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Three-Dimensional Modeling of Green Sand and Squeeze Molding Simulation

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Abstract. The green sand mold with good mold properties are useful to obtain the sound cast iron castings. For example, the green sand mold with high density and uniform for compacting characteristics would be required. Molding simulation is indispensable to make a good sand mold. In recent years, the package software was released from software vendors of foundry CAE, and the demand for molding simulation is increasing. Fundamental algorithms of the green sand particulate model and the three-dimensional Discrete Element Method (DEM) were proposed. They take into consideration of the particle size distribution and the cohesion of green sand particles.

In this study, the squeeze molding simulation is carried out and we execute the re-development of this method under the current computer environment. They are tried to simulate the dynamic behavior during molding and to predict the mold properties after squeeze molding. The characteristics of green sand with cohesion are reflected in the particle model called Hard-Core/Soft-Shell. The compacting behavior of squeeze molding is traced numerically, and the visualization by a three-dimensional model and comparison of dynamics molding are carried out. From the simulation with several kinds of particle distribution, it becomes clear the relationship between the void fraction and the squeeze pressure during molding. The effect of particle size distribution on sand compacting behavior is also clarified. Furthermore, the three-dimensional display of green sand with particle size distribution is very effective in the post-processing.

Introduction

In the field of casting, the computers are also used mainly for the casting CAE (Computer Aided Engineering) including the analysis of various casting phenomena, the prediction of casting defects, to obtain the optimum operating conditions and so on. Package software for the casting CAE almost consists of the mold filling, the heat transfer and solidification and the residual stress and strain of product. On the other hand, the green sand mold with good mold properties are useful to obtain the sound cast iron castings. The molding simulation is indispensable to make a good sand mold and the demand for molding simulation is increasing. Fundamental algorithms of the green sand particulate model and the three-dimensional Discrete Element Method (DEM) were proposed [1-5]. They take into consideration of the particle size distribution and the cohesion of green sand particles. Furthermore, there are interesting reports using the Discrete Element Method. E. Havad et. al. [6] simulated the flow dynamics of green sand in the DISAMATIC moulding process. Y. Nakata and M. Yamanoi [7] analysed the mixed states of granular systems with shannon entropy. The simulation using the DEM is expected to be a powerful tool for the molding process.

In this research, the three dimensional discrete element method considering the particle size distribution of sand particles and the cohesion of green sand is re-developed under the current computer environment. When compared with about 15 years ago of [1], CPU performance evolved dramatically and parallel computing became possible. It is possible to use the enough capacity memory for large number of elements. Further, the dynamics behavior during squeeze molding is analyzed using the present model.

Discrete Element Method

In the present mathematical model, the green sand particles are assumed to be viscoelastic elements. The motion of each element is obtained by integrating the equations of motion step-by-step:

$$\ddot{\boldsymbol{r}} = \frac{1}{m_e}(\boldsymbol{f}_c + \boldsymbol{f}_d) + \boldsymbol{g} \tag{1}$$

where $\boldsymbol{r}$ is the position vector, m_e the element mass, $\boldsymbol{f}_c$ the summation of the contact force, $\boldsymbol{g}$ the gravity acceleration, and dot denotes a time derivative. For squeeze molding, the drag force $\boldsymbol{f}_d$ is zero because the air is not used. After a time step Δt, the velocity and position of an element can be given as

$$\boldsymbol{v} = \boldsymbol{v}_0 + \ddot{\boldsymbol{r}}\Delta t \tag{2}$$

$$\boldsymbol{r} = \boldsymbol{r}_0 + \boldsymbol{v}\Delta t \tag{3}$$

where $\boldsymbol{v}$ is the velocity vector and subscript 0 denotes the value before the first step.

Contact Force

The Hard-Core/Soft-Shell model for the green sand shown in Fig.1 is proposed by Maeda [1,2,3]. The Hard-Core is modelled the basic sand particle such as silica or artificial (ceramic) sand, and the Soft-Shell is also the thin layer of bentonite or oolitics.

The contact force is suggested first by Cundall and Strack [8]. This model expresses the contact forces by a spring, a dash-pot and a slider. The plural particles can be in contact with particle i at the same time. The total contact force acting on particle i is obtained by taking the sum of the normal forces $\boldsymbol{f}_{cnij}$ and tangential forces $\boldsymbol{f}_{ctij}$ with respect to j :

$$\boldsymbol{f}_{ci} = \sum_j \left(\boldsymbol{f}_{cnij} + \boldsymbol{f}_{ctij}\right). \tag{4}$$

The calculation details of contact forces caused by elements and element-wall collisions and friction are described in the literature [9]. Further, the particle size distribution is taken into consideration in the algorithm. For correspondence to a contact depth δ between elements i and j, the stiffness k_{ij} is calculated by using the combined method in the literature [1, 2].

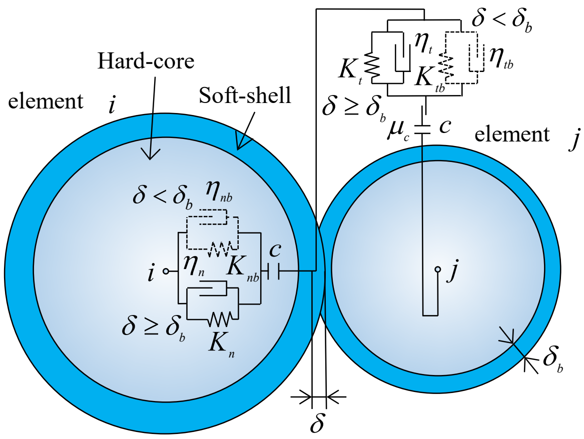


Fig.1 Modeling of contact force for green sand.

Identification of Particle Size Distribution

In the DEM, it is appropriate to adapt one particle to one discrete element. However, the molding sands are composed of 110×10^6 particles/kg in the case of silica sand. Therefore, it is difficult to handle all the particles individually in the green sand molding. To treat the problem reasonably, the identified distinct element is used in the present simulation. Although the discrete elements of uniform diameter are adopted in conventional results, the particle size distribution is an important factor for the sand compacting. The particle size distribution is taken into consideration in the simulation. The distribution of mass percentage and the number of sand particle per unit mass are used in the present study.

The particle size distributions in this study are shown in Table 1. Figure 2 shows the distribution of mass percentage and the number of sand particle per unit mass. In these figures, d_{si} is the diameter of particle on i steps of size distribution map. Conserving the mass of green sand, the particle number is assigned by increasing the diameter of particle. Concretely, the practical distribution of the mass percentage and the number percentage with the dimensionless diameter divided by the characteristic diameter agree with simulation results as shown in the literature [1].

(Total mass) $$\sum m_s = \sum m_e \quad (4)$$

(Dimensionless number ratio) $$\frac{d_{si}}{d_{sav}} = \frac{d_{ei}}{d_{eav}} \quad (5)$$

(Number ratio) $$P_{nsi} = P_{nei} \quad (6)$$

where, P_n denotes the number percentage, subscripts s and e denote the green sand, and discrete element respectively, and av denotes the characteristic diameter as average value. Using eqs.(4)-(6), the relationship between size and percentage of discrete elements in the simulation region is shown in Fig.3.

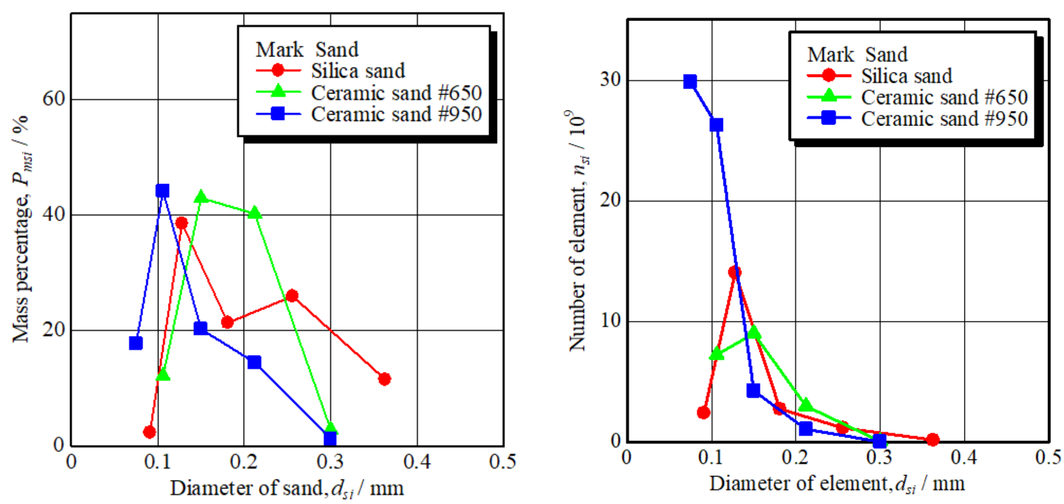
Table 1 The particle size distributions.

(a) Silica sand, ceramic sand of mono-size M650 and M950

Sieve [mm]	0.363	0.256	0.181	0.128	0.091	0.064	GFN
Silica	11.6	26	21.4	38.6	2.4		69
M650	14.1	83.2	2.6				68
M950			5.4	90.4	4	0.2	100

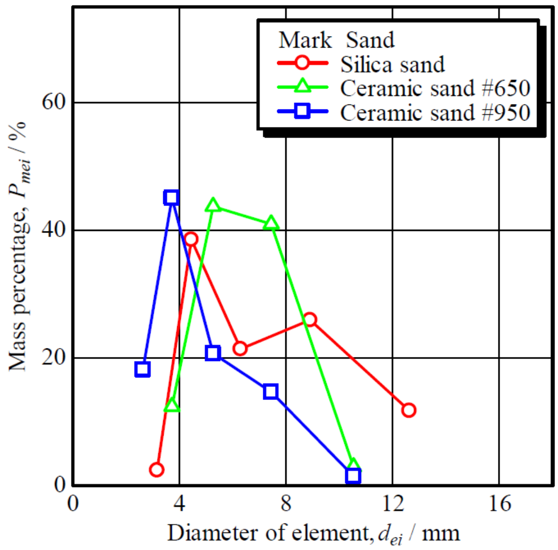
(b) Ceramic sand of #650 and #950

Sieve [mm]	0.425	0.3	0.212	0.15	0.106	0.075	GFN
#650		2.9	40.3	43	12.2		66
#950		1.3	14.5	20.3	44.2	17.8	95

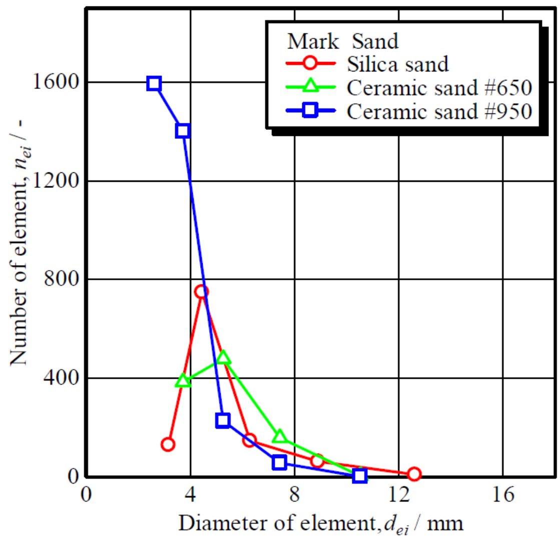


(a) mass percentage (b) number of particles

Fig.2 Particle Size distribution of green sand.



(a) mass percentage



(b)number of elements

Fig.3 Size distribution of discrete elements.

Squeeze Molding

In this study, the object is the same of the squeeze molding as shown in the literature [1]. The squeeze molding was carried out to make test-piece $\phi 50 \times 50h$. A cylindrical flask $\phi 50 \times 170h$ was used and the squeeze pressure was adjusted to 0.98MPa. The literature [1] showed the pressure on squeeze plate, the pressure on the side wall, the dynamic compacting behavior of green sand and the void fraction (bulk density) for mold properties. The compactability of green sand is adjusted as 40%. In the analysis, the case which molding was performed at a speed of 0.05m/s by the squeeze surface of $\phi 50$ was calculated.

Verification of Identification Method of Particle Size Distribution

The verification of identification method of particle size distribution is carried out in this section. For the squeeze process of test-piece using the ceramic sand of #650, the literature [1] used the element number of 942. The total number of elements is changed to 942, 2029, 3181 and the calculation conditions are shown in Table 2, 3, 4, respectively. Although the total number of elements has changed using the identification method, the form of size distribution is the same as shown in Fig.4.

Table 2 Element parameters of ceramic sand #650 in the case of total number of elements is 942.

Number of element [-]	4	146	439	353
Diameter of element [m]	1.01×10^{-2}	7.16×10^{-3}	5.07×10^{-3}	3.58×10^{-3}
Diameter of Hard-core [m]	9.00×10^{-3}	6.36×10^{-3}	4.50×10^{-3}	3.18×10^{-3}
Thickness of Soft-shell [m]	5.67×10^{-4}	4.00×10^{-4}	2.83×10^{-4}	2.00×10^{-4}
Stiffness of Hard-core [N/m]	361135	303590	255374	214656
Stiffness of Soft-shell [N/m]	72227	60718	51075	42931

Table 3 Element parameters of ceramic sand #650 in the case of total number of elements is 2029.

Number of element [-]	4	146	439	353
Diameter of element [m]	1.01×10^{-2}	7.16×10^{-3}	5.07×10^{-3}	3.58×10^{-3}
Diameter of Hard-core [m]	9.00×10^{-3}	6.36×10^{-3}	4.50×10^{-3}	3.18×10^{-3}
Thickness of Soft-shell [m]	5.67×10^{-4}	4.00×10^{-4}	2.83×10^{-4}	2.00×10^{-4}
Stiffness of Hard-core [N/m]	361135	303590	255374	214656
Stiffness of Soft-shell [N/m]	72227	60718	51075	42931

Table 4 Element parameters of ceramic sand #650 in the case of total number of elements is 3181.

Number of element [-]	13	492	1483	1193
Diameter of element [m]	6.76×10^{-3}	4.77×10^{-3}	3.38×10^{-3}	2.39×10^{-3}
Diameter of Hard-core [m]	6.00×10^{-3}	4.24×10^{-3}	3.00×10^{-3}	2.12×10^{-3}
Thickness of Soft-shell [m]	3.78×10^{-4}	2.67×10^{-4}	1.89×10^{-4}	1.33×10^{-4}
Stiffness of Hard-core [N/m]	288982	242922	204341	171772
Stiffness of Soft-shell [N/m]	101144	85023	71519	60120

Figure 5 shows the compacting pressures on squeeze plate P_{sq} changing with total number of elements. The void fractions of each sands are around 0.6 before squeeze molding. In the present simulation, the calculated results are influenced by initial placement of elements which are preset using random number. So, the average value of repetition five times is shown in Fig.5. Even if the total number of identified discrete element is different, the squeeze compacting behavior is almost the same tendency. This result shows that the proposed identification method of sand particle distribution is appropriate.

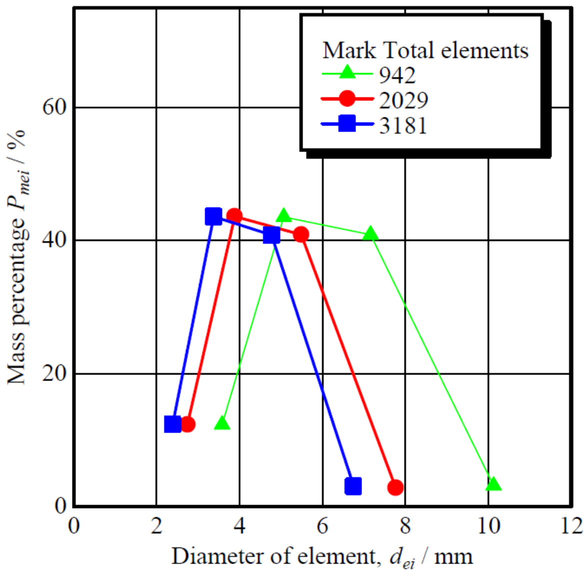


Fig.4 Size distributions of elements changing with total number of elements.

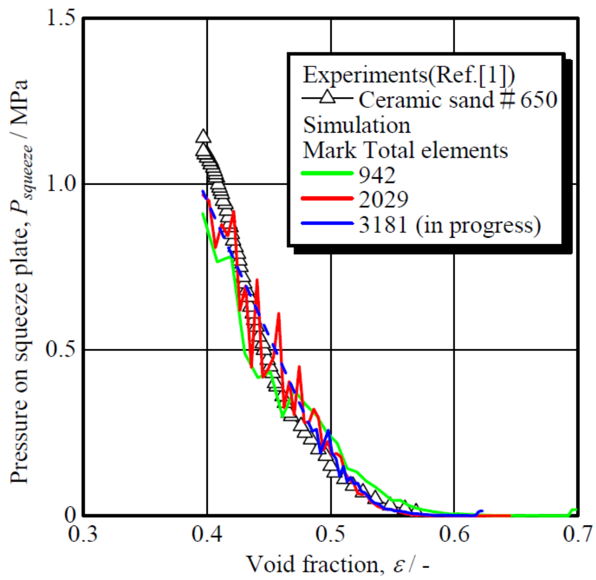


Fig.5 Compacting pressures on squeeze plate P_{sq} changing with total number of elements.

Silica Sand and Ceramic Sands

Comparison of compacting behavior between silica sand and ceramic sands is shown in Fig.6. The simulation is performed using silica sand, ceramic sand #650 and ceramic sand #950, as shown in Fig.3. The calculation conditions are shown in Table 2, 5 and 6. The final void fraction of silica sand is lower than those of ceramic sands. The results are influenced by the densities of sands. These consideration accords with the result of literature [1]. However, it is difficult to simulate the compacting behavior in accordance with sand particle distribution difference, as shown in [1]. They are two compacting mechanism in the green sand molding. One is the rearrangement of the green sand particles occurring in the early stage of compacting. The other is the deformation of cohesion layers. Especially, the identification of parameters are not satisfied in the rearrangement mechanism.

Table 5 Element parameters of silica sand in the case of total number of elements is 1017.

Number of element [-]	120	694	136	58	9
Diameter of element [m]	3.04×10^{-3}	4.28×10^{-3}	6.05×10^{-3}	8.56×10^{-3}	1.21×10^{-2}
Diameter of Hard-core [m]	2.73×10^{-3}	3.84×10^{-3}	5.43×10^{-3}	7.68×10^{-3}	1.09×10^{-2}
Thickness of Soft-shell [m]	1.56×10^{-4}	2.20×10^{-4}	3.11×10^{-4}	4.40×10^{-4}	6.24×10^{-4}
Stiffness of Hard-core [N/m]	145145	172136	204691	243437	289883
Stiffness of Soft-shell [N/m]	16127	19126	22744	27049	32209

Table 6 Element parameters of ceramic sand #950 in the case of total number of elements is 3007.

Number of element [-]	120	694	136	58	9
Diameter of element [m]	3.04×10^{-3}	4.28×10^{-3}	6.05×10^{-3}	8.56×10^{-3}	1.21×10^{-2}
Diameter of Hard-core [m]	2.73×10^{-3}	3.84×10^{-3}	5.43×10^{-3}	7.68×10^{-3}	1.09×10^{-2}
Thickness of Soft-shell [m]	1.56×10^{-4}	2.20×10^{-4}	3.11×10^{-4}	4.40×10^{-4}	6.24×10^{-4}
Stiffness of Hard-core [N/m]	145145	172136	204691	243437	289883
Stiffness of Soft-shell [N/m]	16127	19126	22744	27049	32209

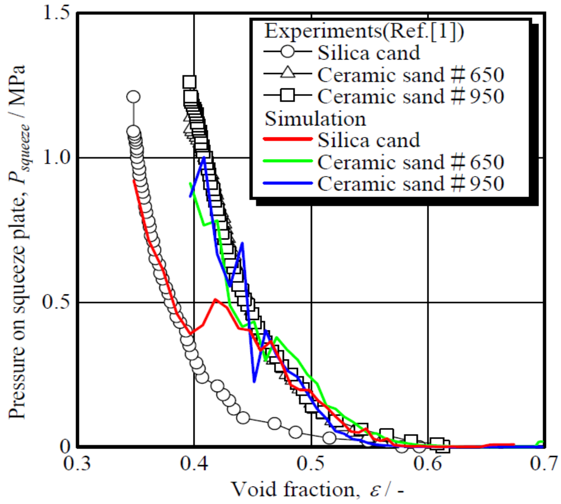


Fig.6 Relationship between void fraction and pressure on the squeeze plate in the case of ceramic and silica sand.

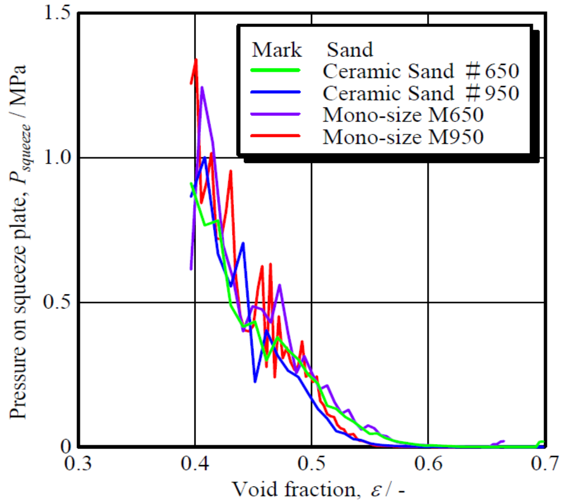


Fig.7 Relationsip between void fraction and pressure on the squeeze plate.

Particle Size Distribution and Mono-Size

The ceramic sands without the size distribution are prepared to investigate the influence of the particle size distribution on the compacting behavior. They are the M650 and M950 in Table 1(a). The identified discrete elements are shown in Table 7 and 8. The relationship between the void fraction and the squeeze pressure shows in Fig.7. It is difficult to be rearrangement filling, because of there is not the particle size distribution and there are few particles which are smaller than the void cavity. The sand without particle size distribution shows linear compression behavior and the sand with particle size distribution shows a small curve tendency affected by rearrangement filling. It is necessary to check any parameters of DEM and to study the experiment.

Table 7 Element parameters of ceramic sand of mono-size M650 in the case of total number of elements is 961.

Number of elements	51	836	74
Diameter of elements [m]	7.16×10^{-3}	5.07×10^{-3}	3.58×10^{-3}
Diameter of hard-core [m]	6.36×10^{-3}	4.50×10^{-3}	3.18×10^{-3}
Thickness of Soft-shell [m]	4.00×10^{-4}	2.83×10^{-4}	2.00×10^{-4}
Stiffness of Hard-core [N/m]	297319	250099	210222
Stiffness of Soft-shell [N/m]	59464	50020	42044

Table 8 Element parameters of ceramic sand of mono-size M950 in the case of total number of elements is 2998.

Number of elements	54	2576	322	46
Diameter of elements [m]	5.07×10^{-3}	3.58×10^{-3}	2.53×10^{-3}	1.79×10^{-3}
Diameter of hard-core [m]	4.50×10^{-3}	3.18×10^{-3}	2.25×10^{-3}	1.59×10^{-3}
Thickness of Soft-shell [m]	2.83×10^{-4}	2.00×10^{-4}	1.42×10^{-4}	1.00×10^{-4}
Stiffness of Hard-core [N/m]	241785	203233	170951	143708
Stiffness of Soft-shell [N/m]	84625	71132	59833	50298

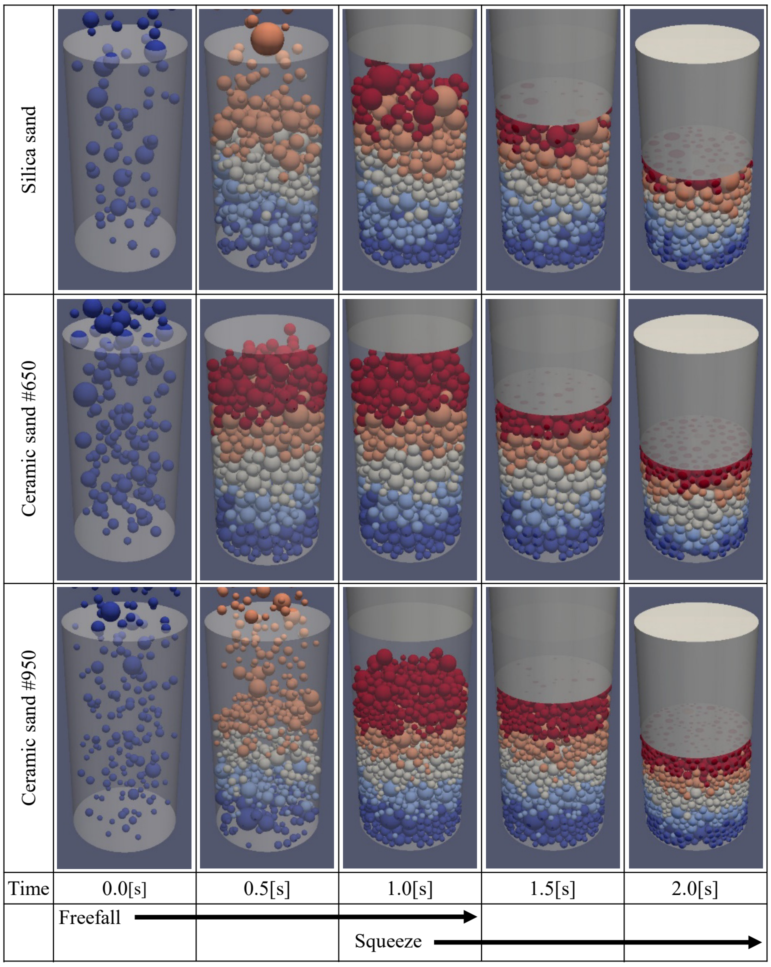


Fig.8 Three-dimensional visualization results of analysis results of Ceramics sand #650, #950, and Silica sand by ParaView.

Three-Dimensional Visualization Using ParaView

In this study, 3D graphic in the post-processing is investigated. ParaView [11] is software developed by Kitware Inc. and distributed as open source. The initial conditions before operating squeeze press are created by the free falling of molding sands for both experiment and simulation. The compacting behaviors during the squeeze molding obtained by the simulation are shown in Fig.8. Figure 8 shows the outside views of squeeze molding process for silica sand, ceramic sand #650 and ceramic sand #950 obtained by the simulations. The results are discriminated by 5 colors depending on the initial position in order to clarify the dynamic behavior. The free-fall behavior is calm. Then just after acting the squeeze press, 5 sand layers are simply compacted without disturbance during the squeeze molding. It is very useful for CAE engineer to display the visual images of the compacting behavior in the flask.

Conclusion

The compacting behavior of squeeze molding is traced numerically, and the visualization by a three-dimensional model and comparison of dynamics molding are carried out. The characteristics of green sand with cohesion are reflected in the particle model called Hard-Core/Soft-Shell. From the simulation with several kinds of particle distribution, the following results are obtained. The effectiveness of the identification method from a real particle size distribution to the discrete element is investigated. The silica sand and the ceramic sand showed different compression behavior. The results are influenced by the densities of sands. Three-dimensional display of green sand with particle size distribution is very effective. It is necessary to take the consideration of the compacting behavior by the rearrangement in the future.

Acknowledgment

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