was proposed, which can be calculated from the Kozeny-Carman equation. And from the results of one-dimensional permeation experiments of micro-particles, it was confirmed that permeability of suspension grout can be evaluated accurately by the pore index.
Keywords: suspension grout, coefficient of permeability, pore index.

1. INTRODUCTION

Grouting materials for chemical grout injection methods are categorized into two types; solution and suspension. Generally, the solution type of chemical grout has been used for the liquefaction countermeasures under existing buildings. However, this type of grout is unsuitable for residential areas because of its high construction cost. On the other hand, the suspension type of grout has been mainly applied for the improvement of ground under important buildings because of its high strength. However, the permeability of suspension grout is lower than that of solution grout (Yoneda et al 1994). Since the size of micro-particles of suspension grout is close to that of pore, there is possibility of clogging. Therefore, suspension grout has been used for only coarse soil. Recently, however, micro-particles under sub-μm such as spherical silica grout (Naito et al. 2010) was developed by the latest micronization technology. Herewith, the permeability of micro-particles has been improved and the applicability of suspension grout has been expanded.

For reasonable design in chemical grout injection method, it is necessary to confirm the permeability of chemical grout and its gel-time beforehand. In particular, since the permeation of suspension grout can be impeded because of clogging of micro-particles in the pore of soil, it is essential to confirm the permeability of micro-particles to soil. However, most researches in the permeability of suspension grout have mainly targeted the application to cracks of rock (Yoneyama et al. 2015).

In this study, first, previous researches in the permeability of suspension grout are reviewed. Next, from the results of one-dimensional permeation experiments of micro-particles, a new permeability evaluation method is proposed.

2. PREVIOUS STUDIES ON SUSPENSION GROUT PERMEABILITY

Permeability of suspension grout has been conventionally evaluated using "groutability ratios" (hereinafter referred to as G_r) obtained from size of micro-particles contained suspension grout and particles size of soil (Mitchell 1981). G_r is proposed in conformity to the theory that pore size is closely related to that of soil. Gr is expressed in Eq. (1).

$$G_r = \frac{D_{15}}{D_{85}} \quad (1)$$

$G_r < 11$ not possible of grouting
$G_r > 15$ possible of grouting

where D_{15} is grain size of soil at 15% and G_{85} is particle size of grouting material at 85% in its grain size accumulation curve, respectively. Here, G_r was originally defined as filter criteria to prevent outflows of fine particles through a filter attached to pipe drainage (Terzaghi et al. 1948). In the previous studies of G_r (Johnson 1958 and Mitchell 1970), the applicability of G_r was discussed.

However, the permeability of micro-particles is affected by not only grain size of particles but also characteristics of suspension grout. For examples, the effect of particles viscosity on permeability was confirmed through the injection tests where suspension grouts with different viscosities were injected to sand deposit and cracks of rock (Yoneda et al. 1993). The permeability was expressed as viscous fluid to analyse the behaviour of permeation of suspension grout (Yoneyama et al. 2015). While the effects of grouting pressure, relative density and concentration of grout were indicated (Akbulut et al. 2002).

In addition, permeability is subjected to be affected by characteristics of pore of soil as well. It was indicated that the permeability of micro-particles changed depending on the relative density and the fine content of the soil (Zebovitz et al. 1989). A distribution of pore diameter of sand skeleton was measured by " air intrusion method" (Kamiya 1999) and based on these results, the relationship between capillary spreading pore of soil and grain size distribution was formulated using " diameter estimating grain size distribution" (Fukuda et al. 1997, Kamiya 1999). In the researches, the permeability of micro-particles was evaluated from a comparison of the size of micro-particles and the minimum size of pore of soil which was estimated from an uniformity coefficient, a void ratio and grain size of soil at 50% in its grain size accumulation curve. Moreover, in order to prevent an outflow of fine particles from filters, a stability index of filters was derived from "the constriction size of filter" (Kenny et al. 1985).

As known from the previous studies, the permeability of micro-particles was evaluated by the comparison of a pore diameter and a diameter of micro-particles. However, a particular experimental apparatus is required to estimate pore diameter so that it is difficult to apply these methods for practical constructions. In this study, the pore index was proposed, which is an estimation value of pore diameter obtained from a coefficient of permeability of soil. Since the coefficient of permeability can be generally estimated from a preliminary investigation in chemical grout injection method, this method is easier for permeability evaluation and suitable for practical constructions.

In this paper, in order to establish a new evaluation method, the pore index was formulated from the Kozeny-Carman equation and its applicability was confirmed through one-dimensional permeation experiments of micro-particles for mixed sand

Table 1 Properties of Samples

Sample No.	D_{15} (mm)	U_c
1	0.276	1.30
2	0.273	2.20
3	0.271	3.12
4	0.269	5.11
5	0.228	5.07
6	0.180	5.06
7	0.140	5.09
8	0.200	5.14
9	0.208	4.06
10	0.308	2.97
11	0.288	3.86
12	0.238	5.35
13	0.217	5.51
14	0.469	1.44
15	0.257	1.57
16	0.210	1.43
17	0.108	1.62

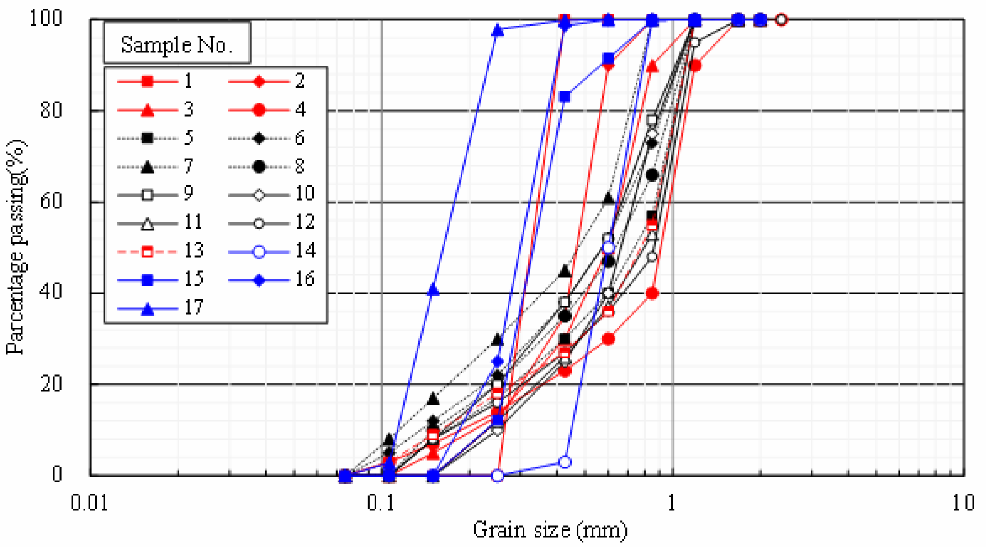


Figure 1 Grain size distribution of sand samples

3. DERIVATION OF PORE INDEX

In order to estimate the permeability of micro-particles more accurately, it is necessary to evaluate pore diameter of soil. In this chapter, a derivation method of the pore index is proposed using the Kozeny-Carman equation which is based on the Hagen-Poiseuille equation (Loudon et al. 1999).

The Kozeny-Carman equation (Emmanouil et al. 2012) was chosen among the several previous studies regarding coefficients of permeability of soil in this paper because this equation is formulated from the pore conditions of soil such as grain size of soil, porosity *n*, and correction of curvilinear pipe in pore of the soil skeleton. Assuming that pore of the soil skeleton is circular capillary tube, actual velocity v' in a circular tube is expressed as Eq. (2).

$$v' = \frac{r^2 \rho_w g}{32\mu_w} \frac{\partial h}{\partial x} \tag{2}$$

where r is diameter of circular tube (cm), ρ_w is density of water (g/cm^3), μ_w is viscosity of water (g/(cm・s)), g is acceleration of gravity (cm/s^2) and $\partial h/\partial x$ is hydraulic gradient. In Eq. (2), diameter of circular tube r is estimated as uniform pore diameter of soil skeleton. In this paper, estimated r is defined as the pore index d; an index to evaluate permeability of micro-particles.

Next, actual velocity v' in Eq. (2) is converted to Darcy velocity v, to be applied for the permeation in pore of the soil skeleton. Since v' is velocity of flow in pore of the soil skeleton, it is necessary to consider bending-related extension of pipe in pore of the soil skeleton when converting. The relationship of actual velocity v' and Darcy velocity v is expressed as Eq. (3)

$$v' = \frac{1}{n} \frac{l_r}{l} v \tag{3}$$

where l is a length of soil specimen (cm), l_r is length of bending-related extension of pipe in pore of the soil skeleton (cm) and n is porosity of the soil. Then, l_r expresses the actual length of the flow channel. Eq. (4) is obtained by substituting Eq. (3) for Eq. (2).

$$v' = \frac{l_r}{l} \frac{nd^2 \rho_w g}{32\mu_w} \frac{\partial h}{\partial x} \tag{4}$$

Assuming that Darcy flow can be applied for permeation in pore of the soil skeleton, Eq. (4) is converted to Eq. (5)

$$v' = \frac{1}{32} \frac{l_r}{l} \frac{nd^2 \rho_w g}{\mu_w} \tag{5}$$

where k is a coefficient of permeability.

In Eq. (5), circular channel is assumed and according to Carman (Carman et al. 1937), ratio of l_r to l (l_r/l) is approximately 2.5. Therefore, the pore index d is expressed as Eq. (6).

$$d = 4\sqrt{5 \cdot k \frac{\mu_w}{n \rho_w g}} \tag{6}$$

As seen from Eq. (6), the pore index d is not depending on grain size of soil particles but the coefficient of permeability and the porosity. Furthermore, containing the parameter of viscosity of fluid, Eq. (6) can be applied for the cases even when grouting material is regarded as viscous fluid.

4. PERMEABILTY EVALUATION METHODS OF MICRO-PARTICLES

In order to confirm the applicability of the pore index for permeability evaluation of micro-particles, one-dimensional permeation experiments were carried out. First, soil samples for these experiments were introduced. Next, the pore indexes of soil samples were estimated from coefficients of permeability samples. Finally, from the results of one-dimensional permeation experiments of micro-particles, applicability of the pore index was confirmed.

4.1 Summary of samples for permeation experiments

The samples used for the experiments were mixed sand with 0.075mm to 2.000mm in diameter. The conditions and the grain size distribution of the samples are shown in Table. 1 and Figure 1. In order to consider the effect of uniformity coefficient; U_c and the grain size of soil at 15%; D_{15} on permeability of micro-particles, mixed sand was prepared by mixing classified sands. The D_{15} of samples No.1 to No.4 were made to be same. In order to confirm the effect of uniformity coefficient, U_c on permeability of micro-particles, the U_c of samples No.5 to No.13 were set at 3.0 to 5.5. Then, U_c of samples No.14 to 17 were made to be same to compare the change of the coefficients of permeability depending on the particle sizes.

4.2 Permeability tests of mixed sand

In order to calculate the pore index, permeability tests were carried out on each sand sample shown in Figure 2. The specimens for permeability tests were prepared to be 5.0cm in diameter and 10.0cm tall and their void ratio e was set at 0.82 by air-pluviation method. Only in the sample No.16, the void ratio was set at e 0.70. Then, CO_2 gas and de-aired water were infiltrated into them to heighten the saturated rates and permeation tests were conducted. Here, the coefficients of permeability of specimens were the average of three values measured within 0.5 of hydraulic gradient.

The results of permeability tests were shown in Figure 2. Since the void ratios e of specimens were almost equal, the dispersion in the permeability seen in Figure 2 was likely to be caused by the differences in uniformity coefficient; U_c and grain size of sand particles. Therelationship between the calculated pore index d and the grain size of soil at 15% D_{15} is shown in Figure 3. From the figure, the pore index d cannot be expressed by D_{15} uniquely.

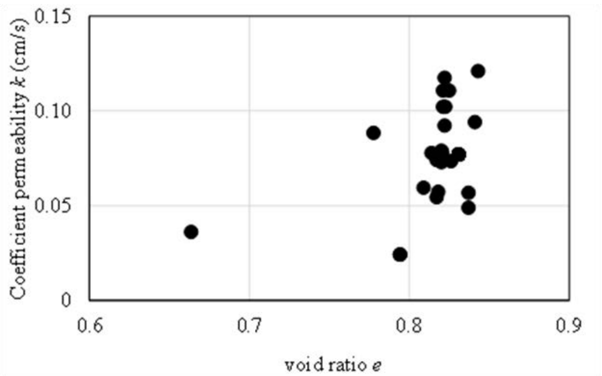


Figure 2 Void ratio e and coefficient permeability k of specimen

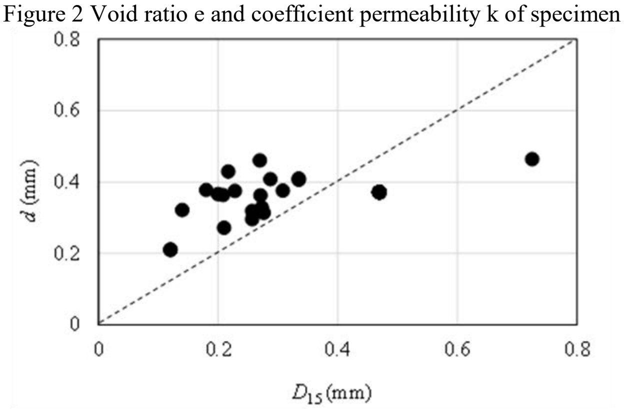


Figure 3 The pore indexes d and D_{15}

4.3 ONE-DIMENSIONAL PERMEATION EXPERIMENTS OF MICRO-PARTICLES

4.3.1 Experimental conditions

One-dimensional permeability experiments of micro-particles were carried out using the sand samples in Figure 1. The flow chart of permeability evaluation of micro-particles is shown in Figure 4. Even though at least 50cm in radius is required for the ground improvement in chemical grout injection methods, in order to save time and effort, micro-particles were permeated to the specimens with 5.0cm in diameter and 10.0cm and 15.0cm tall (hereinafter referred to as short specimens) in first screening. From these result, the samples for second screening were decided. In second screening, specimens with 50.0cm or 90.0cm tall (hereinafter referred to as long specimens) were prepared. When the volume of permeated micro-particles is greater than that of pore in a long specimen, the micro-particles are determined to be permeable.

The samples of specimens are shown in Figure 1. Both the grain size distribution of micro-particles measured by the laser diffraction particle size analyser (SALD-3100 produced by Shimadzu Corporation) and the grain size of micro particles at 85% G_{85} are shown in Figure 5. The weight concentration C of micro-particle was set by mixing with water as follows; WC-1(G_{50}=18.5μm), WC-2(G_{50}=14.9μm) and WC-3 (G_{50}=8.9μm). Then, they were permeated into the specimens with stirring to avoid deposition of micro-particles. The concentrations of mixture C were set at 10.0% in every case, which was calculated from Eq. (7).

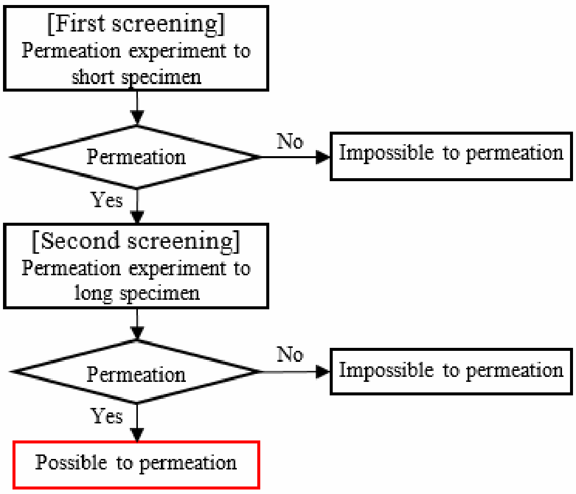


Figure 4 Decision of permeation micro-particles

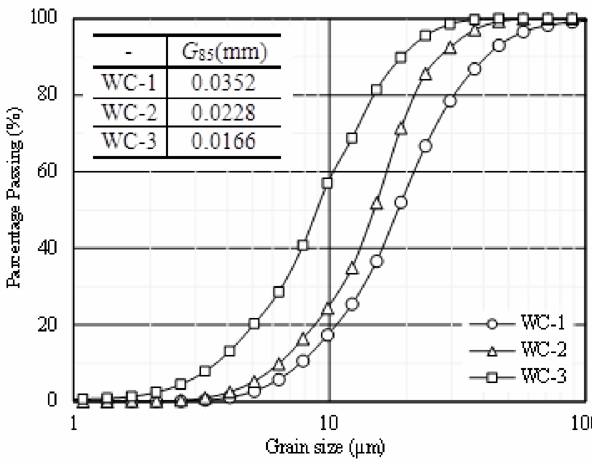


Figure 5 Grain size (μm)

Table 2. Experimental Conditions of Specimens

Case No.	Sample No.	Height of Specimens H (cm)		Type of micro-particles	G_r
Case1	1	14.97	-	WC-1	7.85
Case2	2	14.90	-	WC-1	7.75
Case3	3	15.02	50.11	WC-1	7.69
Case4	4	14.96	50.02	WC-1	7.65
Case5	5	9.97	50.02	WC-1	6.47
Case6	6	10.00	49.81	WC-1	5.11
Case7	7	9.99	-	WC-1	3.98
Case8	8	9.98	-	WC-1	5.68
Case9	9	10.03	50.00	WC-1	5.92
Case10	10	10.02	49.98	WC-1	8.76
Case11	11	10.01	49.99	WC-1	8.17
Case12	12	9.99	49.89	WC-1	6.75
Case13	13	9.95	50.11	WC-1	6.16
Case14	14	15.00	50.00	WC-1	13.33
Case15	15	15.00	-	WC-1	7.29
Case16	16	-	90.00	WC-2	9.68
Case17	17	-	90.00	WC-2	4.99
Case18	17	-	90.00	WC-3	6.53

$$C = \frac{M_m}{M_w} \times 100(\%) \quad (7)$$

where M_m is weight of micro-particles and M_w is that of water, respectively. In addition, the concentrations of mixture C and particle size of micro-particles before/after permeation were measured to confirm that no flocculation/separation had been generated in the specimens. than 11 is regarded as unpermeable and shown in red. As seen from this table, the micro-particles in most of the cases were determined to be unpermeable by conventional methods.

The apparatus of the experiment and its details are shown in Figure 6 and Figure 7, respectively. In order to permeate microparticles uniformly, fine gravel with 2.000mm to 3.360mm in particle size was paved as a filter layer on top and bottom of the specimens. Mixture was stored in a column in Figure6 and injected into the specimens by air-pressure. At this time, to avoid volume expansion of specimen and fracture grouting, 5kPa air-pressure was loaded on the upper piston besides the injection air-pressure. In Case1 to Case15, the initial hydraulic gradient was set at approximately 20. In addition, when the permeation velocity decreased to almost 0 due to clogging, the injection pressures were increased to 100kPa and 200kPa on short and long specimens, respectively. Here, their limitations were set not to occur leak of mixture or fracture grouting. Neither sand running out nor fracture of specimen was visually observed during injection. In Case16 to Case18, the permeability of micro-particles with different particle sizes was confirmed under 10kPa of constant injection pressure. Furthermore, the drainage was measured by a platform-scale.

4.3.2 Experimental results

Experimental results of short and long specimens are shown in Figure 8(a)~(d) which indicate the permeation volume normalized by the pore volume of a specimen. In Figure 8, when vertical axis is greater than 1, the pore water of the specimen was considered to be replaced by the mixture of micro-particle and water more than once. In addition, the relative amount of injection volume of each specimen became smaller according as the height of specimen became greater.

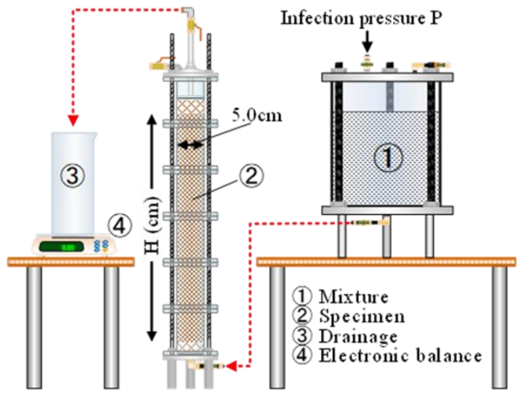


Figure 6 Summary of experimental apparatus

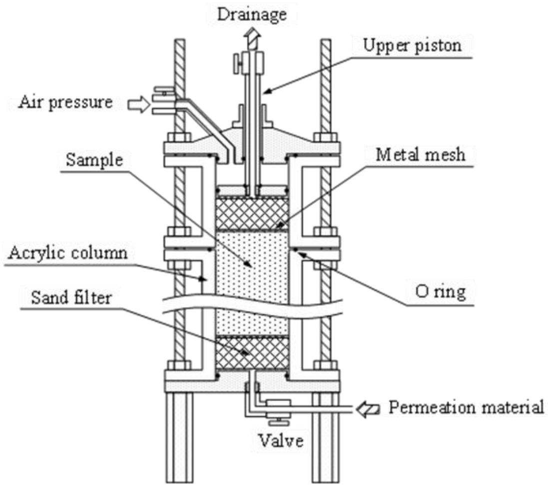


Figure 7 Detail of experimental apparatus

From the results, the injection pressure decreased due to clogging accompanied by increasing of injection volume and the decreasing trends were different depending on the physical properties of samples. In order to confirm the effect on the permeability of micro-particles by both characteristics of grain size and coefficients of permeability of samples, the results of the specimens with 10.0cm tall shown in Figure 8(a) were sorted as Figure 9(a)~(c) where each figure was sorted with reference to the properties of Case5. Comparison was made on coefficient of permeability k, uniformity coefficient U_c and grain size of soil at 15% D_{15} in Figure 9(a), (b) and (c), respectively. Furthermore, Table.3 shows the details of physical properties of indicated Cases in Figure 9. Each result was discussed in the next section.

(a) Difference in coefficient of permeability *k*

In Figure 9(a), the effect of difference in the coefficient of permeability k was considered. From Table.3, even though coefficient of permeability k in Case12 was only 1.4 times as great as that of Case5, the permeability of micro-particles was substantially different. Comparing between the results of Case5 and Case12, although clogging occurred at very early stage in Case5, the injection velocity hardly decreased by clogging and the mixture was able to be permeated more than three times and the permeated amount was as much as the pore volume in Case12.

(b) Difference in uniformity coefficient U_c

In Figure 9(b), the effect of difference in uniformity coefficient U_c was considered. Even though coefficients of permeability are similar values, higher permeability of micro-particles was observed when the uniformity coefficient was smaller. In the case of high uniformity coefficient, it was confirmed that the sand skeleton was constructed by various sizes of sand particles mutually and accordingly clogging occurred locally in small pores of the sand skeleton, which led low permeability of micro-particles even at the initial stage of injection. From this result, it was revealed the permeability of micro-particles is affected by uniformity coefficient U_c.

(c) Difference in grain size of soil at 15% D_{15}

In Figure 9(c), the effect of difference in grain size of soil at 15% D_{15} which is used for G_r was considered. All the cases in Figure 9(c) showed same trend, that is, the injection velocities decreased to almost 0 by clogging. From this result, it was confirmed that the size of micro-particles was close to those of pore diameter even in Case5 where the particle size was bigger than other cases. As seen from Figure 9(a), on the other hand, even though the D_{15} of Case13 was smaller than that of Case5, satisfactory permeability was obtained. From these results, it was confirmed that it is difficult to evaluate permeability of micro-particles only by G_r.

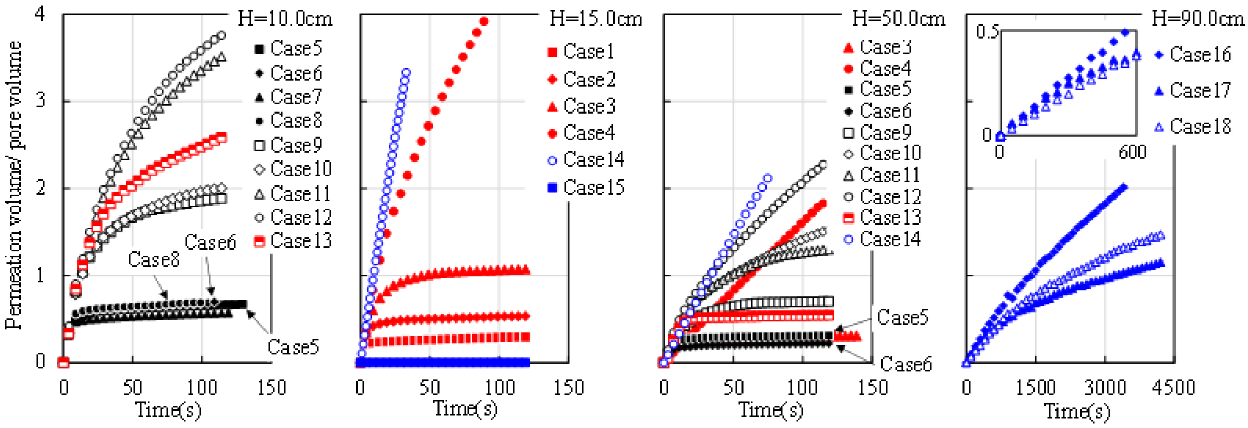
4.4 Permeability evaluation of micro-particles

From the results of experiments, the permeability of micro-particle was evaluated. Figure 10 shows the relationship between G_r and coefficient of permeability *k*. A red frame indicates a range of G_r less than 11, which means the permeation of micro-particles is estimated to be impossible. Figure 10 indicates that permeation of micro-particles succeeded in some cases even in a red frame.

As observed above, the permeability of micro-particles cannot be evaluated accurately only by G_r. Figure 11 shows the relationship between uniformity coefficient U_c and the pore index *d* normalized by the grain size of micro-particles at 85% G_{85}. It is clear whether the micro-particles are permeable or not in Figure 11. The experimental discriminant was obtained from uniformity coefficient U_c, a pore index *d* and the grain size of micro-particles at 85% G_{85} using the following equation; Eq. (8).

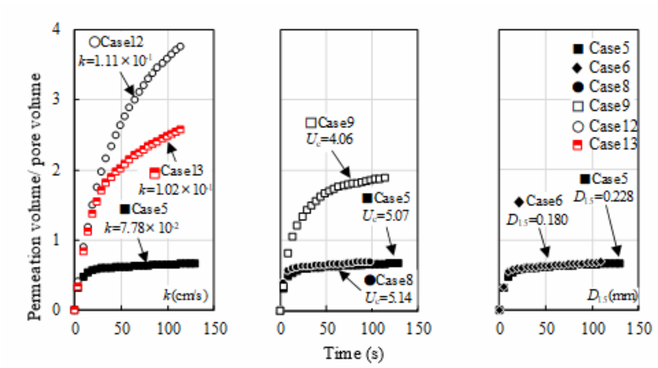
$$\frac{d}{G_{85}} > 0.887 \cdot U_c + 8.125 \tag{8}$$

If calculated value from Eq. (8); d/G_{85} is plotted upper than the approximate line, permeation of micro-particles could be determined to be possible. For obtaining an equation with high-precision, it is necessary to accumulate more experimental data since Eq. (8) was estimated from the measured values during the experiments.



(a) H=10.0cm (b) H=15.0cm (c) H=50.0cm (d) H=90.0cm

Figure 8 Experimental result of one-dimensional regarding height of specimen



(a) Difference of *k* (b) Difference of U_c (c) Difference of D_{15}

Figure 9 Experimental result regarding index (H=10.0cm)

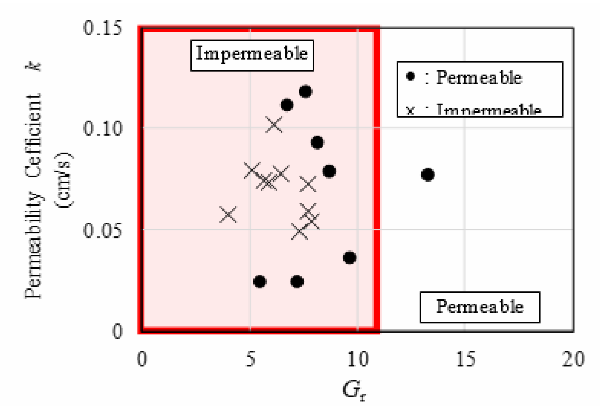


Figure 10 Relationship of Gr and coefficient permeability k

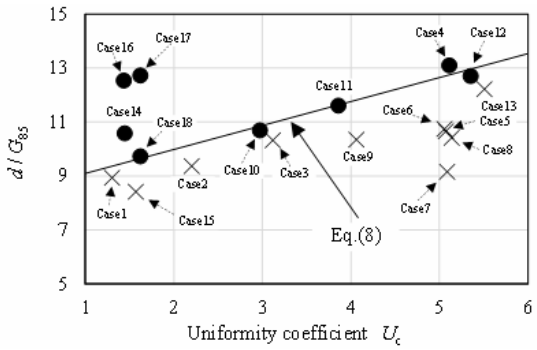


Figure 11 Relationship of d/G85 and uniformity coefficient Uc

Table 3 Properties of Each Specimens at Figure 8

Case No.	Specimen No.	*k* (cm/s)	D_{15} (mm)	U_c
5	5	7.78×10^{-2}	0.228	5.07
6	6	7.91×10^{-2}	0.180	5.06
8	8	7.41×10^{-2}	0.200	5.14
9	9	7.35×10^{-2}	0.208	4.06
12	12	1.11×10^{-1}	0.238	5.35
13	13	1.02×10^{-1}	0.217	5.51

5. CONCLUSIONS

In this study, first, the pore index *d* was proposed using coefficient of permeability *k* and porosity of soil *n*. Next, one-dimensional permeation experiments of micro-particles were carried out. Finally, the permeability of micro-particle was evaluated by the pore index *d*. The conclusion obtained is shown as follows.

1. The pore index was formulated using coefficient of permeability *k* and porosity of soil *n* from the Kozeny-Carman equation without grain size of soil.
2. Permeability of micro-particles is affected by not only particle size but also coefficient of permeability *k* or uniformity coefficient U_c.
3. It is difficult to evaluate the permeability of micro-particles by G_r which has been used in conventional evaluation methods.
4. Permeability evaluation of micro-particles can be expressed by the pore index *d* accurately.

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