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3-D Particle Flow Analysis for Fluidization Treated Soils

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Abstract: This paper presents results of a fluidity evaluation for fluidization treated soils using the Distinct Element Method (DEM). In recent years within Japan, fluidization treated soils have been frequently used as soil materials for land reclamation projects, backfilling underground spaces, etc. However, the design and mixing of fluidization treated soils is based on previous experiences applied to new situations. It is useful to consider the findings based the application of the DEM method to the fluidity assessment and theory of fluidization treated soil, which is the focus of this study. As a result, it was clarified that the fluidity of fluidization treated soil could be sufficiently reproduced by using the 3-D particle flow analysis with the DEM method.

Keywords: Fluidization Treated Soils, Particle Flow Analysis, Distinct Element Method, Flow Test

1. Introduction

In recent years within Japan, there has been a trend towards using fluidization treated soil as filling or backfilling materials for backfilling construction works (see Figures 1 and 2). Fluidization treated soil refers to a type of wet stabilized soils that is composed of muddy soil containing sufficient fine fractions of clay, silt and solidification materials for stabilization. The mixture is established to meet predetermined mechanical properties [1]. Although fluidization treated soils are frequently used, the design and mixing is based on empirical rules established on-site after taking site conditions into account. Therefore, it is considered useful to determine flow and filling behavior based on the findings from the theories on the design and combination of fluidization treated soil taking the following points into consideration:

(1) The optimal design of mix proportion for fluidization treated soil is determined.
(2) The on-site conveying and filling distances can be determined quantitatively.
(3) The conveying equipment or devices are selected appropriately.

The author considers the flow analysis that can be performed for fluidization treated soil when primarily using cement as solidification materials. We focused on DEM in this study, one of the particle analysis methods, to develop the findings based on the theories regarding the design and construction of fluidization treated soil. Specifically, a fluidity test or flow test is carried out to understand the actual phenomenon concerning the flow of fluidization treated soil. In addition, the flow analysis is performed using the 3-D particle flow analysis with DEM. These actual phenomena and analysis are then compared to study the validity of DEM. Finally, a fluidity assessment of the fluidization treated soil based on DEM is performed.

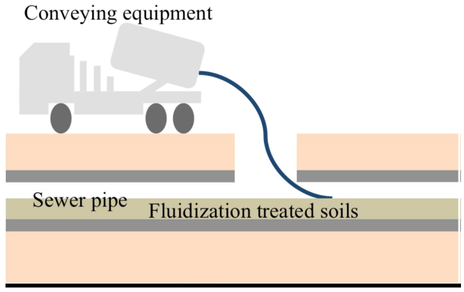

Figure 1. *Pumping of underground space.*

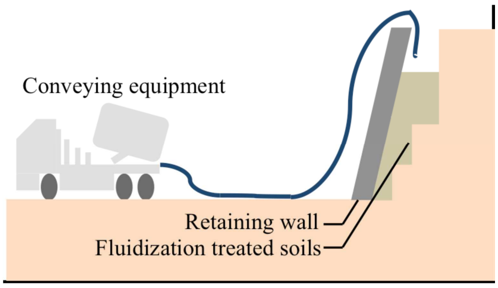

Figure 2. *The backfilling of the retaining wall.*

2. General Description of Fluidization Treated Soils

Fluidization treated soil refers to the materials developed to efficiently use surplus construction soil when adequate compaction is impossible during back-filling of various structures and refilling of underground structures. The basic concept of fluidization treated soil is that it does not need compaction and the curing effect is expected from an appropriate amount of mixing solidification materials with muddy soil of proper fluidity. Fluidization treated soil retains a high fluidity, and the construction is carried out using pumping methods. The features of fluidization treated soil are mentioned as of follows [1]:

(1) All surplus construction soil is available.
(2) Compaction is unnecessary since the soil has fluidity.
(3) The fluidity and intensity can be arbitrarily set.
(4) As the hydraulic conductivity is low and the adhesion is high, it suffers no groundwater erosion.
(5) As the adhesion is high, no liquefaction occurs at the time of an earthquake.
(6) The volumetric shrinkage and compression is small after installation.

Fluidization treated soil refers to the materials that are made of raw material soil that includes surplus construction soil and construction sludge as the base materials. Additionally, gravel in diameters up to approximately 40 mm is available.

The manufacture methods of the base materials are different depending on the percentage of the fine and coarse grain content in the raw material soil. When a significant amount of fine grains is contained, the fluidization treated soil is manufactured by adding the raw material soil and water in the required percentages per the formulation design. When the sand content is insufficient, the fluidization treated soil is manufactured by adding sandy soil to the muddy water containing sufficient fine grains to achieve the predetermined density. When much coarse grain is contained and the viscosity is insufficient, the fluidization treated soil is manufactured by mixing artificial clay with muddy water as the base material. Water is then added to adjust the viscosity to meet the required design specifications. It is necessary to implement these adjustments for the fine grain content of the clay and silt to be sufficiently contained.

In recent years, recycling of construction materials has been preferred or required. Hence, fluidization treated soil is now more widely used in the urban areas [2], [3]. An understanding of the properties of fluidization treated soil should lead to the promotion of the reuse of construction waste soil as a base material.

In past studies on fluidization treated soil [2], [3], experimental investigation into the mechanical properties and fluidity has been performed. In addition, the mechanical properties and fluidity when fiber is mixed into the fluidization treated soil have been investigated as well as changes to the type of muddy soil [2], [3]. However, the analytical evaluation and understanding on the fluidity of fluidization treated soil have not been sufficiently developed.

In this study, a flow analysis is performed using DEM after a flow test is performed for the advanced fluidization treated soil (A) and advanced fluidization treated soil (B). Additionally, the main difference between advanced fluidization treated soil (A) and advanced fluidization treated soil (B) is the difference in stock solution (i.e., muddy soil) including the difference in grain size distribution.

2.1. Advanced Fluidization Treated Soil (A)

In this study, construction sludge subjected to intermediate treatment such as dehydration and classification is used as a stock solution, and a mixture containing cementitious solidification material is treated as advanced fluidization treated soil (A). This advanced fluidization treated soil (A) utilizes a dehydrating solution generated during the dehydration treatment of construction sludge and has been allowed the mixing of particle size 74μm or more fine sand [4].

2.2. Advanced Fluidization Treated Soil (B)

The advanced fluidization treated soil (B) used in this study uses a dehydrating solution generated during dehydration treatment of construction sludge as a base material. Generally, construction sludge is received at one site along with other ones, is processed very complicated process up to wastewater treatment, and is classified. Among them, as a result of investigating a process usable as a base material of advanced fluidization treated soil (B), a dehydrating liquid containing particle size of not more than 74μm which passed through a vibrating screening machine is determined as a base material. The dehydrating solution containing this fine grain content is called "dehydrated stock solution" in this study. Construction sludge has variations in soil properties and lacks stability of quality [1]. Therefore, dehydrated stock solution which passed through the vibrating screening machine and improved the stability of quality is used. Furthermore, in order to further stabilize the quality of the dehydrated stock solution, this advanced fluidization soil contains a cement-based solidifying material as a solidifying material. As a feature of this advanced fluidization treated soil, it is possible to pump at 500m or more (700m or more under favorable conditions) even at low pumping pressure as compared with conventional fluidization treated soil of a short pumping distance (about 100-300m). In addition, this advanced fluidization treated soil can be expected to reduce incidental work such as reducing the installation position of intermediate piles according to filling distance, restoring pavement by intermediate standing pile. And it can be expected that the filling amount per day is three to four times larger than that of the conventional construction method, further effects such as less breathing and adapting to the purpose of filling the waste pipe can be obtained. At the same time, it is possible to shorten the construction period considerably and to reduce the budget [4], [6].

The environmental safety of this advanced fluidization treated soil (A) and (B) is judged based on soil contamination countermeasure law standards by soil dissolution amount test and soil content test. In the soil dissolution test, first class specific hazardous substances (carbon tetrachloride, dichloroethane, etc.), second class specified hazardous substances (cadmium and its compounds, hexavalent chromium compounds, etc.) and third class specific hazardous substances (simazine, thiuram, etc.) are measured. In the soil content test, second class specified hazardous substances are measured. In the measurement result of each specific hazardous substance with respect to this advanced fluidization treated soil, for example, the measured value of carbon tetrachloride is less than 0.0002mg/L, which meets the soil pollution countermeasure standard value 0.002mg/L or less. All other specified hazardous substances also meet the criteria specified by the soil contamination countermeasures act. In other words, this advanced fluidization treated soil satisfies the criteria for soil pollution, and it is a material that ensures environmental safety. In addition, regarding mechanical properties as well, it is a material that fully satisfies the quality as fluidization treated soil [4], [6].

3. Understanding and Evaluation of Flow-Ability by the Flow Test

3.1. Understanding of Flow-Ability by the Flow Test

In order to understand the flow-ability of the advanced fluidization treated soil (A) and (B), the flow test based on "Test Method for Air Mortar and Air Milk (JIS A 313-1992, using an air cylinder of φ80mm h 80mm)" is performed [7]. Table 1 shows the combination of the advanced fluidization treated soil (A) and (B).

Table 2 shows the flow test results for the advanced fluidization treated soil (A) and (B). From these results, it is evident that the advanced fluidization treated soil is significantly superior in fluidity when compared with the fluidization treated soil.

In addition, in order to compare the flow behavior in the flow cross section based on the discrete element method with the flow test result, moving image shooting was also carried out from just above the flow test, and the flow value for each elapsed time is obtained (see Figure 3).

Table 1. *Combinations of each advanced fluidization treated soil.*

	(A)	(B)
Specific gravity (undiluted solution)	1.238	1.123
Cement type solidification (kg/m^3)	150	150
Specific gravity	1.324	1.238
Moisture ratio (%)	46.7	56.8

Table 2. *Results of the flow test for each advanced fluidization treated soil.*

	(A)	(B)
Flow value (mm)	469	612

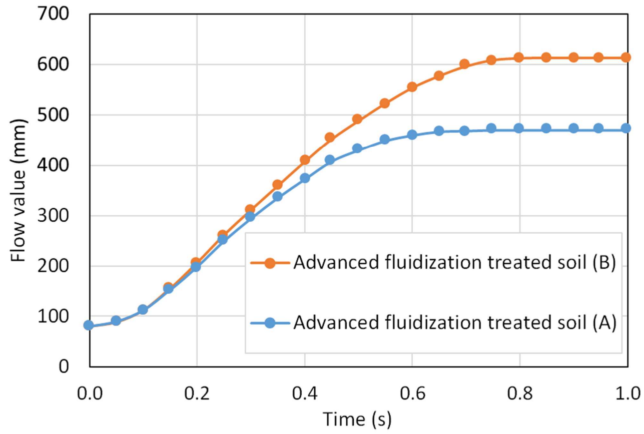

Figure 3. *Flow behavior of each advanced fluidization treated soil by image analysis.*

3.2. Measurement of Viscosity by Rotational Viscometer

In this study, the viscosity was measured using a rotational viscometer. For the rotational viscometer, a B type viscometer (DV2T) which is easy to handle was used, and LV-3 was used as the spindle (see Figure 4). The rotation speed is measured between 50 and 200 rpm so that the torque exceeds 10%. The torque is set to exceed 10% because when the torque is less than 10%, the measurement accuracy deteriorates markedly. Measurement of plastic viscosity is carried out for 20 seconds, and the average value of measured values from 15 seconds to 20 seconds is outputted as a result.

Figure 5 shows the measurement results of the viscosity of the advanced fluidization treated soil (A), and Figure 6 shows the measurement result of the viscosity of the advanced fluidization treated soil (B). At the time of measurement, the temperature of the sample is about 20°C. In the measurement results of these viscosities, it can be confirmed that the advanced fluidization treated soil (A) and (B) are non-Newtonian fluids, since the viscosity changes according to the rotation speed. In addition, the viscosity decreases as the rotation speed increases, and convergence does not occur completely, but this tendency can be grasped. Therefore, viscosity at rotation speed of 200 rpm shown in Table 3 shall be treated as viscosity in this study.

Figure 4. *Rotational viscometer.*

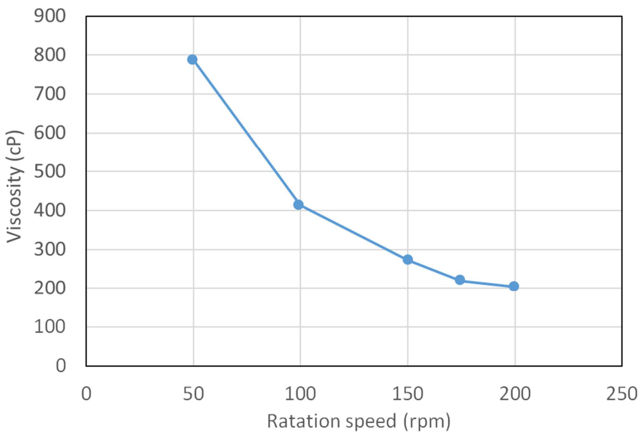

Figure 5. *The measurement results of the viscosity of the advanced fluidization treated soil (A).*

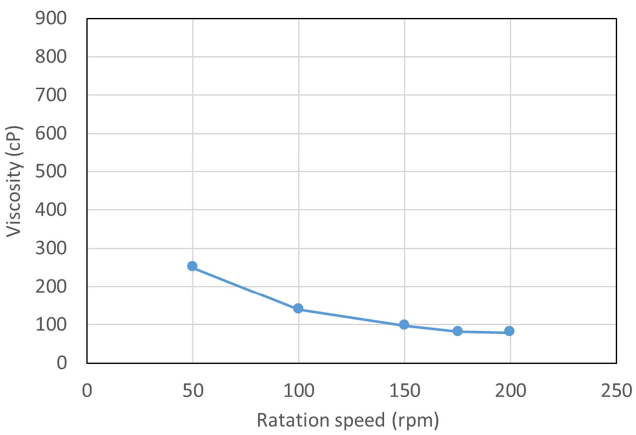

Figure 6. *The measurement results of the viscosity of the advanced fluidization treated soil (B).*

Table 3. *Viscosity at rotation speed of 200 rpm.*

	(A)	(B)
Viscosity (cP)	204.0	78.6

3.3. Flow-Ability of the Advanced Fluidization Treated Soil (A) and (B)

Normally, as a measure of fluidity of fluidized soil used for backfilling and cavity filling, the flow value is often set to about 140 mm or more in consideration of pump ability and workability. Also, when filling and finishing the remaining very narrow gaps, fluidized soil having a flow value of about 300 mm or more is used. By doing so, very high packing properties are obtained [4], [6]. The advanced fluidization treated soil (A) used in this study has a flow value of 469mm and advanced fluidization treated soil (B) of 613mm, and it is obvious that the fluidity is improved as compared with normal fluidization treated soil.

In the foregoing, it is described the finishing of fluidized soil with high fluidity. However, it is considered that filling is insufficient in normal fluidization treated soil for reclamation and filling of a space having a complicated structure. In the advanced fluidization treated soil, it is possible to fill a narrow space, so it is expected to have a high packing property with a lower pumping force.

The stock solution used in advanced fluidization treated soil (A) permits the inclusion of fine sand having a particle size exceeding 74μm. On the other hand, as the stock solution used in the advanced fluidization treated soil (B), a stock solution having a maximum particle size of 74μm is used. Therefore, the particle size distribution is different. That is, as a factor of the difference in fluidity, it is considered that the particle size distribution is different, which is influential.

In addition, Table 3 shows the viscosities of advanced fluidization treated soil (A) and (B), and it was confirmed that the viscosity of advanced fluidization treated soil (B) is smaller than that of (A). Therefore, also from the viscosity measurement result, advanced fluidization treated soil (B) is considered to flow more easily than (A) in the same way.

4. Understanding and Evaluation of Flow-Ability by Distinct Element Method

4.1. Distinct Element Method

The distinct element method is an analysis method proposed by Peter A. Cundall. It is a method of analyzing the behavior and reaction force of the whole aggregate by analyzing the motion of each particle, considering the analysis target as a collection of minute particles. Unlike the finite element method and particle method based on continuum dynamics, DEM is an analysis method based on a discontinuous body model. Elements used for calculation are represented as rigid bodies that do not deform and have a finite size. Also, when the elements touch each other, the contact force acts, and by solving the motion of each element based on the force, it is possible to express the behavior of the aggregate of discontinuous bodies. Initially proposed by Cundall, a polygonal element was used, but as it was applied in various fields, the spherical element became popular because the contact algorithm is simple. DEM models the object of analysis into an aggregate of polygons, circles (2D), and spheres (3-D) that can move freely. And establish two independent ordinary differential equations for each individual element in aggregate of elements separated by discontinuities, solve them in time domain by difference approximation. Then it tracks the behavior of the element and attempts to analyze dynamic behavior and deformation as its aggregate [4], [8], [9].

Figure 7 is a general contact force model used in DEM. it considers a spring and dashpot in the normal direction and a slider in the tangential direction. Here, the normal direction and the tangential direction are expressed specifically in Figure 8. In other words, the normal direction is the direction connecting the center points of the spherical elements, and the tangential direction is the direction orthogonal thereto. Basically, the model in the normal direction exists to express the repulsive force between the elements, and the tangential direction exists to express the frictional force between the elements. Spring exists to exert repulsive force and frictional force, and dashpot expresses viscous behavior to attenuate energy. In addition, the slider is responsible for controlling the magnitude of the frictional force based on the friction law. In actual calculation, contact force occurs only when the elements overlap. Since it is assumed that the element is a rigid body that does not deform, occurrence of overlap will be inconsistent, but a contact force model that allows this is introduced. It is not necessary to generate a mesh which is generally required for an analytical method often used, and it is also easy to rearrange elements.

Initially, Peter A. Cundall and Cundall and Stack introduced them into rock engineering issues. After that it began to be applied to geotechnical engineering issues. Since each particle can be simulated as actual soil sand, the sediment shape can be expressed in a near realistic form. Therefore, it is often used for analysis of ground behavior such as liquefaction and debris flow at present, and it is drawing attention as a solution to the large deformation problem of the ground accompanied by destruction. On the other hand, there are few cases where it is applied to materials having fluidity.

Since each element is connected by a spring-like one, it is possible to analyze the motion of the discontinuous body such as separation, contact, sliding between the elements [10]. And by considering it as an aggregate of elements, it can also analyze the behavior of solid materials including dynamic destruction of various substances, structures, rock, concrete and others.

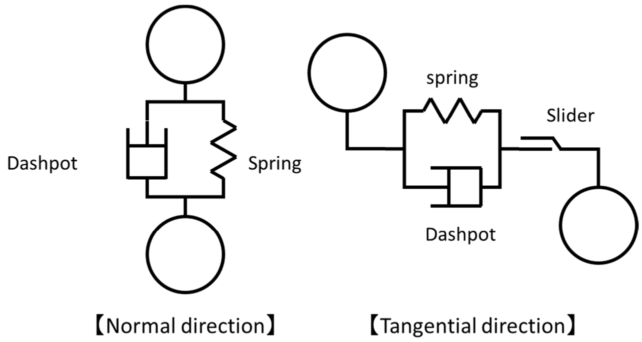

Figure 7. *General contact force model used in DEM.*

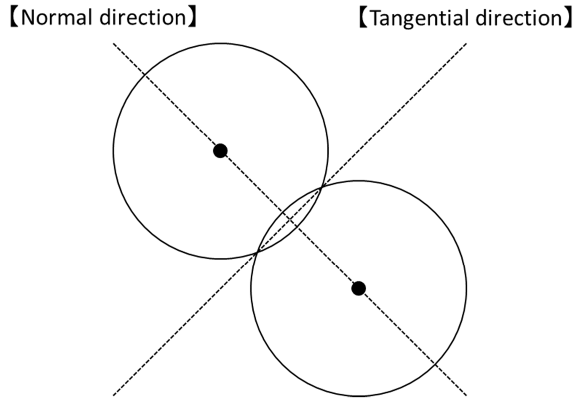

Figure 8. *The normal direction and the tangential direction.*

4.2. Application of Distinct Element Method to Fluidization Treated Soil

In order to apply the distinct element method to the fluidization treated soil, the flow behavior in the flow test was reproduced. Numerous studies have been done on the method of setting the parameters of the DEM, and various theories and formulas have been proposed, but clear setting methods are not yet decided. In general, parameters are changed so as to match the behavior in the actual test, and it is determined by trial and error. In this study, we tried modeling fluidization treated soil by setting spring constant, damping constant, rolling friction and friction coefficient with reference to the analysis of DEM being done in the world.

(1) Spring constant

Based on the consideration of the one-dimensional wave propagation velocity, the method of trializing the linear spring coefficient is proposed as shown in Eqs. (1) by using the velocities of the acoustic wave P-wave and S-wave in the granular body.

$$kn = 1/4\pi\rho V_p^2, \; ks=1/4\pi\rho V_s^2 \tag{1}$$

Here, ρ is the density of the whole granular body. Assuming that the Poisson's ratio is equivalent to 1/3, V_p is about twice V_s, so that ks/kn = 1/4. For the sake of simplicity in this study, the above equation is adopted.

For materials such as rocks that exceed $V_p = 10^3$ (m/s), kn is set with a large number of digits such as 10^9 N/m or more. However, as kn increases, the computation time increment is reduced, resulting in an increase in calculation time as a result. On the other hand, in the deformation, fracture behavior, flow behavior, impact force behavior of the granular material, compressibility due to overlapping of the particle elements becomes remarkable when the spring constant is 10^6 N/m or less. And it is known that it is far from the behavior of the granular body [11]. In addition, if kn is 10^7 N/m or more, there is also a result that there is not much difference in the characteristics obtained by calculation. For the sake of convenience, it can be considered that a spring constant exceeding 10^7 N/m should be used in order to avoid calculation load. Therefore, in this analysis, the spring constant was set to the same value for each sample as kn = 2×10^8 and ks = 5×10^7.

(2) Damping ratio

According to the study of fresh concrete [12], it is known that the damping constant is a parameter that determines the deformation rate of the sample in the slump test. In addition, the influence of the damping constant is hardly seen in the final state of flow. Therefore, in this analysis, the damping constant is set so as to match the flow stopping time of the actual behavior.

(3) Rolling resistance

When modeling fluidized soil in this analysis, to make analysis easier from the balance with calculation load, a spherical element shape was used. However, when a circular element is used, it is shown that inter-particle collision becomes point contact and particle rotation is excessive because resistance generated at rolling cannot be taken into account. In order to avoid such excessive rotation, it is found that introduction of a rolling resistance model can suppress excessive rotation of particles [13]. Therefore, in this analysis, rolling resistance is set with reference to the past research.

(4) Friction coefficient

The Study in fresh concrete [12] has shown that the coefficient of friction has a linear relationship with slump flow. It seems that the same relation also exists in fluidized soil. Therefore, in this analysis, it is assumed that it is a parameter that can express the viscosity of fluidization treated soil. Then, the coefficient of friction is finely adjusted and determined so that the final flow value agreed with the actual test.

4.3. Reproduction Result of Flow Test

The DEM parameters set in this analysis are shown in Table 4. Changes in the analysis cross section of each obtained fluidized soil are shown in Figures 9 and 10. And the comparison between “the flow behavior by the flow analysis by DEM” and “the flow behavior by the flow test” in each fluidization treated soil are shown in Figures 11 and 12 (the case of advanced fluidization treated soil (A) is shown in Figure 11 and the case of advanced fluidization treated soil (B) is shown in Figure 12). From Figures 11 and 12, the flow behavior of each advanced fluidization treated soil is well suited between the flow analysis by DEM and the flow test. At first glance, it does not seem to well match between the flow analysis by DEM and the flow test. However, the range has become very small compared to a scale of real field of constructions. Therefore, it has become a comparison at the micro range. Thus, it can be said that there is validity. So, it can be said that 3-D particle analysis using DEM can be applied to fluidization treated soil.

Table 4. *The DEM parameters set in this analysis.*

	(A)	(B)
density	1.324	1.238
normal stiffness	2.0e8	2.0e8
shear stiffness	5.0e7	5.0e7
normal damping	2.0e-3	2.0e-3
shear damping	2.0e-3	2.0e-3
rolling resistance coefficient	0.1	0.1
friction coefficient	0.120	0.085

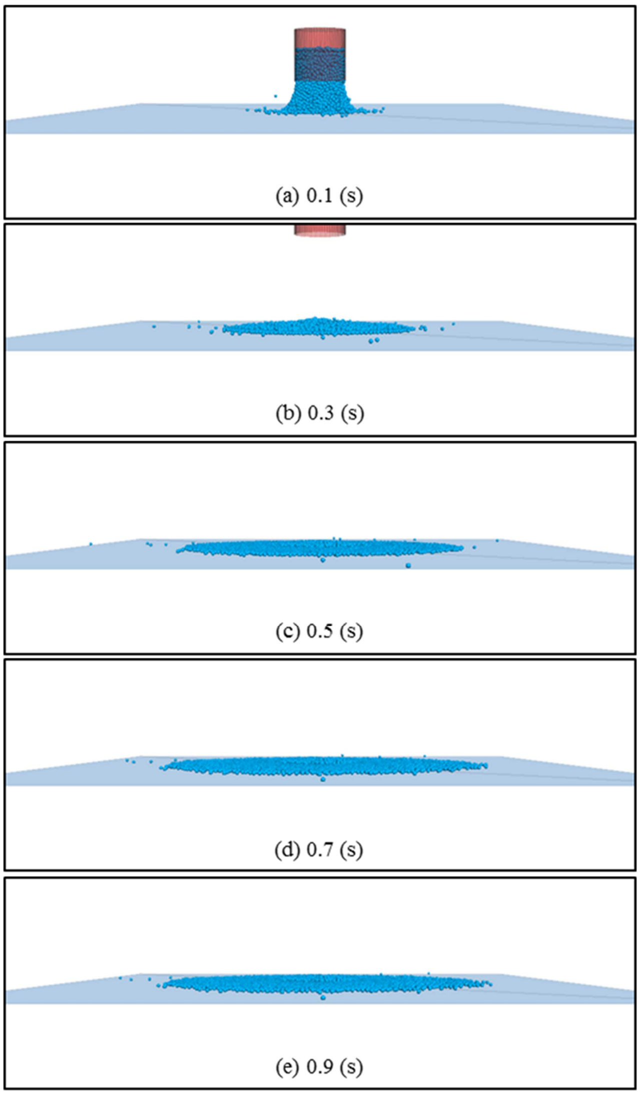

Figure 9. *Visualized results on the flow analysis by DEM for the advanced fluidization treated soil (A).*

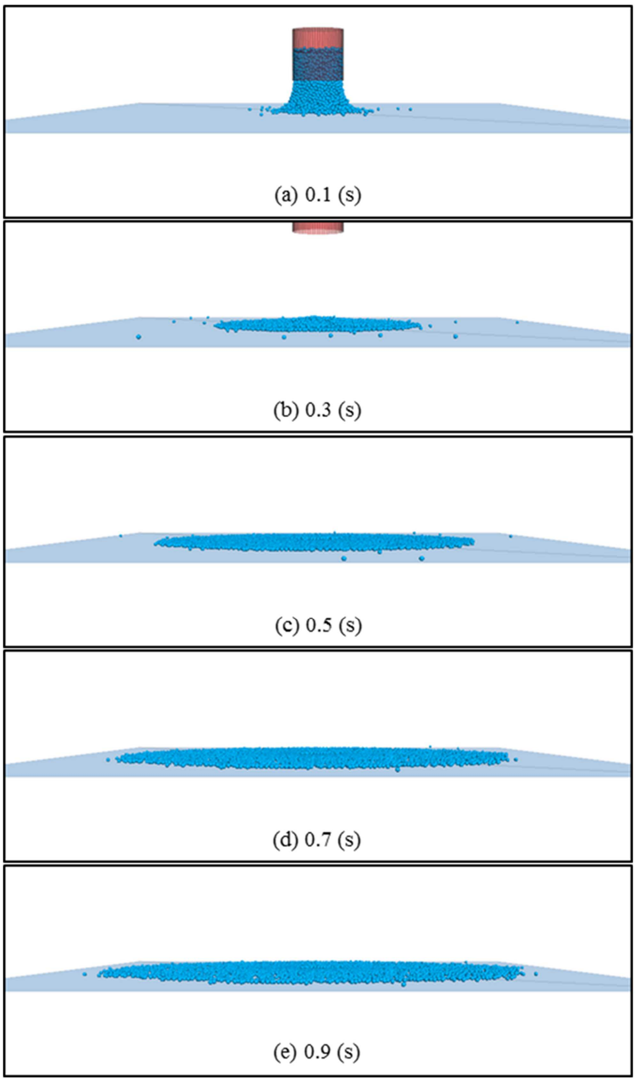

Figure 10. *Visualized results on the flow analysis by DEM for the advanced fluidization treated soil (B).*

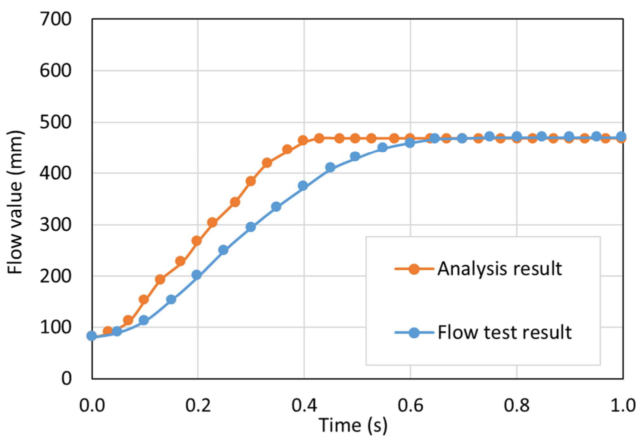

Figure 11. *Simulated flow-ability for the advanced fluidization treated soil (A).*

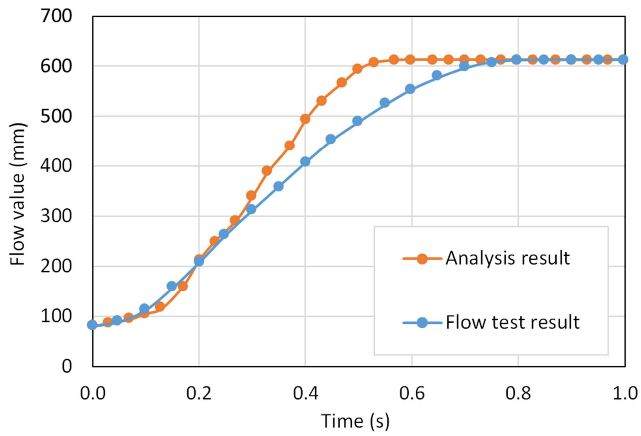

Figure 12. *Simulated flow-ability for the advanced fluidization treated soil (B).*

4.4. Simulation of Pressure Pumping in Pipeline

In the construction of the fluidization treated soil, the backfilling work is carried out by pump pressure pumping of raw compump vehicles and the like. Based on the results of the previous study, it is considered that a simulation that allows fluidization treated soil to flow into the pipeline is possible. Analysis is performed assuming the cross section and inflow point shown in Figure 13. In this analysis, fluidization treated soil pumped under pressure is reproduced in a pseudo manner by giving velocity at the time of generation of particle group in the pipe. Speeds of 1.0m/s and 2.0m/s are given from one end of the linear portion of the pipe at the time of generation of the particle group, and a particle group of $0.042m^3$ is continuously flowed for 15 seconds in 1 second. Then, analysis is performed for a total of 20 seconds until flow stopped. For each parameter of DEM, the one obtained by the flow test reproduction is used. The analysis results in advanced fluidization treated soil (A) are shown in Figures 14 and 15 (the case of the inflow velocity set to 1.0m/s is shown in Figure 14 and the case of the inflow velocity set to 2.0m/s is shown in Figure 15). And the analysis results in advanced fluidization treated soil (B) are shown in Figures 16 and 17 (the case of the inflow velocity set to 1.0m/s is shown in Figure 16 and the case of the inflow velocity set to 2.0m/s is shown in Figure 17). Then, after the flow stopped, the filling distance was measured and the results are shown in Table 5.

In the above results, it was confirmed that when the inflow rate was increased, the filling distance increased and the filling distance was larger for advanced fluidization treated soil (B) than for (A) at any rate. In addition, it was confirmed that there was a clear difference in advanced fluidization treated soil (B), although the filling distance was about 5m in all cases of advanced fluidization treated soil (A) speed. The fluidization treated soil (B) is considered to have a high filling property and workability even with a low pumping force because the filling distance is large even when the inflow rate is low.

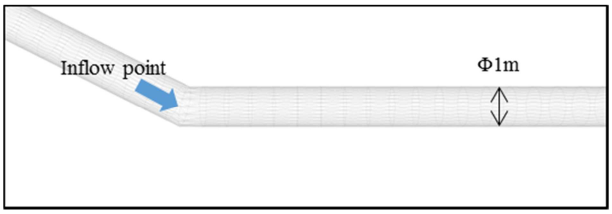

Figure 13. *Simulation of pressure pumping in pipeline.*

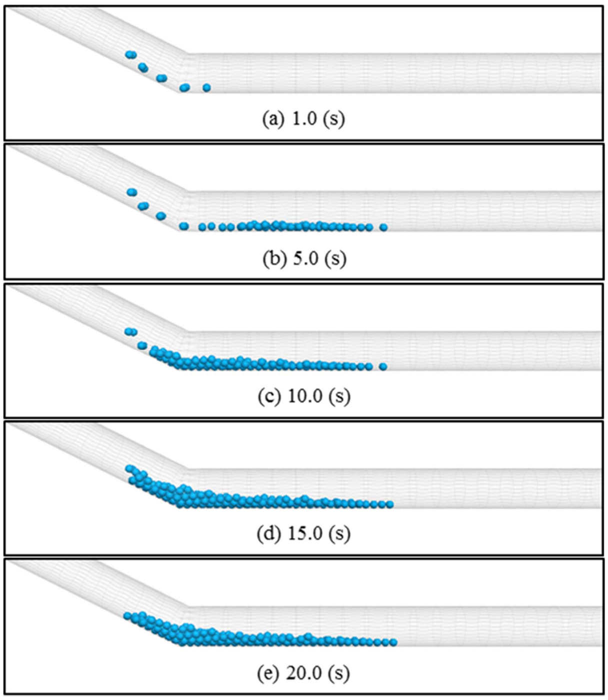

Figure 14. *The analysis results in advanced fluidization treated soil (A) (1.0m/s).*

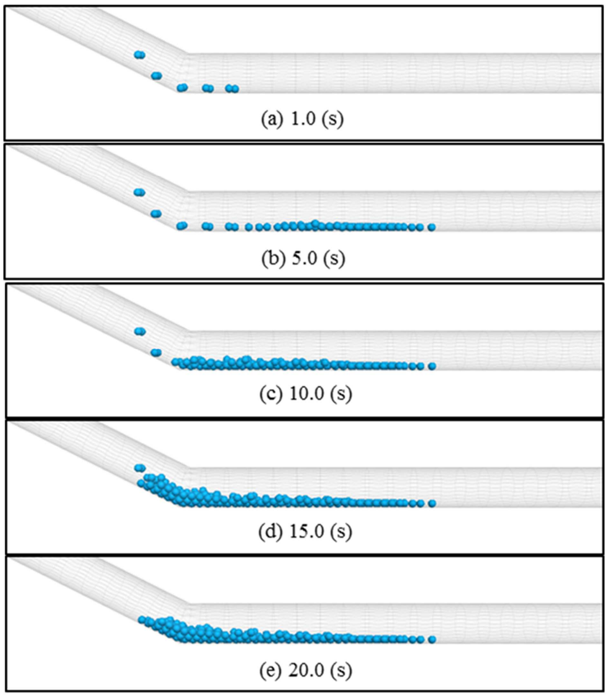

Figure 15. *The analysis results in advanced fluidization treated soil (A) (2.0m/s).*

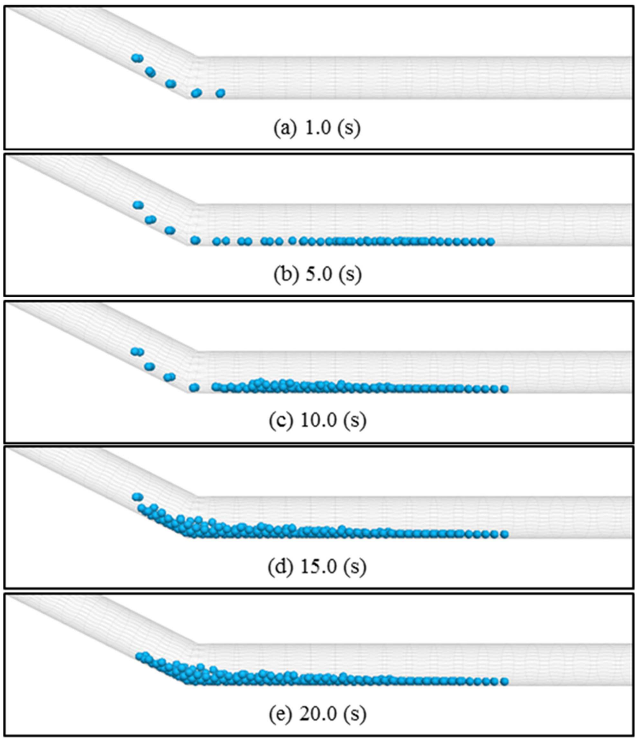

Figure 16. *The analysis results in advanced fluidization treated soil (B) (1.0m/s).*

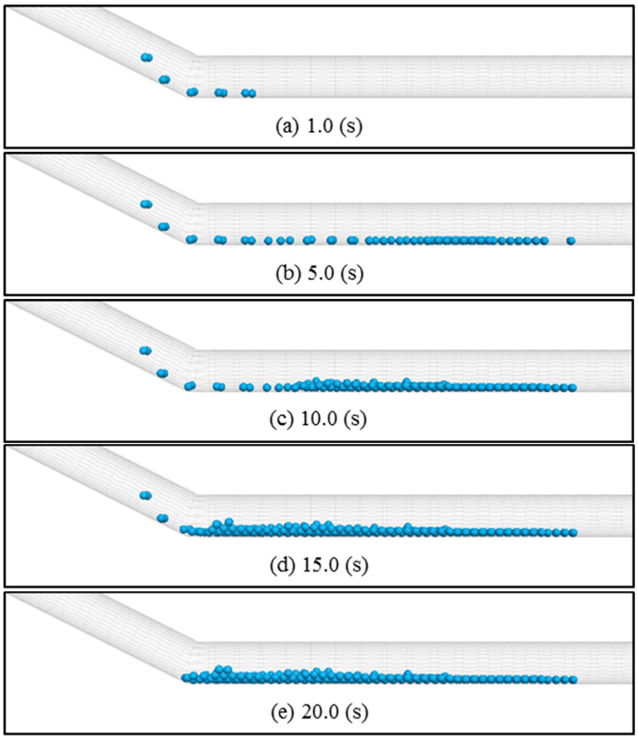

Figure 17. *The analysis results in advanced fluidization treated soil (B) (2.0m/s).*

Table 5. *Comparison of filling distance.*

Inflow velocity (m/s)	(A)	(B)
1.0	5.23m	7.41m
2.0	5.90m	9.04m

It is revealed by 3-D particle analysis by DEM that the difference in flow characteristics in the flow test greatly influences the filling property in the field.

5. Conclusions

In this study, it has evaluated the flow-ability of the advanced fluidization treated soils based on the flow analysis by DEM and the experimental evaluation. The results and findings of this study are shown in follows.

(1) With regard to the flow-ability, high-flow advanced fluidization treated soil (B) was higher than that of advanced fluidization treated soil (A). Comparison of the flow-ability of the advanced fluidization treated soils with a maximum particle size of different matrix soils, the particle size distribution of the matrix soils affected the flow-ability

(2) The results using DEM was consistent with the challenges in the field for the fluidization treated soils, and the validity of DEM was confirmed.

(3) The advanced fluidization treated soil (B) was confirmed to have a high flow-ability based on the results of the flow analysis by DEM.

(4) Regarding the parameter setting method, it was confirmed that the friction coefficient is a parameter that can express the viscosity of fluidized soil and can be matched with the actual phenomenon.

(5) Since DEM can estimate filling distance in simulation of pumping in pipeline, it can be said that it is an effective method for pumping design of fluidized soil and grasping on-site fluidity.

(6) The two types of advanced fluidization treated soil used in this study are more fluid than general fluidization treated soil. In particular, the advanced fluidization soil (B) can reduce the pressure required for pumping with high fluidity. Therefore, efficiency improvement of long distance pumping construction is expected.

As an issue, examination of the validity of simulation of pumping in pipeline can be mentioned. From now on, it is necessary to grasp applicability by comparing with real phenomenon etc.

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