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EVALUATION OF AGGREGATE PARTICLE MOTION OF LIQUID-SOLID FLOWS IN MODEL CONCRETE

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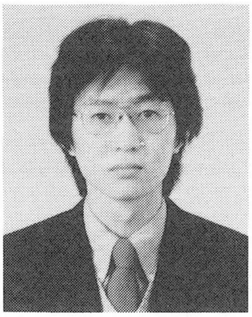
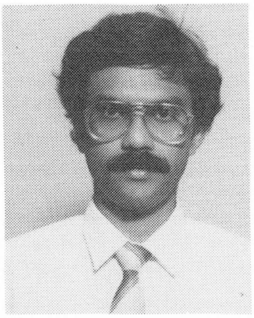
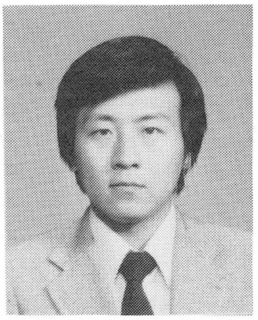

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SYNOPSIS

The objective of this research is to evaluate the kinematics and deformation of solid phase in flowing two-phase material for the purpose of understanding the segregation process of fresh concrete as liquid-solid material. Studying the segregation process of flowing fresh concrete, the motion of coarse aggregate which closely relates with blocking of flow was observed in the visualized test with model material simulating fresh concrete. In image analysis, all particles in flowing model concrete were processed by a video-computer system. Not only Lagrangian but also Eulerian expression of aggregate phase, spatial averaging technique, was found to be useful as to understand the flow and segregation of two-phase model concrete.

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EVALUATION OF AGGREGATE PARTICLE MOTION IN LIQUID-SOLID FLOWS OF MODEL CONCRETE

By Kazumasa OZAWA, Anura NANAYAKKARA** and Kohichi MAEKAWA****

The objective of this research is to evaluate the kinematics and deformation of solid phase in flowing two-phase material for the purpose of understanding the segregation process of fresh concrete as liquid-solid material. Studying the segregation process of flowing fresh concrete, the motion of coarse aggregates having close correlation with blocking of flow was observed in the visualized test with model material simulating fresh concrete. The image analysis was conducted and all solid particles were processed by a video-computer system. Not only Lagrangian but also Eulerian expression of aggregate phase, spatial averaging technique, was found to be so useful as to understand the flow and segregation of two-phase model concrete.

Keywords: *liquid-solid flow, visualized test, aggregate particle motion, Eulerian evaluation, segregation process*

1. INTRODUCTION

Fresh concrete should be placed without segregation everywhere, during pumping and casting in the formwork. The transient variation of volume content of constituent materials for concrete, such as gravels, sands, cement particles and water, called segregation, will cause troublesome problems relating to the durability of concrete structures.

Blockage of flowing concrete is one of the extreme cases which are concerned about segregation of fresh concrete. Basically, there exists no problems concerning blocking or segregating of flowing concrete without deformation, but we may often encounter the blockage or segregation of deformed fresh concrete in heavily reinforced area or around tapered, bending and bifurcation points in pipe lines. It is because fresh concrete is not a uniform material, but consists of various materials having various size, shape and specific gravity. Especially the larger size of material, that is a coarse aggregate, plays an important role on the shear deformation of fresh concrete for the effect of its solid particle, such as shear dilatancy and collision between particles. These behavior of solid particles may trigger the blocking or segregation of flowing fresh concrete. It is, therefore, invaluable to observe the deformational behavior of aggregate phase as solid in fresh concrete for understanding the segregation process of flowing fresh concrete and creating the concept of high performance concrete with high deformability and segregation resistance.

In this study assuming fresh concrete as solid-liquid two phase material, the evaluation methods of the two-dimensional kinematics and deformational behavior of aggregate phase are proposed, using the visualized test with model concrete, developed by Hashimoto et al[1].

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2. VISUALIZED TEST

Visualized test with model concrete is useful by applying Hashimoto's method[1] so as to get information on aggregate movement.

(1) Apparatus and material

The apparatus used, as shown in Fig. 1, consists of a rectangular pipe, pistons with rods and a video camera which records motion of model aggregates, such as plastic balls. A rectangular pipe section, instead of a circular pipe used in Hashimoto's method[1], was selected so as to watch movement of all solid particles away from pipe walls, which is made of two transparent acrylic panels supported by frames. Thickness of the pipe section should be also designed so that only one layer of solid particles could be accommodated inside the pipe, which enables us to observe the idealized two-dimensional behavior of particles clearly. It is convenient that the piston head in the inlet pipe should be controlled by an electric motor at a constant speed.

Model concrete used consists of transparent water-absorbent polymer as mortar (liquid) phase and plastic balls or lightweight aggregates as aggregate (solid) phase which is considered to trigger segregation of flowing concrete. Water-absorbent polymer dissolved in water was confirmed to be equivalent to actual mortar in the flowing test[1]. Its viscosity can be controlled by adding cellulose-type polymer agent. Specific gravity ratio of solid particles to polymer media should be about 1.4, which corresponds to that of normal aggregates to mortar in actual concrete.

In this visualized test we idealize and simplify the material and the dimension of flowing condition, which is different from the practical conditions[1], in order to get information on the movement of all solid particles and to build up the concept of segregation process and mechanism of flowing concrete. The size of solid particles versus the section size is also one of the important factors with respect to the behavior of flowing concrete, which should be equivalent to the maximum size of coarse aggregates in actual concrete versus actual boundary condition.

(2) Testirig procedure and image analysis

At first, polymer media is poured into the pipe section and then solid particles are arranged uniformly in such a way that particles touch with each other. After charging the polymer and particles in the pipe section set up horizontally, the piston head in the inlet pipe is moved at a constant speed and the movement of particles is recorded with a digital video camera.

Using the video data recorded, as shown in Fig. 2, image analysis is conducted, based on the A/D converter and micro processor. Through this image analyzer, gravity center position of all aggregates at regular intervals can be obtained. Each gravity center in a screen will be connected to that corresponding in the next screen with the micro processor, which can draw stream lines and velocity vectors of all particles

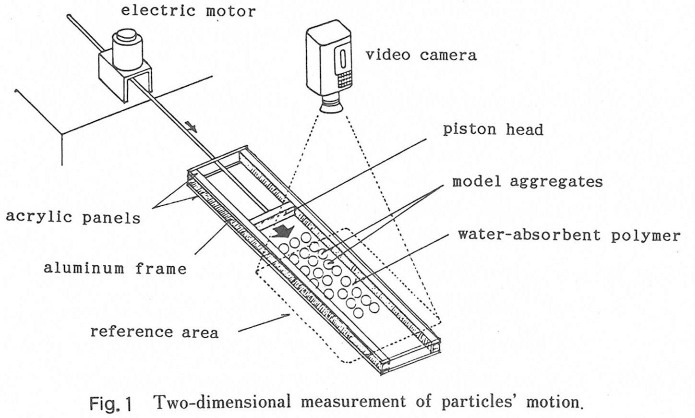


Fig. 1 Two-dimensional measurement of particles' motion.

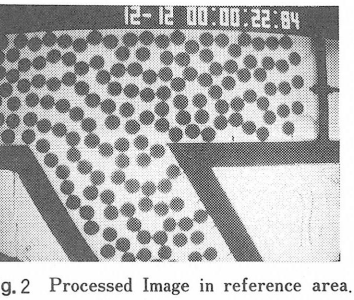


Fig. 2 Processed Image in reference area.

at each time and each location. The time interval measured should be decided so that each particle may not move over the radius of particle at the intervals.

3. EVALUATION OF AGGREGATE PHASE

Using position data of each aggregate connected through a series of screen, the behavior of aggregate phase can be evaluated with two methods, that is, Lagrangian and Eulerian treatments.

(1) Lagrangian expression of aggregate phase

From Lagrangian expression such as a particle trace line of aggregates, fluctuational and turbulent movement of each aggregate can be observed, which may signify the segregation indirectly[3]. It can also say that how particles from an inlet pipe flows into an outlet pipe, and where and how locational interrelation of some particles is transformed. But particle interaction to the neighboring particles cannot be perfectly evaluated with the trace of only some particles, and all particles should be processed in order to clarify the particle interactions. Trace lines of particles, of course, will match the stream lines under the steady flow condition.

Under the unsteady flow condition, however, it is difficult to describe the global flowing condition with the use of only one trace of particles. On the view point of simulation model for two phase flow, Lagrangian description of aggregate phase is so useful to apply the discrete model of solid phase such as P. A. Cundall's model[2] for granular flow. Moreover taking the unsteady flow of fresh concrete on such boundary condition into account, it may be needful to simulate the flow and deformation. It takes, however, the huge mathematical computation to simulate with such a granular model.

(2) Eulerian expression of aggregate phase—spatial averaging technique—

On the other hand, assuming the aggregate phase in model concrete as a continuous phase, the global deformation field of aggregate can be represented based on Eulerian expression. Eulerian expression should be adopted so as to observe and to understand the mutual interaction of flowing aggregate phase. Its macroscopic information is also so valuable for computational modeling of fresh concrete as two-phase material based on the interparticle stress concept. Eulerian description is convenient for computing the spatially averaged deformation of each phase and total pressure integrated from each stress of each phase. Both treatments may be, however, helpful to understand the behavior of aggregate phase perfectly.

Virtually using discrete velocity data derived from each aggregate, the interpolated velocity field of aggregate phase can be obtained on the assumption that velocity varies linearly between each aggregate data. Based on this assumption, the velocity vector at any point can be continuously defined. This is so-called spatial averaging process and the detail is explained later.

In the two-dimensional strain problem, normal co-ordinates system (x-y) is defined for this purpose. Normal strain ε_x in the x direction and ε_y in the y direction are defined in the velocity field of smoothed aggregate phase as follows.

$$\varepsilon_x = \partial u / \partial x \quad \cdots (1)$$

$$\varepsilon_y = \partial v / \partial y \quad \cdots (2)$$

where u is a velocity of aggregate phase in the x direction and v is that in the y direction. We have a shear strain of ε_{xy} as follows.

$$\varepsilon_{xy} = (\partial u / \partial y + \partial v / \partial x)/2 \quad \cdots (3)$$

Normal strains ε_x and ε_y give the velocity gradient of the aggregate phase in the x and the y direction respectively, in other words, describe the variance of relative distance between aggregates in each direction. Positive values of ε_x mean that the relative distance of aggregates in the x direction is increasing. Then, ε_{xy} expresses the shear deformation component with constant relative distance of aggregates. Using the above strain components, the deformation rate or "intensity" of the aggregate phase can be represented with invariants "I" and "J", independent on the co-ordinate transformation in two-dimensional tensorial expression[7].

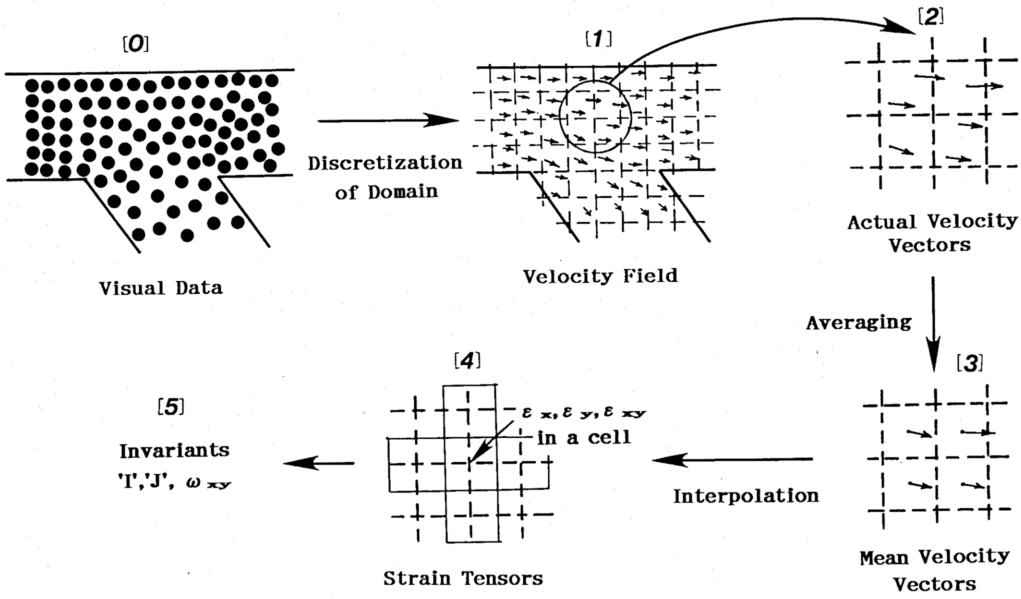


Fig. 3 Spatial averaging procedure.

$I=(\varepsilon_x+\varepsilon_y)/2$ ·· (4)

$J=\sqrt{((\varepsilon_x-\varepsilon_y)/2)^2+\varepsilon_{xy}^2}$ ·· (5)

The first invariant "I" denotes the mean deformation rate and represents the variance of mean relative distance between aggregates. "I" of positive values means divergence of aggregate phase and "I" of negative values gives convergence of aggregates. Assuming incompressibility in a continuum body, we have "I" as zero, then "I" represents the segregation at each point.

The second invariant "J" denotes the deviatoric deformation rate representing the intensity of shear mode. The spin tensor ω_{xy} peculiar to hydrodynamics can be defined positive in counter-clockwise direction as follows.

$\omega_{xy}=\left(-\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)/2$ ·· (6)

The deformation on aggregate phase can be represented by these invariants "I", "J" and a tensor ω_{xy}, provided that the aggregate phase is assumed as a continuous phase.

The procedure of deriving spatial distribution of "I", "J" and ω_{xy} in practice is as shown in Fig. 3. Firstly, the target area on a screen is divided into finite square elements having four sides equivalent to the diameter of a solid particle. Mean velocity vector at the gravity center of an element can be given by computing mean value of velocity data of aggregates in the element, though vacant elements should be filled up with mean velocity of surrounding elements by means of the linear interpolation. At last "I", "J" and ω_{xy} can be calculated at a point by using the strain components derived from the mean velocity vector of surrounding four points in elements by means of the interpolation of isoparametric finite element method[4]. Stress produced in each element may depend on the concentration of aggregates within the element.

(3) Time averaging and deviation of flow

In steady flow or unsteady flow, time averaging and some deviation to the average behavior will be of interest and of importance for understanding the additional transfer of momentum like turbulent flow. In discussing the momentum transfer due to turbulence, we must assess the deviation of flow in time domain and compare it with the spatially averaged strain field[5]. Then Eulerian treatment is powerful.

In velocity field of aggregate phase in Eulerian description, time averaging and standard deviation of aggregate movement also represent the turbulent movement of aggregates at each location and two deviations can be defined, that is, that normal to the mean velocity direction and that parallel to the mean direction. Both of them may be caused by the disturbed movement of aggregate phase, and especially the former deviation represents the turbulent behavior introduced by the aggregate interaction such as collision, sliding and rearrangement of aggregate phase. This technique with deviation distribution in velocity field of solid particles may be, therefore, so useful as to discuss the additional energy generated by the turbulence[6].

Time averaging and standard deviation of flow can be computed as follows. Mean velocity vector at each location can be calculated from some velocity vector data in time domain. And standard deviation can be derived from the variance to mean velocity vector at each element in the parallel to the mean velocity direction and the perpendicular to the mean direction respectively.

4. KINEMATICS AND DEFORMATIONAL BEHAVIOR OF AGGREGATE PHASE IN VISUALIZED TEST

In this section examples of kinematics and deformational behavior of aggregate phase are shown using the above mentioned evaluation method on various visualized tests.

(1) Lagrangian evaluation of aggregate phase

Trace of specified four particles in a tapered portion, where a steep angle of 27 degree and plastic sphere were adopted, is shown in Fig. 4. It can be seen that arches supported by the side walls are formed near the outlet. Arch formation by the solid phase implies the development of high internal stress which act directly to block the flow of solids. As a result, segregation between solid and liquid phase takes place. But in this case the formation of arch by plastic spheres is broken by the following model concrete because of smooth surface of plastic spheres.

Trace of particles in adjoining two lines around bifurcation point is shown in Fig. 5. This case gives unbalanced speeds of flowing model concrete in two outlet pipes, where the ratio of speed in the branched outlet pipe to that in the straight outlet was 1.5. It can be seen that more than half of particles (10 particles) flow into the straight outlet pipe in spite of the slower speed condition, which means the accumulation of particles in the straight outlet pipe. It may be considered that particles cannot flow into the branched outlet pipe associated with liquid phase, which implies the segregation of solid and liquid phase. And locational interrelation of particles is found to be less transformed specially in the straight pipe. Particle interaction is considered to restrain the rearrangement of solid particles.

These two examples shows that Lagrangian description of solid particles gives the flow and movement of each particle clearly, such as a formation of arch and distribution of particles divided into two outlet pipes, which represents indirectly the segregation between solid and liquid phase. It is, however, difficult to

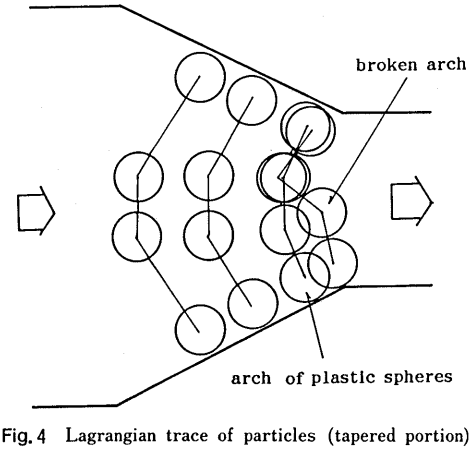


Fig. 4 Lagrangian trace of particles (tapered portion).

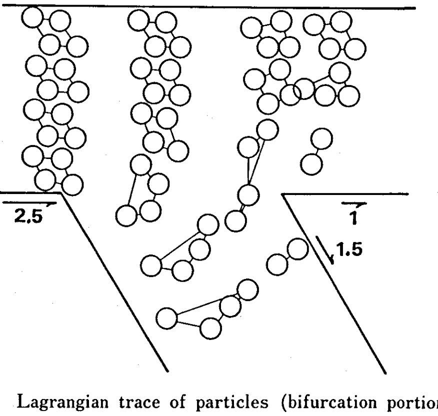
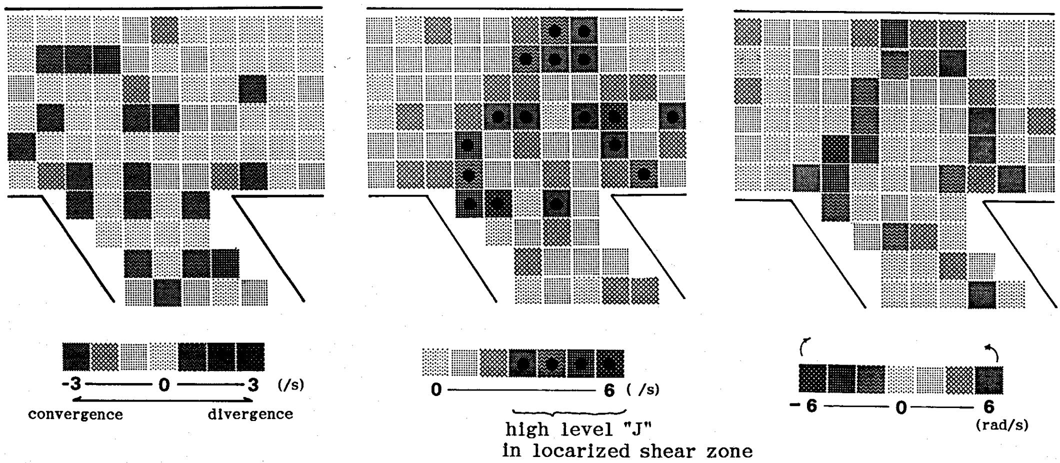


Fig. 5 Lagrangian trace of particles (bifurcation portion).



(a) mean deformation rate "I" (b) deviatoric deformation rate "J" (c) spin tensor ω_{xy}

Fig. 6 Eulerian evaluation of particles' motion (bifurcation portion).

have an image regarding the interaction of solid particles and its distribution with only the trace of some particles.

(2) Eulerian evaluation of aggregate phase

Eulerian evaluation of motion of aggregate phase around bifurcation point, where the experimental condition is the same as that in Fig. 5, is shown in Fig. 6. Mean deformation rate "I" represents the variance of mean relative distance between particles. It can be seen in Fig. 6(a) that the convergence of particles where "I" is negative and the divergence where "I" is positive are distributed around the bifurcation zone, which means the segregation between solid particles and liquid phase. Furthermore deviatoric deformation rate "J" represents the intensity of shear deformation rate and distinct sliding zones denoted by dot marks can be observed in Fig. 6(b), which implies the localization of shear deformation of solid phase. The deformation in the sliding zones can be divided into negative rotation and positive rotation as shown in Fig. 6(c), which represents a spin tensor ω_{xy}.

It is natural to consider that the greater values of "I" and "J" we have, the higher inter-particle stresses are produced. The localized zone with high shear interaction is clarified by this procedure. This evaluation of solid particles directly represents the mode of deformation for solids and indirectly shows the spatially distributed stress intensity which is also dependent on the stiffness of solid phase. These global informations of solid particles cannot be derived without Eulerian evaluation. This evaluation method is so useful to understand the relative motion of particles and the segregation of solid phase in flowing two-phase material.

(3) Deviation distribution in velocity field

Standard deviation distribution of velocity field around bifurcation portion is shown in Fig. 7, where experimental condition is same as that in Fig. 5 and Fig. 6. It is computed from the variance

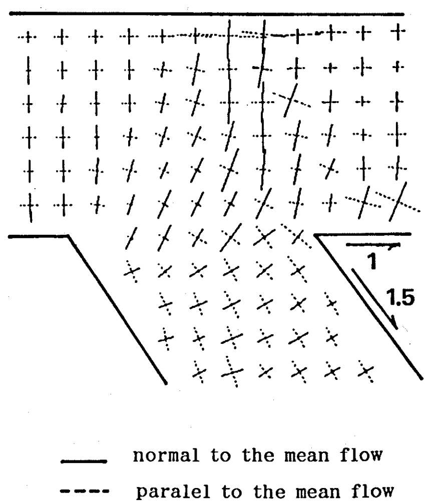


Fig. 7 Distribution of standard deviation to the mean flow of particles (bifurcation portion).

about time averaging velocity vector at each element for 1.6 seconds in time domain. It can be seen that the higher magnitude of standard deviation, especially that normal to the mean velocity direction, is distributed in the bifurcating zone dividing the inlet flow into two outlet, which implies the turbulent flow of particles. This particle behavior may be caused by the high particle interaction, such as collision and sliding between particles and due to mixing effect in the normal direction, the additional momentum must be transferred similar to the turbulent flow of continuum liquid.

Thus, time averaging and standard deviation of solid flow in Eulerian description clarifies the turbulent conditions of solid particles, especially the spatially distribution of turbulent behavior in deformation of solid phase related to the segregation of solid-liquid flows.

5. CONCLUDING REMARKS

Studying the segregation process of flowing fresh concrete as a two-phase material, we idealized and simplified the material and the dimension of flowing condition in the visualized test for the purpose of getting information on the kinematics and deformation of aggregate phase. And using the image analysis, not only Lagrangian expression but also Eulerian expression was found to be so useful as to evaluate the kinematics and deformation of aggregate phase in two-phase model concrete.

Lagrangian description of solid particles can clarify the flow and movement of each particle clearly, such as a formation of arch and distribution of particles divided into two outlet pipes, which represents indirectly the segregation between solid and liquid phase. It is, however, difficult to understand the global deformation of solid phase and the interaction of solid particles associated with the concept of interparticle stress with only the trace of some particles.

Eulerian evaluation of solid particles, using the strain invariants "I", "J" and a tensor ω_{xy}, is so useful to understand the global deformation and the segregation process of solid phase in flowing two-phase material. Time averaging and deviation distribution of solid particles in velocity field clarify the turbulence condition in deformation of solid phase related to the segregation process of solid-liquid flows.

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REFERENCES

1) Hashimoto, C., Maruyama, K. and Shimizu, K. : Study on Visualization of Blocking of Fresh Concrete Flowing in Pipe, Concrete Journal, Vol. 26, No. 2, pp. 119-127, Feb. 1988 (in Japanese).
2) Cundall, P. A. and Strack, O. D. L. : A discrete numerical model for granular assemblies, Geotechnique, Vol. 29, No. 1, pp. 47-65, 1979.
3) Hashimoto, C. et al. : Study on Visualization of Deformability of Fresh Concrete Pumping, Proceeding of Japan Concrete Institute, Vol. 10, No. 2, pp. 79-84, 1988.
4) Zienkiewics, O. C. : The Finite Element Method, Third Edition, McGraw-Hill Book Co. Ltd., 1977.
5) Rotta, J. C. : Turbulent Flow (translated by Oji), Iwanami Book Co. Ltd., 1975.
6) Roco, M. C. and Shook, C. A. : Turbulent Flow of Incompressible Mixture, Journal of Fluid Engineering, Vol. 107, pp. 224-231, June 1985.
7) Maekawa, K. and Okamura, H. : The Deformational Behavior and Constitutive Equation of Concrete Using the Elasto-Plastic and Fracture Model, Journal of the Faculty of Engineering, The University of Tokyo (B), Vol. XXXVII, No. 2, 1983.

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