論文 Three-dimensional Simulation of Shotcrete using Distinct Element Method

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ABSTRACT: In Japan, shotcrete has been used for over 30 years, especially for tunnel lining and slope stabilization. The quality of shotcrete is well known to fluctuate under various conditions of construction and materials. Computer-based simulation becomes a very useful tool to reduce the cost of research on shotcrete whose experiments need huge finance and labour. In this research, a three-dimensional numerical analysis using Distinct Element Method (DEM) was utilized to model the shotcrete process. This simulation provides a fundamental knowledge and understanding about shotcrete process.

KEYWORDS: Shotcrete, Rheology, Accelerator, Simulation, Distinct Element Method.

1. INTRODUCTION

Shotcrete, or sprayed concrete, is a technical term representing a method for placing concrete rather than a particular type of concrete. Shotcrete is used in tunnel lining, hydropower projects, slope stabilization, mining operation and even in civil construction works. Nowadays, more than 90% of all shotcrete is used for rock support. Describing briefly, concrete is conveyed in hose by compressed air and mixed with accelerator before projected onto the target surface (Fig. 1).

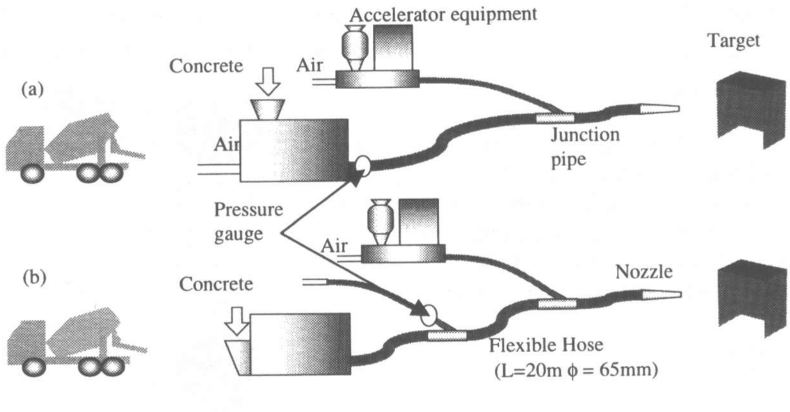

Figure 1. Schematic diagram of wet-mix shooting system
a) Transport system with compressed air; b) Transport system with pump and compressed air

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This paper is to report the results of a three-dimensional simulation of shotcrete using distinct element method. The DEM was introduced by Cundall [1] for the analysis of rock-mechanics problems and then applied to soils by Cundall and Track [2]. In the DEM, the interaction of the particles is treated as a dynamic process with states of equilibrium developing whenever the internal forces balance. The contact forces and displacements of a stressed assembly of particles are found by tracing the movements of the individual particles. For more details of DEM, reader can refer to the review of Cundall and Hart [3]. In this model, shotcrete process is simulated with two kinds of particles representing coarse aggregate and mortar. This simulation set up allow the consideration of high rebound ratio of coarse aggregate at the beginning of shooting when only mortar remains at the target surface.

2. SIMULATION MODEL

2.1 OUTLINES OF DISTINCT ELEMENT MODEL

(1) Viscous damping contact model

In linear contact model, the contact stiffness relates the contact forces and relative displacements in the normal and shear directions. This linear contact model is almost sufficient in most cases of simulation. However, in simulation of shotcrete, in which particle impact on each other or against the target wall at high velocity, it is important to consider the damping property. In viscous damping model, a contact consists of a spring in parallel with a dashpot. Contact forces acting at i^{th} contact in normal and tangential direction can calculated as follows:

$$\Delta F_i^n = K^n \Delta U_i^n + \eta_d^n \left(\frac{\Delta U_i^n}{\Delta t} \right) \tag{1}$$

$$\Delta F_i^s = -K^s \Delta U_i^s + \eta_d^s \left(\frac{\Delta U_i^s}{\Delta t} \right) \tag{2}$$

Where K^n and K^s are the normal and tangential stiffness of the contact. η_d^n and η_d^s represent the viscosity coefficient of the dashpot in normal and tangential directions. The second terms in the above equation are added to original equation of linear contact model to consider the effect of damping. ΔU_i^n and ΔU_i^s are the increments of normal and shear displacement, respectively. Δt is the calculation time step.

The stiffness in the above contact model are calculated from the normal and shear stiffness, k_n and k_s [force/displacement], of the two contacting entities (ball-to-ball) with the assumption that the stiffness of the two contacting entities act in series. The contact normal secant stiffness is given by

$$K^n = \frac{k_n^{[A]} k_n^{[B]}}{k_n^{[A]} + k_n^{[B]}} \tag{3}$$

And the contact shear tangent stiffness:

$$K^s = \frac{k_s^{[A]} k_s^{[A]}}{k_s^{[A]} + k_s^{[B]}} \tag{4}$$

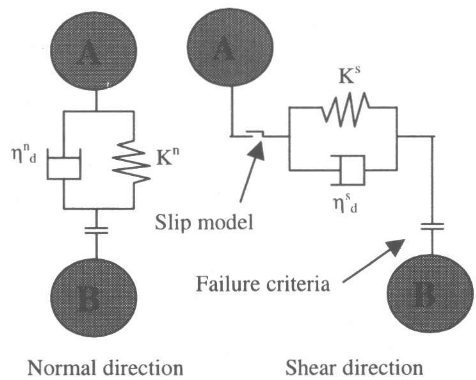

Figure 2. Viscous damping contact model

Where the superscripts [A] and [B] denote the two balls in contact.

(2) Slip model
The slip model is an intrinsic property on the two balls in contact. It provides no normal strength in tension and allows the slip to occur by limiting the shear force. This model is always active unless a contact bond is present. The threshold value of shear force in slip model is calculated in proportion to normal contact force.

$$F_s^{\max} = \mu \left| F_i^n \right| \quad (5)$$

If $\left| F_i^s \right| > F_{\max}^s$, the slip is allowed to occur during the next step of calculation.

Where, $F_{max}^s, F_i^n, and\ F_i^s$ are threshold value of shear force in slip model, normal and shear contact forces, respectively. μ is the friction coefficient.

(3) Contact-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 strengths. The existence of a contact bond precludes the possibility of slip, i.e., the magnitude of the shear contact force is not adjusted to remain less than the allowable maximum value in Equation (5).

2.2 SIMULATION SET-UP

(1) Single-phase-particle model and DEM parameters for simulation
In this research, concrete was modelled with two kinds of particle representing mortar and coarse aggregate. The effect of shooting distance, pressure, materials, mix proportion and accelerator was considered in this simulation. The assumption was made that all particles are spherical in shape. This two-phase-in two-particle model was firstly successfully used in the simulation of flowable concrete in our laboratory [6]. The flow chart of the simulation is shown in Figure 3. Aggregate particles were generated following the grading curve and their DEM parameters were obtained from one-dimensional wave propagation theory [4]. Mortar particles were generated following apparent grading curving, which is the grading curve of fine aggregate multiplied by a factor so that the mix proportion is satisfied after the compaction under gravity. Overlap between particles was allowed to satisfy the porosity of actual concrete.

(2) Effect of accelerator
When accelerator is added to concrete, DEM parameters have to be modified. For now, there is

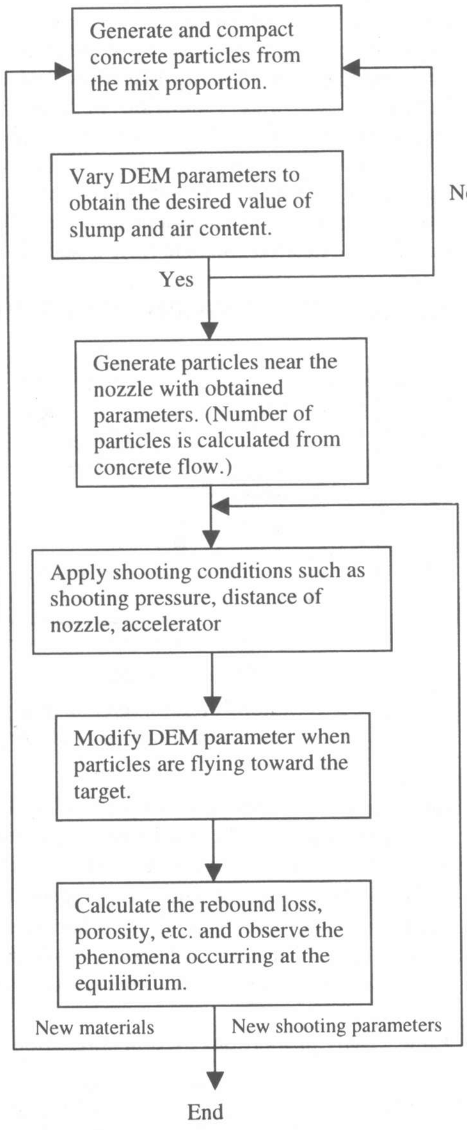

Figure 3. Flowchart of simulation

no experimental method available for checking the effect of accelerator. In this simulation, the model proposed by Puri [5] was adapted for the qualitative simulation (Fig. 4). At the current stage of this research, DEM parameters were obtained from many try-and-error calculations. The try-and-error process is usually unavoidable in DEM simulation when micro properties are mostly unknown, especially bonding behaviour of mortar.

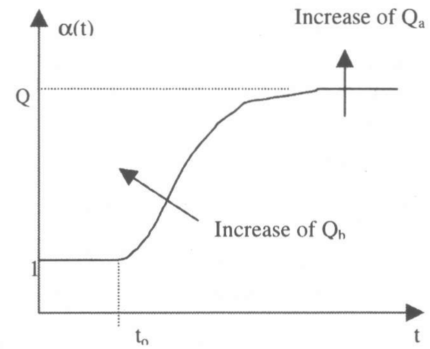

Figure 4. Stiffening mechanism of DEM parameters when accelerator is added

(3) Target wall and "shooting segments"
The target wall of shotcrete was constructed from large number of particles. The contact properties of wall particles are treated like those of aggregate. Unlike the previous simulation in 2-D [5], in this model, concrete particles of shooting were generated discretely, i.e., segments of concrete flow were generated one after another at nozzle position. New segment of particles were generated just after the preceding segment had already come out of the nozzle. The number of segments and the calculation time in each segment were calculated in such a way that the desired concrete flow is satisfied.

2.3 MATERIAL AND SHOOTING CONDITIONS

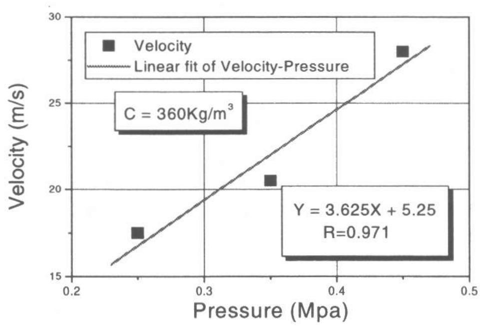

Figure 5. Relationship between concrete velocity and shooting pressure

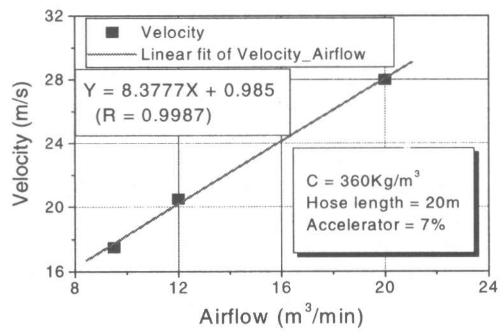

Figure 6. Relationship between concrete velocity and airflow

One actual case was picked up from of shotcrete experiment with mix proportion and shooting conditions shown in Tables 1 and 2. The initial velocity applied on particles in simulation can be obtained from fitting curve in Figures 5 or 6. The velocities in these figures were obtained by analysing the result of super high-speed video camera [7]. It is believed that a similar linear relationship will be obtained for other case of mix proportion. Figures 5 and 6 indicate that it is possible to obtain the velocity of concrete coming out of the nozzle from measurable and controllable parameters: shooting pressure and airflow.

Table 1. Mix proportions used in simulation

W/C (%)	s/a (%)	Content (kg/m³)				Slump (cm)	Air content (%)
		C	W	S	G		
56.9	60	360	205	1035	703	12	2

Table 2. Shooting conditions

Shooting pressure (MPa)	Shooting distance (m)	Accelerator (B x %)	Concrete flow (m^3/hour)
0.25, 0.35, 0.45	1, 1.5, 2.5	7	8

Abbreviations: W, C, B, s/a, W/C, S, G, are water, cement, binder contents, fine/coarse aggregate ratio, water cement ratio, fine aggregate, coarse aggregate, respectively.

3. CALCULATED RESULTS AND DISCUSSIONS

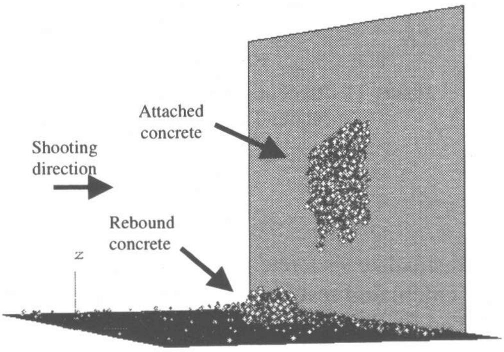

Figure 7. Shooting with distance of 1m and pressure of 0.35 MPa. Rebound ratio: 25%.

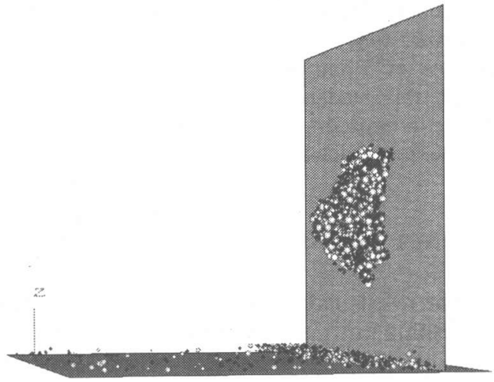

Figure 8. Shooting distance of 1.5 m and pressure of 0.35 MPa. Rebound ratio: 16%.

3.1 EFFECT OF SHOOTING DISTANCES

With the same mix proportion, shooting conditions, etc., only the shooting distance was varied to study the effect of shooting distance on the rebound loss as well as on the porosity of shotcrete (Figs. 7 and 8). It was found that the rebound loss increases at shorter shooting distance (Fig. 9). However, if shooting distance is so large, the small impacting force of coming particles (due to dissipation of energy when particles fly from the nozzle to the wall) may result in the increase of rebound ratio as can be seen in the case with shooting distance of 2.5m (Fig. 9).

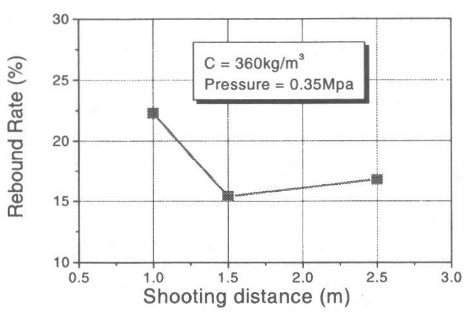

Figure 9 Effect of shooting distance on rebound ratio at pressure of 0.35 MPa

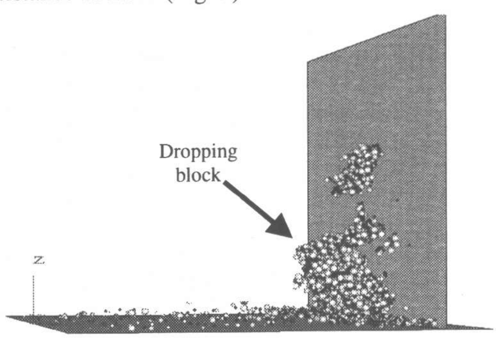

Figure 10 Dropping of concrete block due to excessive build-up thickness.

3.2 BUILD-UP THICKNESS

Accelerator is added to shotcrete to shorten the setting time and, as a result, increase the build-up thickness. However, there should be a threshold for that build-up thickness. Figure 10 shows a large shotcrete block dropped down after bond-contact have broken at the weakest position.

3.3 EFFECT OF SHOOTING PRESSURE

In order to investigate the effect of shooting pressure on the rebound ratio, calculations were carried out with three values of pressure: 0.25, 0.35, and 0.45MPa. As can be seen in Figure 11, the rebound ratio increases at higher pressure. However, this is for the case with shooting distance of 1.5m. If the shooting distance is varied, this tendency may change due to the change in impacting force against the target wall of concrete particles.

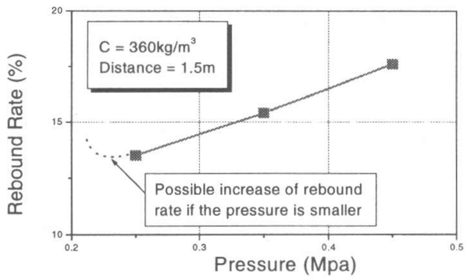

Figure 11 Effect of shooting pressure on the rebound ratio

4. CONCLUSIONS

- The results indicate that DEM is a potential tool to simulate shotcrete process. At the time of writing this paper, it is difficult to compare the calculated results with experimental ones because many factors are still not considered. The final target of this study is to simulate shotcrete process quantitatively. After carrying out rheological research, especially on the effect of accelerator, it may be possible to correlate between experiment and analysis.
- With one kind of material, the rebound ratio of shotcrete depends on shooting pressure, shooting distance and the amount of accelerator. This model can be used to predict the effect of distance and pressure while the effect of accelerator needs more consideration.
- After verification, this simulation can be used to support the design as well as practical application of shotcrete.
- The DEM parameters used in the simulation were obtained from try-and-error approach. Therefore, the final target would be a correlation between actual materials and DEM parameters, directly or via rheological parameters.

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