研 究 速 報

Numerical Simulation of Fresh Concrete (1)

Three-Dimensional Discrete Element Model for Fresh Concrete
フレッシュコンクリートの数値シュミレーション (1)
－3次元個別要素法によるフレッシュコンクリートのモデル化－

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1. INTRODUCTION

The discrete element method (hereafter, DEM), which models a problem as a discrete assemblage of particles, has features that make it attractive for modeling large deformation problems in fresh concrete engineering. Although computer simulated experimentation using the DEM was originally developed, as a tool, for examining geomechanical problem[1]; the dynamic nature of the methodology used lends itself more readily to many other areas of scientific and industrial interest. One such area is process engineering, in which large volumes of particulate materials have to be handled in the context of flow problems. Before any modeling is attempted on large-scale problem several issues must be resolved, such as choosing appropriate model parameters and reducing the enormous number of particles required for a realistic model. This research will provide guidelines for choosing parameters appropriate for fresh concrete. Guidelines will also be given for choosing the DEM model parameters necessary for obtaining realistic aggregate and mortar behavior. In this study, three dimensional particle flow code (hereafter, PFC^{3D}) has been used, as a tool, to simulate behaviors of fresh concrete.

2. JUSTIFICATION OF USING DEM

The following are the justifications for the use of DEM instead of a continuum approach to simulate fresh concrete. The difficulty of continuum modeling approach, such as finite element method, for concrete is due to its inability to explain the considerable movement and rotation of granular particles. Traditional theoretical (continuum models) and experimental investigations of the behavior of particulate systems are restricted by the limited quantitative information about what actually happens inside particulate assemblies. The central problem in the processing of particulate materials is the need for improved understanding of the nature and magnitude of the forces involved in the particle-particle interaction. In addition, what is not well understood is the way in which the inter-particle behavior is affected by the spatial and size distributions of the constituent particles. The concrete material is discrete at some level. The heterogeneous property of the concrete makes it an unrealistic trade-off to assume the homogeneity within samples or elements. The microscopic model, PFC^{3D}, was used because a) it has the criteria of DEM that allows finite displacements and rotation of discrete bodies and recognizing new contacts automatically and b) it uses an explicit time marching method to solve the equations of motions directly.

3. CONTACT CONSTITUTIVE MODELS

The overall constitutive behavior of a material was simulated in PFC^{3D} by associating a simple constitutive model with each contact. The constitutive model acting at a particular contact consists of three parts: a stiffness model, a slip model, and a bonding model. PFC^{3D} provides two contact stiffness models: a linear model, and a simplified Herz-Mindlin[2] model. In this paper linear model has been used. The slip model is an intrinsic property of the two entities (ball-ball or ball-wall) in contact. It provides no normal strength in tension and allows slip to occur by limiting the shear force. In this research slip model was always kept active, unless a contact bond was present- in which case, the contact bond model behavior supersedes the slip model behavior. PFC^{3D} allows particles to be bonded together at contacts. Two bonding models are supported: a contact bond model and a parallel bond model. The presence of a contact bond, however, inactivates the slip model. Once a bond is formed at a contact between two particles, that contact continues to exist until the bond is broken. Here,

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only contact bond model has been used not the parallel bond model. A contact bond can be envisioned as a pair of elastic springs (or a point of glue) with constant normal and shear stiffness acting at the contact point. These two springs have specified shear and tensile normal strength. Contact bonds allow tensile forces to develop at a contact. The magnitude of the tensile normal contact force is limited by the normal contact bond strength. If the magnitude of the tensile normal contact force equals or exceeds the normal contact bond strength, the bond breaks, and both the normal and shear contact forces are set to zero. If the magnitude of the shear contact force equals or exceeds the contact bond strength, the bond breaks, but the contact forces are not altered. The constitutive behavior relating the normal and shear components of contact force and relative displacement for particle contact occurring at a point is shown in Fig. 1. As parallel bond model has not been used in this research, it is not described.

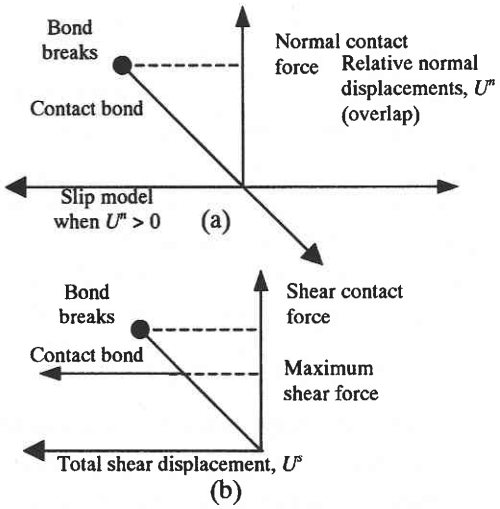

Fig. 1 Constitutive behavior for contacts occurring at a point, (a) normal component of contact force, (b) shear component of contact force.

4. DEM MODEL FOR FRESH CONCRETE

The level of detail to be included in a model often depends on the purpose of the analysis. It is tempting to include complexity in a model just because it exists in reality. Complicating treatment, however, should be omitted if they are likely to have little influence on the purpose of the model or if they are irrelevant to the model purpose. The secret of success in computer experiments is to devise a model, which is sufficiently detailed to reproduce faithfully the important physical effects, and yet not so detailed as to make the calculation impracticable. It is considered that single-phase model is enough for the flow simulation of granular material. However, it was shown that fresh concrete can not be modeled as single-phase and must be modeled as multi-phase material[3,4]. In DEM model, the increase of phase numbers and small particle sizes like that of cement and sand extremely complicates the simulation and the calculation speed also becomes very slow.

All previous models known to the authors used either one-phase model or two-phase model, which includes aggregate and mortar property in the same element. In this research, two-phase model has been adopted but in a different way. Here, aggregate and mortar have been modeled using separate element shown in Fig. 2. Nevertheless, DEM model can be composed of cement paste, fine aggregate and coarse aggregate element separately. However, the huge number of fine aggregate would make the numerical simulation time consuming. Thus, two-phase model, one mortar element and one coarse aggregate element were used. The major parameters used in the simulation are contact stiffness, bond strength both for shear and tangential direction, and friction factor between two elements at each contact point. To get successful model for concrete simulation the constituent models, i.e., mortar model and aggregate model should be verified before hand.

4.1 EQUIVALENT DENSITY CONCEPT

Mortar, more or less, can fill every part of a volume. If the mortar element is modeled using element and same density is given then, for the same volume, mass will be less. At the same time it is very difficult to determine this equivalent density before final particle compaction. This also depends on the stiffness, which cannot be changed after compaction without changing the volume of the initial compacted state. Then particle number in a given volume and porosity will be changed again. Thus, it requires trial and error procedure, which is not feasible at present time. An approximate method based on solid crystal structure has been adopted. To calculate the equivalent density face centered solid crystal structure unit cell, as shown in Fig. 3, has been used. This unit cell uses 14 lattice points eight of which are corner atoms (forming the cube) with other six in the center of each of the faces. Since two cubes share the face atoms they only contribute three atoms to the unit cells. These three atoms plus one from the corners yield the four net atoms in unit cells. Now the unit cell was considered as real mortar and the four net atoms as DEM mortar element. Equivalent density is that density, which equates both the masses. This equivalent density is independent of ball size but depends on the unit cell porosity. If further decrease in porosity in excess of the face centered cube provided is needed, extra ball can

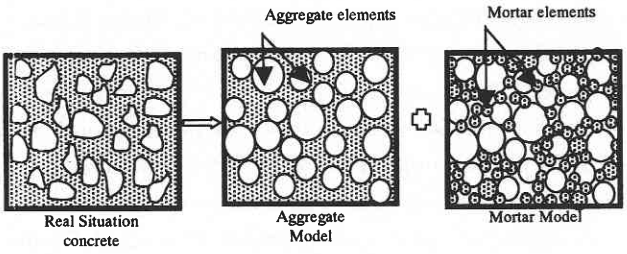

Fig. 2 Two-phase concrete model adopted in the present study.

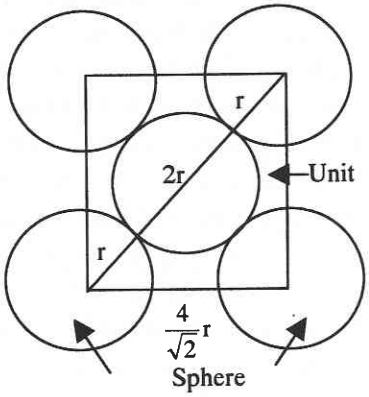

Fig. 3 Face centered cube used for equivalent density calculation.

be used in between the every corner element. This method approximately conserves the mass, if the porosity of the final compacted state does not become too low; this independence on ball size might make it suitable for simulation, which has several ball sizes.

4.2 EQUIVALENT GRADING CONCEPT

Mortar element simulates the effect of combined sand and cement in simulation. No particular grading curve can be applied. Use of actual grading curve, for fine aggregate, to get the compacted assembly, might not be judicious enough. So, a method has been proposed. The actual grading curve, for fine aggregate, has been shifted to the right, as shown in Fig. 4(a). Lowest value of the sieve opening has been kept equal to 7.5 mm. This has been selected using several test runs with different ball size keeping a similar condition for each simulation. It has found that as the ball size decreases running time increases, which is shown in Fig. 5. It can be observed from Fig. 5 that for ball size below 7.5 mm, running time increases very fast. For this grading curve percent finer has been kept equal. Because it should give the same fineness modulus (FM) if the original sieve size is changed to equivalent selected size of the ball. The same has been done for coarse aggregate. In the case of coarse aggregate, the element size should not be greater than dragging ball diameter (15mm) and also should not be less than 7.5 mm as described earlier. Grading curve selected for both the elements are shown in Fig. 4. During the parameter selection it is recommended to use a reasonable constant ball size. Author suggests that grading curve should be generated from large particle to small particle, due to the easiness of filling a volume with random particle.

4.3 MORTAR, AGGREGATE AND CONCRETE MODEL

Mortar element is a hypothetical element in the simulation. It is difficult to determine any entity such as grading of mortar element, parameter values etc. This is due to the fact that there is no definite rule to determine fresh mortar stiffness. To calculate the stiffness of mortar a new approach has been adopted, which is shown in Fig 6. Contact spring stiffness (both normal and shear direction) has been calculated by fixing the amount of overlap between the two-mortar element. In this study the largest ball size and smallest ball size have been averaged to calculate the mortar stiffness, for a specified grading curve. For a fixed equivalent density, the value of stiffness, which gives the fixed overlap, should be chosen as mortar element stiffness. In this study, 1-percent overlap has been selected. For mortar element contact bond between the elements has been used, and friction value has been kept zero. Bond value should be selected using trial and error method. The value,

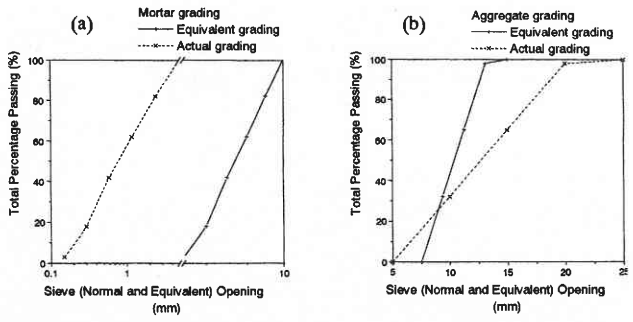

Fig. 4 Grading curve diagram (a) for mortar element (b) for concrete element.

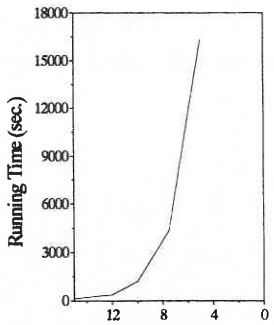

Fig. 5 Running time vs. Ball Diameter.

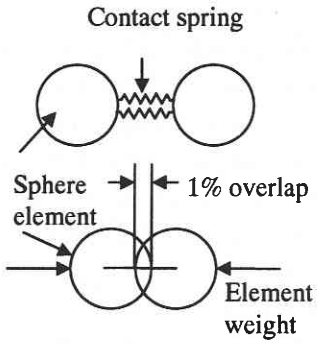

Fig. 6 Method used to calculate the mortar contact spring value.

which gives the qualitative behavior of mortar, should be selected for the analysis. To model the aggregate, actual grading curve has not been used. If the actual grading curve had been used it would have taken large computing time. So, for the present research equivalent grading curve has been proposed. As for the parameter value, Ting[5] assumed elastic granite cylinders to have normal stiffness ranged from 108 to 1010 pa. Mindlin[6] assumed the elastic bodies in contact with elliptical contact areas to have the ratio of shear stiffness to normal stiffness to be between 2/3 to 1, the estimations for normal shear stiffness pairs for gravel-gravel contacts should be kept within the above range. For aggregate element no inter-particle bond has been selected, only friction value has been taken and quantitative value for normal and shear stiffness must be selected from several trial simulations. To model concrete, the separate models for mortar and aggregate has been combined. For concrete model an extra bond property has been introduced between mortar and aggregate.

5. DISCUSSIONS AND CONCLUSIONS

In this present study, various problems of numerical simulation have been discussed. Suitable solutions have been suggested. In future, author will publish some work conducting trial simulation using the model proposed here. In this paper, two problems have been discussed: (a) methods to choose appropriate simulation parameters, and (b) method to reduce element number and consequently running time of the simulation. Mortar and aggregate normal and shear stiffness selection procedure has been proposed in this paper. To select the qualitative value of the other parameters like friction and bond value sensitivity analysis is required. This selection procedure should not relate with mortar or aggregate model. This should be done to get the idea of behavior of each parameter. Running time is very important in this regard. For simulation where grading curve is used equivalent grading curve has been proposed, to reduce the element number and running time. To perform detail parametric study the ball size has to be selected in such a way that the running time can be reduced significantly. Other parameter such as normal and shear bond has to be selected from a test simulation. Then, the simulated experiment should be compared with real experiment. The parameter, which gives the close comparison, should be selected for further simulation. A new concept, equivalent density concept, has been proposed to approximately conserve the mass between simulation and experiment. Future trial simulation, simulating various test methods for fresh concrete, would verify the proposed model in this paper.

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