International Journal of GEOMATE, Jan., 2017, Vol. 12, Issue 29, pp. 53-58
Geotec., Const. Mat. & Env., ISSN: 2186-2982(P), 2186-2990(O), Japan

EVALUATION OF FLOW-ABILITY ON FLUIDIZATION TREATED SOILS BASED ON FLOW ANALYSIS BY MPS METHOD

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ABSTRACT: Recently, fluidization treated soils have come to be used as landfill materials or fillers in such landfill of underground space in Japan. However, the design and construction of the fluidization treated soils at present is based only on empirical knowledge. Therefore, taking into account the findings based on a theory is thought to be useful. In this study, it has evaluated the flow-ability of the fluidization treated soils based on the flow analysis by the MPS method and the experimental evaluation. Favorable results have been obtained in the numerical flow analysis by using the Bingham model to the MPS method. In addition, the authors have developed a fluidization treated soil with increased flow-ability (super-fluidization treated soil). It has evaluated from two aspects of mechanical properties and flow properties of the high flow of the super-fluidization treated soil. The flow properties show that it has a high flow-ability than the fluidization treated soil.

Keywords: bi-viscosity model, flow simulation, fluidization treated soil, MPS method,

1. INTRODUCTION

A fluidization treated soil is defined as a wet stabilized soil which in principle be composed of muddy soil, the material contains the fine particle of clay and silt enough, and solidification material to stabilize the mechanical characteristic. The fluidization treated soils tend to be used many as filler in a sewage pipe or the backfill of the undergrounds (*see* Figs. 1 and 2). However, the design and the construction are based on the heuristics of the past in the field at present state. Therefore, the following points can be realized by taking into account the theoretical knowledge in addition to the heuristics of the past.

(1) The most suitable combination design of the fluidization treated soils will be enabled.
(2) It is possible to quantitatively understand for the pumping distance and the filling distance in a field.
(3) Proper selection of equipment (apparatus) can be performed.

From the above mentioned, it is useful to take theoretical knowledge into account.

For knowledge-based theory, a particle method as a method of dealing with large deformation in recent years is attracting attention. The particle method is using the particles as a method of discretization of continuum unlike the grid method. So there is no need to perform production of the lattice requiring complicated working time. The particle method is based on a Lagrangian description. Therefore, there is no need to calculate the convection section is required in a Euler description (*see* Table 1). The large deformation of the free boundary surface can be easily expressed. A flow analysis by the moving particle simulation (MPS method) in the fresh concrete and high flow-ability of concrete on the basis of the advantage of the particle method has been tried. Therefore, it is considered that it is possible to carry out the same way flow analysis also in the fluidization treated soils as the solidifying material. In this study, the authors focus on the MPS method. It is a kind of particle method as a theoretical knowledge. In addition, it is conducted

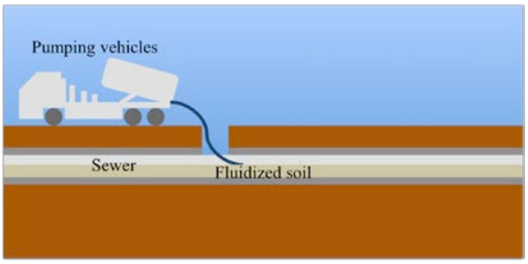


Fig. 1 Pumping of underground space

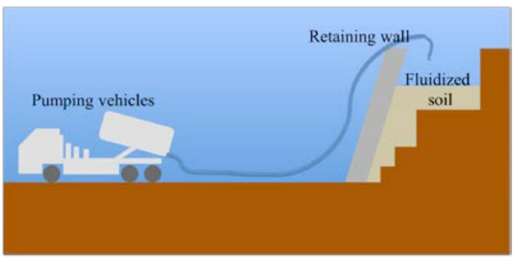


Fig. 2 The backfilling of the retaining wall

flow analysis of fluidization treated soil using the MPS method.

2. OVERVIEW OF THE FLUIDIZED PROCESSING SOIL

The fluidization treated soils are the material used at the time of backfilling of various structures and backfilling underground structures. In addition, it is the material that has been developed in order to make effective reuse of construction waste soils (muddy soils). The basic characteristic of fluidization treated soils is to expect a hardening effect by mixing a solidifying material in an appropriate amount to muddy soils. For the installation of fluidization treated soils is not required with a compaction, they can keep appropriate flow-ability.

In recent years, the waste recycling has been becoming socially important issues. Therefore, the fluidization treated soils have been widely used in urban areas [1]. In other words, to understand in relation to the characteristics of the fluidization treated soils also can be said that also lead to the promotion of recycling construction waste soils.

Past research on the fluidization treated soil has been performing experimental approaches regarding the mechanical properties and flow-ability. The mechanical properties and flow-ability have also been studied when mixed with the fibers or changing the type of muddy soils. However, analytical understanding with respect to the flow-ability of fluidized treated soils has not been performed.

In this study, the authors conduct some experiments and analysis for flow-ability of two types of fluidization treated soils. For the two types of fluidization treated soil, it differs the matrix soil (difference between the maximum particle sizes). In the matrix soil of the fluidization treated soil, the particle size of fluidization treated soil (B) in this study is composed of 74μm or less. The matrix soil of fluidization treated soil (A) has been allowed the mixing of particle size 74μm or more fine sand. Some fundamental properties for the fluidization treated soils (A) and (B) have been mentioned by Inazumi et al. [2], [3].

3. THE PARTICLE METHODS

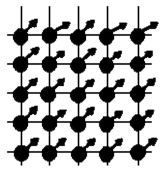
Particle method is a method of analyzing the motion of the continuum as the motion of a finite number of particles. It has not used mesh division. The particle method is also easy to apply to three-dimensional. In recent years, it has attracted attention as an analytical method for three-dimensional continuum.

The particle method is a relatively new technology. The first particle method is the particle and force method (PAF method), it has been proposed in 1965 in the United States Rosuaromosu National Laboratory. After that, the marker and cell method (MAC method) has been proposed. However, particles in this method is used as a tracer of the liquid surface. Furthermore, the particle-in cell method (PCI method) has also been proposed. This method uses a particle in the advection terms. The other terms, it is a method of calculating a grid. Therefore, a large numerical diffusion is occurred.

In using the particle only, pure particle method that is the smoothed particle hydrodynamics (SPH method) has been proposed in 1977. The SPH method is a method of calculating the compressible flow. So far it has been mainly handled in the area of astrophysics. In recent years, its using has spread also be applied to the free liquid surface flow and solid mechanics.

Whereas the SPH method was proposed as a method of calculating the compression flow, the moving particle semi-implicit (MPS method) has been proposed in 1995 as a method for calculating the non-compressible flow. The MPS method is calculated the incompressible condition as a particle number density constant. The MPS method has introduced a pressure by Poisson equation. Free surface is determined by a decrease in particle number density. Therefore, there is no need to draw the liquid surface shape [4], [5], [6].

Table 1 Grid method and Particle method

	Grid method	Particle method
Discretization	Use Grid 	Not use Particle 

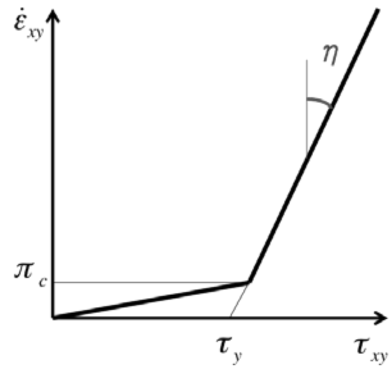


Fig. 3 Bi-viscosity model

4. MPS METHOD APPLYING THE BI-VISCOSITY MODEL

In this study, the fluidization treated soils are focused on the flow analysis the MPS method. These materials can be regarded as a Bingham fluid. Therefore, it is necessary to apply the MPS method to Bingham model. However, it is very difficult to handle the Bingham model in numerical analysis. This is because s stress becomes unstable in the following yield value. Therefore, a bi-viscosity model (*see* Fig. 3) is applied as an approximation model in this study. The constitutive equations employed in this model are expressed in Eqs. (1) and (2).

$$\tau_{ij} = -P\delta_{ij} + 2\left(\eta + \frac{\tau_y}{\sqrt{\Pi}}\right)\dot{\varepsilon}_{ij} \qquad \Pi \geq \Pi_c \tag{1}$$

$$\tau_{ij} = -P\delta_{ij} + 2\left(\eta + \frac{\tau_y}{\sqrt{\Pi}}\right)\dot{\varepsilon}_{ij} \qquad \Pi \geq \Pi_c \tag{2}$$

Where, τ_{ij} $\dot{\varepsilon}_{ij}$ represent stress components and strain ratio component of the viscous fluid. P represents pressure. η represent plastic viscosity. τ_y represent yield value. $\Pi = \dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}$. The governing equation obtained from these constitutive equations is expressed by Eq. (3) and Eq. (4).

$$\frac{\partial \dot{u}}{\partial t} = \frac{1}{\rho}\left(-\nabla P + \left(\eta + \frac{\tau_y}{\Pi}\right)\nabla^2\dot{u} + 2\dot{\varepsilon}_{ij}\frac{\partial}{\partial x_j}\left(\frac{\tau_y}{\Pi}\right)\right) + \dot{F} \tag{3}$$

$$\frac{\partial \dot{u}}{\partial t} = \frac{1}{\rho}\left(-\nabla P + \left(\eta + \frac{\tau_y}{\Pi_c}\right)\nabla^2\dot{u} + 2\dot{\varepsilon}_{ij}\frac{\partial}{\partial x_j}\left(\frac{\tau_y}{\Pi_c}\right)\right) + \dot{F} \tag{4}$$

Eq. (3) is an expression of the state in which the flowing. Eq. (4) is an expression of the state in which the immobile. $\dot{u}$ represent flow velocity vector. t represent time. ρ represent density. $\dot{F}$ represent external force vector. Π_c is using the fluidized limit strain rate(π_c) $\Pi_c = (2\pi_c)^2$.

In the MPS method, continuous body puts as particles of finite number. Particle interaction model utilizes the weighting function w represented by the Eq. (4). This force acting on arbitrary particle assumed to interact with the particles present from the particles within a certain range. In this analysis it is used a logarithmic weighting to improve accuracy than the standard weighting function [7]. It shows the weighting function in Eq. (5)

$$w(r) = \begin{cases} log\left(\frac{r_e}{r}\right) & r \leq r_e \\ 0 & r_e > r \end{cases} \tag{5}$$

Where, r is the distance between particles, r_e is the radius of influence ranging interaction between the particles. Also, evaluate the density of the fluid using the particle number density. Calculation of particle number density has used the weighting function. Particle number density is determined from Eq. (6).

$$\langle n \rangle_i = \sum_{j \neq i} w(|\dot{r}_j - \dot{r}_i|) \tag{6}$$

Where, n_i represents the particle i-th particle number density. $\dot{r}_i$ is the i-th particle position vector, $\dot{r}_j$ is the particle j-th position vector. Incompressible fluid is the density and particle number density is constant. Therefore, it is represented by n^0 the particle number density in the initial placement of the particle as a reference value of the particle number density.

The MPS method discretization is performed in first and second terms of the right-hand side of Eq. (7).

$$\frac{\partial \dot{u}}{\partial t} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\dot{u} + \dot{F} \tag{7}$$

In MPS method Gradient model and Laplacian model, as these discretization, are represented by Eq. (8) and Eq. (9).

$$\langle \nabla\phi \rangle_i = \frac{d}{n^0}\sum_{j \neq i}\frac{\phi_j - \phi_i}{|\dot{r}_j - \dot{r}_i|^2}(\dot{r}_j - \dot{r}_i)\, w(|\dot{r}_j - \dot{r}_i|) \tag{8}$$

$$\langle \nabla^2\phi \rangle_i = \frac{2d}{\lambda n^0}\sum_{j \neq i}(\phi_j - \phi_i)\, w(|\dot{r}_j - \dot{r}_i|) \tag{9}$$

Where $\langle\ \rangle_i$ represents that it has the approximated using a particle model in the i-th particle. d represents the number of dimensions. λ is a coefficient for matching the analytical solution and variable distribution. This is represented by Eq. (10).

$$\lambda = \frac{\sum_{j \neq i}\left[w(|\dot{r}_j - \dot{r}_i|)|\dot{r}_j - \dot{r}_i|^2\right]}{\sum_{j \neq i}[w(\dot{r}_j - \dot{r}_i)]} \tag{10}$$

The discretization of differential operators that gradient model that Laplacian model represented is a feature of the MPS method.

5. UNDERSTANDING AND EVALUATION OF FLOW-ABILITY BY THE FLOW TEST

In order to understand the flow-ability of the fluidization treated soils (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) [8], [9]” is performed. At the same time, an animation of the flow test is also taken. Some characteristic of the fluidization treated soils (A) and (B) is shown in Table 2 [2], [3].

Table 2 The setting parameters of the fluidization treated soils on the flow analysis

	A	B
Specific gravity	1.302	1.224
Plastic viscosity (Pa･s)	2.349	1.209
Yield value (Pa)	2	3
Distance between particles of first (m)	0.0002	
π_c	0.5	

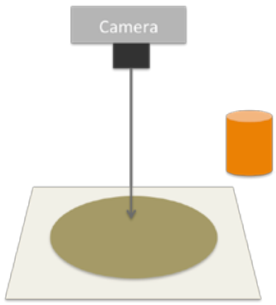


Fig. 4 Overview of image analysis

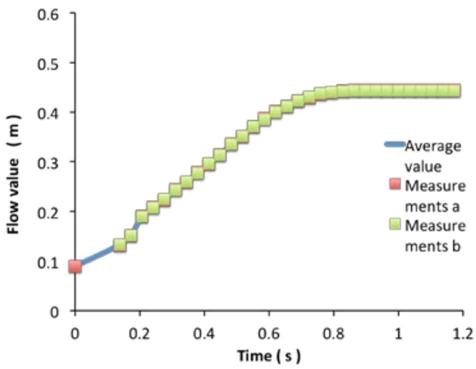


Fig. 5 Flow behavior of the fluidization treated soil (A) by image analysis

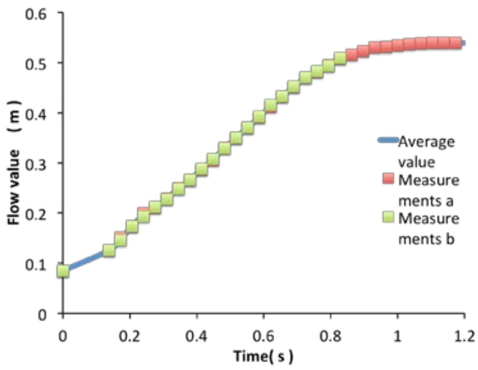


Fig. 6 Flow behavior of the fluidization treated soil (A) by image analysis

This study has conducted an image analysis to make a comparison with the flow analysis by the MPS method. The image analysis is intended to understand the flow behavior of the fluidization treated soils. It is based on the flow test video (*see* Fig. 4). The flow value is measured in the x and y (measured values with a and b respectively) direction orthogonal. The results of the image analysis on the fluidization treated soil are shown in Figs. 5 and 6.

In Figs. 5 and 6, it can be found that the fluidization treated soil (A) has a short flow stop time compared to the fluidization treated soil (B). Furthermore, the fluidization treated soil (A) can be read that has a high flow-ability. The flow-ability of the difference is thought to be due to differences in particle size of the matrix soil. In addition, each fluidization treated soil is read that spread evenly, because the measured value '*a*' and measured value '*b*' are almost identical.

6. UNDERSTANDING AND EVALUATION OF FLOW-ABILITY BY PARTICLE METHOD

To understand the flow-ability of fluidization treated soils from a theoretical point of view, the authors have conducted the flow analysis by the MPS method using bi-viscosity model as a response to Bingham fluid [7]. The the flow analysis by the MPS method is being carried out in two-dimensional, because the flow of fluidization treated soils shows uniformly. The setting parameters for the flow analysis by the MPS method are shown in Table 2. A cross section of the flow analysis by the MPS method is the same with the cross section of the flow test (*see* Fig. 7). In addition, Figs. 8 and 9 show one of the visualized results on the flow analysis by the MPS method.

The comparison between "the flow behavior by the flow analysis by the MPS method" and "the flow behavior by the flow test" in each fluidization treated soil are shown in Figs 10 and 11 (the case of fluidization treated soil (A) is shown in Fig. 10 and the case of fluidization treated soil (B) is shown in Fig. 11). From Figs. 10 and 11, the flow behavior of each fluidization treated soil is well suited between the flow analysis by the MPS method and the flow test. At first glance, it does not seem to well match between the flow analysis by the MPS method 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.

From the analytical results by the particle method (*see* Figs. 10 and 11), the fluidization treated soil (B) has a high flow-ability. Therefore, it is expected to higher filling properties and workability. The difference in the flow-ability by the analytical

Fig. 8 Visualized results on the flow analysis by the MPS method for the fluidization treated soil (A)

Fig. 9 Visualized results on the flow analysis by the MPS method for the fluidization treated soil (B)

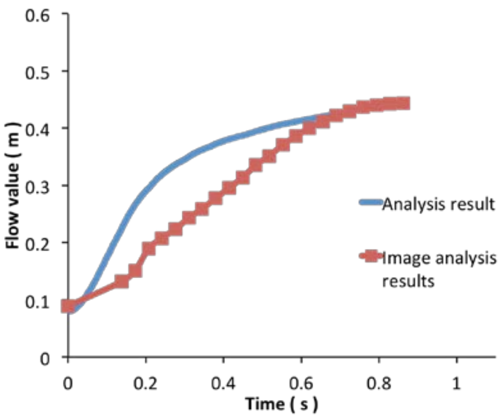


Fig. 10 Simulated flow-ability for the fluidization treated soil (A)

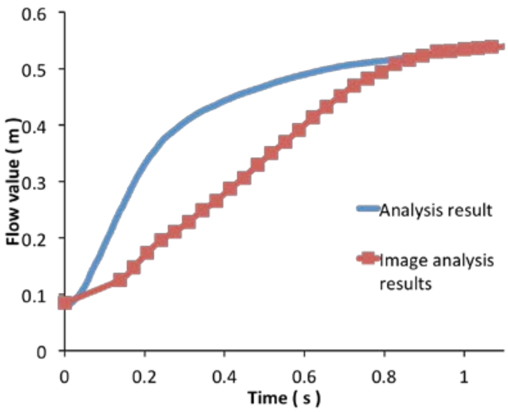


Fig. 11 Simulated flow-ability for the fluidization treated soil (B)

results based on the particle method, it is revealed that the plastic viscosity and the specific gravity is affecting the flow-ability of fluidization treated soils.

7. CONCLUSIONS

In this study, it has evaluated the flow-ability of the fluidization treated soils based on the flow analysis by the MPS method and the experimental evaluation.

The results and findings of this study are shown in follows.

(1) With regard to the flow-ability, high-flow fluidization treated soil (B) was higher than that of fluidization treated soil (A). Comparison of the flow-ability of the 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) Bi-viscosity model was applied for the MPS method. The results using the MPS method was consistent with the challenges in the field for the fluidization treated soils, and the validity of the MPS method was confirmed.
(3) The fluidization treated soil (B) was confirmed to have a high flow-ability based on the results of the flow analysis by the MPS method to correspond to the bingham model.
(4) The main factors that affect the flow-ability of the fluidized processing soils found the specific gravity and the plastic viscosity, by the flow analysis by the MPS method and the experimant by the flow test.

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International Journal of GEOMATE, Jan., 2017, Vol. 12, Issue 29, pp. 53-58.

MS No. 160216 received on Feb. 16, 2016 and reviewed under GEOMATE publication policies.

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