The 2021 World Congress on
Advances in Structural Engineering and Mechanics (ASEM21)
GECE, Seoul, Korea, August 23-26, 2021

Numerical analysis of abrasive waterjet rock drilling according to the standoff distance

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ABSTRACT

Abrasive waterjet technology is being used for the excavation of rock ground. Abrasive waterjet is affected by several variables and drills the target rock materials. In this study, we observed how the jet spreads in the air, focusing on the standoff distance parameters. However, it is difficult to experimentally measure how the jet spreads in the air. Therefore it was observed that the jet spreads by applying the parameters through numerical analysis. Numerical analysis was performed using ANSYS Fluent commercial program. The dispersion of the jet according to the standoff distance was observed by applying different abrasive flow rate and pump pressure. Through this study, it was possible to derive the critical velocity of the jet according to the standoff distance. In addition, this will contribute to efficient rock drilling using an abrasive waterjet.

1. INTRODUCTION

Previous research on rock drilling using waterjet technology has been actively conducted (Summers 1992, Summers 1995). On the other hand, to drill a rock with high strength, it was inefficient to drill using only water. Abrasive waterjet technology, which mixes and sprays abrasives with water, has started to be used to solve this difficulty. The high-pressure water generated by the water pump passes through a small

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diameter orifice and is converted at high speed. At this time, abrasives are injected and mixed with water, and this type is called an injection system (Momber and Kovacevic 1997). The energy of high-speed water is mixed with the abrasive, and momentum is transferred to the abrasive. The accelerated abrasive passes through the focusing tube and is sprayed into the air, and its velocity gradually decreases due to atmospheric pressure and air resistance.

Since it is very difficult to observe these mechanisms and the velocity of abrasives experimentally, this study analyzed them through numerical analysis. In previous studies, ANSYS Fluent, a CFD program, was used to implement the waterjet system (Guha et al. 2010, Baisheng et al. 2011, Long et al. 2017). Therefore, in this study, an abrasive waterjet system was implemented through the ANSYS Fluent program, and analysis was performed. The situation in which water and abrasives are mixed is caused by turbulence, and there is a limit to experimentally observing this. Therefore, this study intends to observe how the velocity changes in air based on the mixing of water and abrasives through numerical analysis.

2. THEORETICAL BACKGROUND

The abrasive waterjet system for rock drilling is shown in the figure below (Fig. 1). The water is under high pressure using a hydraulic pump. High pressure water passes through a small diameter orifice and is converted at high speed. The velocity at this time is called $v_{w,o}$, and it is expressed as an equation through Bernoulli's equation and the law of conservation of energy as follows (Eq. 1). Energy is lost as high-pressure water passes through a small diameter orifice, which is empirically considered by multiplying the resistance constant (K) (Momber and Kovacevic 1998, Oh and Cho 2016).

$$v_{w,o} = \sqrt{(1-K)\frac{2 \cdot p_{w,p}}{\rho_w}} \tag{1}$$

where $v_{w,o}$ is the velocity of water in the orifice section, K is the resistance constant, $p_{w,p}$ is the pressure of water, and ρ_w is the density of water. The resistance constant (K) is 0.04 ~ 0.28 for a rounded orifice, 0.25 for a chamfered orifice, and 0.5 for a square-edged orifice (Mott et al. 2006, Oh and Cho 2016).

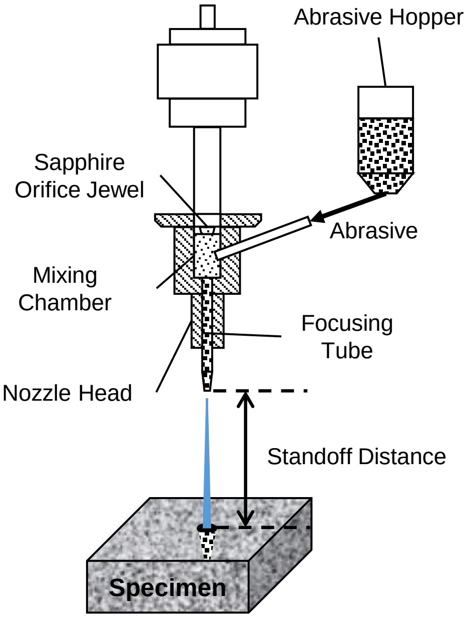

Fig. 1 Abrasive waterjet system (AWJ)

The high-velocity water obtains high energy, which is the first energy in the abrasive waterjet system for rock drilling. The abrasive particles are sucked into the mixing chamber by the venturi effect of the generated high-velocity water stream. Inside the mixing chamber, high-speed water is mixed with the abrasive, and the momentum of the water is transferred to the abrasive particles. The abrasive particles and water that have gained energy in this way have a straight line as they pass through the focusing tube. Finally, the abrasive-water mixture is sprayed into the air from the tip of the focusing tube.

The distance from the tip of the focusing tube to the target rock surface is called the standoff distance (SOD). As the standoff distance increases, water and abrasives have different densities, respectively, and the velocity is lost due to air resistance and atmospheric pressure in the air. An important parameter in abrasive waterjet systems for rock drilling is the velocity of the abrasive (Momber 2004, Nambiath et al. 2007, Oh and Cho 2016). In general, in the case of rock with high compressive strength, the drilling of the rock is made through abrasives of high hardness. Therefore, the kinetic energy that can be obtained through the velocity of the abrasive is called the effective kinetic energy (E_{et}), and it can be expressed in the following way (Eq. 2).

$$E_{et} = \frac{1}{2}\dot{m}_a {v_a}^2 \tag{2}$$

where E_{et} is the effective kinetic energy, $\dot{m}_a$ is the abrasive flow rate, and v_a is the velocity of abrasive.

Another parameter to characterize abrasive waterjets is turbulence (Momber and Kovacevic 1998). As mentioned above, let T_a be the abrasive turbulence, focusing on the abrasive velocity. If T_a is expressed as an equation, it is as follows (Eq. 3).

$$T_a = \frac{\sigma_{v_a}}{\bar{v}_a} \tag{3}$$

where T_a is the turbulence, σ_{v_a} is the standard deviation of abrasive velocity, and $\bar{v}_a$ is the averaged velocity of abrasive.

3. NUMERICAL SIMULATION

In this study, an abrasive waterjet was simulated using ANSYS Fluent, a commercial fluid analysis program based on the Finite Volume Method (FVM).

3.1 Model Geometry

The conditions of the abrasive waterjet system are as follows. The orifice diameter (D_o) is 0.254 mm, the focusing tube diameter (D_f) is 1.02 mm, and the focusing tube length (L_f) is 76.2 mm. To examine the effect of the standoff distance, a free jet domain part with a diameter of 25 mm and a length of 200 mm was constructed at the end of the focusing tube (Fig. 2).

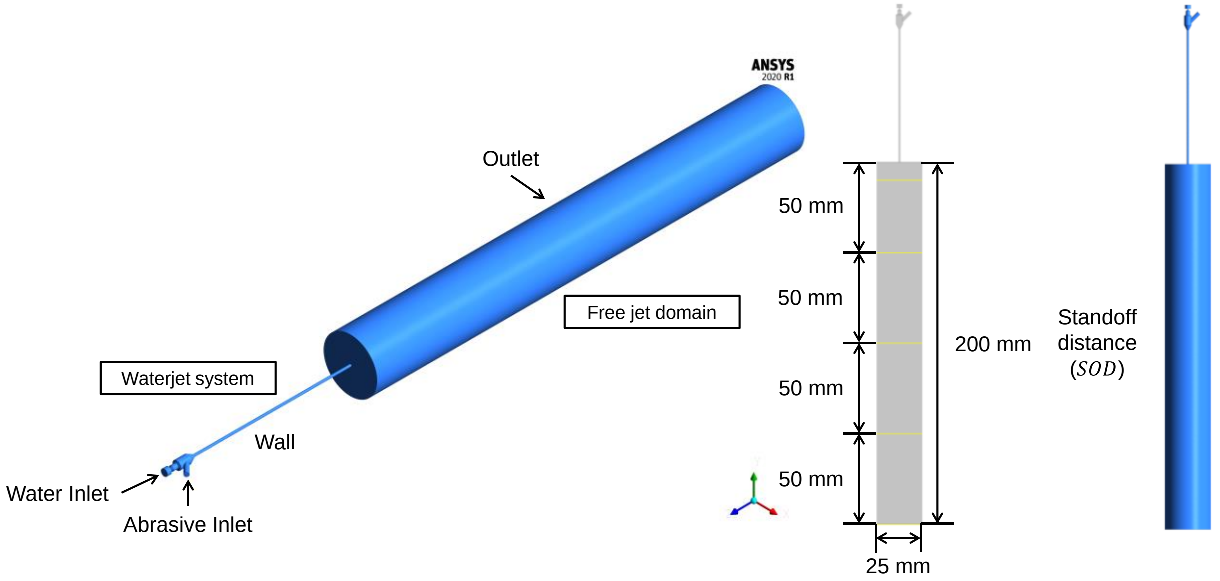

Fig. 2 Waterjet system and free jet domain

3.2 Boundary Condition

In this analysis, water was assumed to be an incompressible fluid, and the abrasive was set as a sphere with a diameter of 0.18 mm. The densities of water and abrasive were set to 998.2 and 3790 kg/m^3, respectively. Five conditions of 100, 150, 200, 250, and 320 MPa were set to see the effect of pump pressure, and four conditions of 5.6, 7.5, 11.1, and 15.0 g/s were set to see the effect of the abrasive input rate. (Table 1).

Table 1 Model conditions

Effect of	$p_{w,p}$ [MPa]	D_o [mm]	D_f [mm]	L_f [mm]	$\dot{m}_a$ [g/s]	SOD [mm]
Water pump pressure ($p_{w,p}$)	100 150 200 250 320	0.254	1.02	76.2	5.6	0 ~ 200
Abrasive flow rate ($\dot{m}_a$)	320	0.254	1.02	76.2	5.6 7.5 11.1 15.0	0 ~ 200

In addition, a volume of fluid (VOF) model was applied to simulate multiphase flow, and a standard k-ε turbulence model was applied for the viscosity of the fluid. A discrete phase model (DPM) was applied to realize abrasive particles, and a pressure of 101.325 kPa, atmospheric pressure, was applied to the free jet domain, which is the abrasive inlet and outlet. In addition, the boundary condition of the wall was considered as a no-slip shear condition, and the SIMPLE scheme was used for pressure-velocity coupling (Table 2). And in all cases, the analysis was completed based on the convergence condition when the residuals of all equations and physical quantities became smaller than 1×10^{-4}, respectively.

Table 2 Solver and discretization scheme setup

Pressure-Velocity Coupling	
Scheme	SIMPLE
Spatial Discretization	
Gradient	Least Squares Cell Based
Pressure	PRESTO!
Momentum	Second Order Upwind
Turbulent Kinetic Energy	Second Order Upwind
Turbulent Dissipation Rate	Second Order Upwind

4. RESULTS AND DISCUSSION

4.1 Model Validation

In previous studies, the velocity of abrasives was experimentally observed through Ultra-fast X-rays (Roth et al. 2005, Henning et al. 2011, Balz et al. 2013). Comparing the experimental value with the numerical analysis value in this study, it can be seen that this numerical analysis model is valid (Fig. 3).

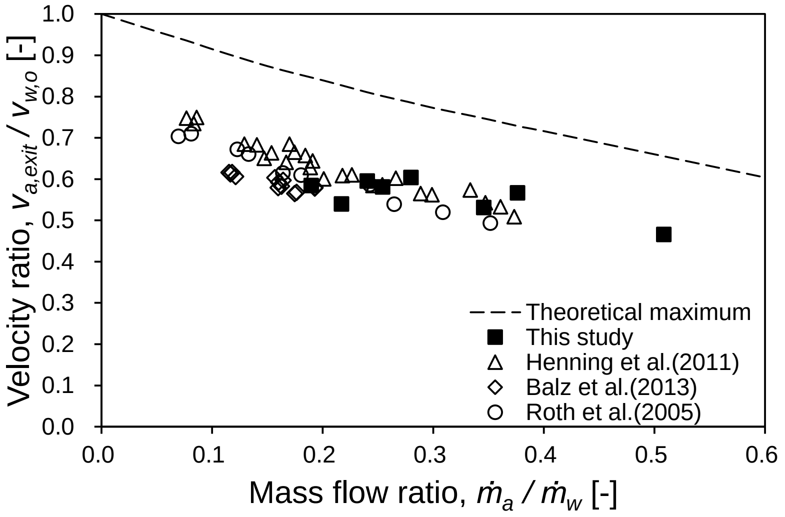

Fig. 3 Comparison of abrasive velocity experimental and numerical results

4.2 Effect of Water Pump Pressure

Varying the pump pressure serves to generate different initial energy of the water in the abrasive waterjet system. As mentioned earlier, high-pressure water passes through a very small diameter orifice and is converted to high-speed water. In the process of obtaining energy, the pressure of the water pump determines the momentum and energy of the water. As the energy of the water itself increases by increasing the pump pressure, the abrasive is accelerated more and the velocity of the abrasive sprayed from the end of the focusing tube increases. Also, as the standoff distance increases, the effective kinetic energy of the abrasive decreases due to atmospheric pressure and air resistance (Fig. 4).

To observe the efficiency when the initial energy of water passing through the orifice meets the abrasive and transfers momentum and accelerates it, the velocity ratio of the abrasive to the initial velocity of water was expressed and analyzed (Fig. 5). While the velocity ratio did not differ significantly as the water pump pressure was changed under the same abrasive input condition, the difference was relatively clear depending on the standoff distance.

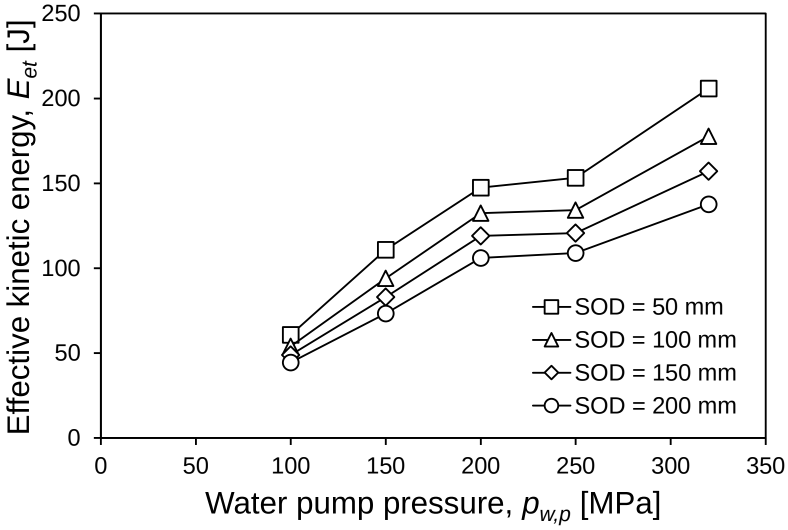

Fig. 4 Effective kinetic energy depending on the standoff distance and water pump pressure

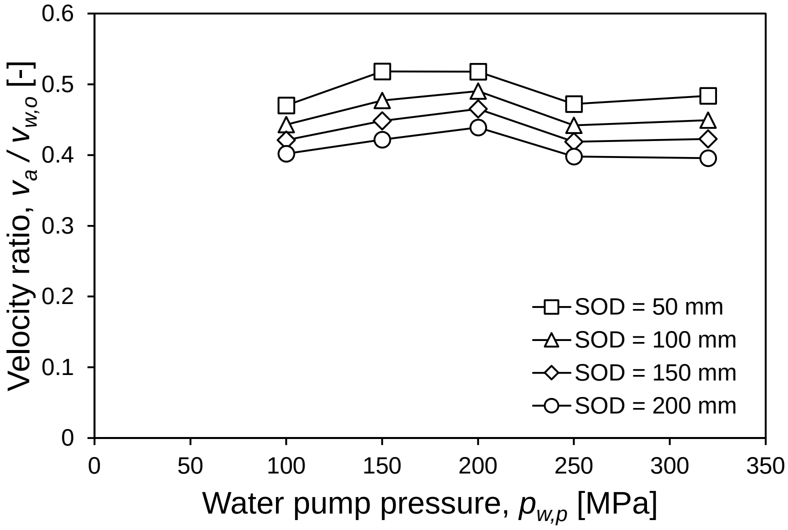

Fig. 5 Velocity ratio depending on the standoff distance and water pump pressure

The larger the turbulence, the more deviation occurs based on the average abrasive velocity, which is because the abrasive is not accelerated evenly. Turbulence showed no significant difference depending on the water pump pressure but showed the smallest value in the part where the standoff distance ratio was about 70 (Fig. 6).

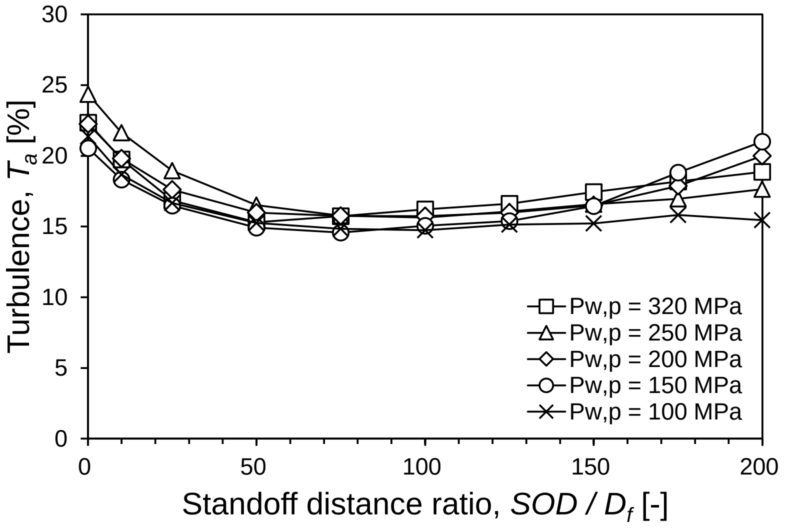

Fig. 6 Effect of water pump pressure on turbulence according to standoff distance ratio

4.3 Effect of Abrasive Flow Rate

In the abrasive waterjet system, the abrasive flow rate is one of the important variables that can determine the velocity of the abrasive under the same water pump pressure condition. Under the same water pump pressure condition, water has the same initial energy and is used to accelerate the abrasive. At this time, the larger the abrasive flow rate, the more abrasive is input, so when observed from the particle's point of view, less energy is transmitted.

However, if there is too much abrasive, energy loss occurs due to collision between particles, so the optimal abrasive flow rate was expected to exist. To analyze this, the following graph was observed (Fig. 7). Observing in terms of effective kinetic energy, which is important for rock drilling, it was found that the maximum value was found when the abrasive flow rate was 11.1 g/s. The effective kinetic energy also showed a difference according to the standoff distance. Therefore, it was found that the optimal abrasive flow rate exists.

As mentioned above, the abrasive acceleration efficiency according to the abrasive flow rate and the standoff distance was analyzed under the same water pump pressure condition through the velocity ratio (Fig. 8). Looking at the shape of the graph, the optimal abrasive flow rate in terms of effective kinetic energy was analyzed to be around 11.1 g/s, which could also be confirmed through the velocity ratio graph.

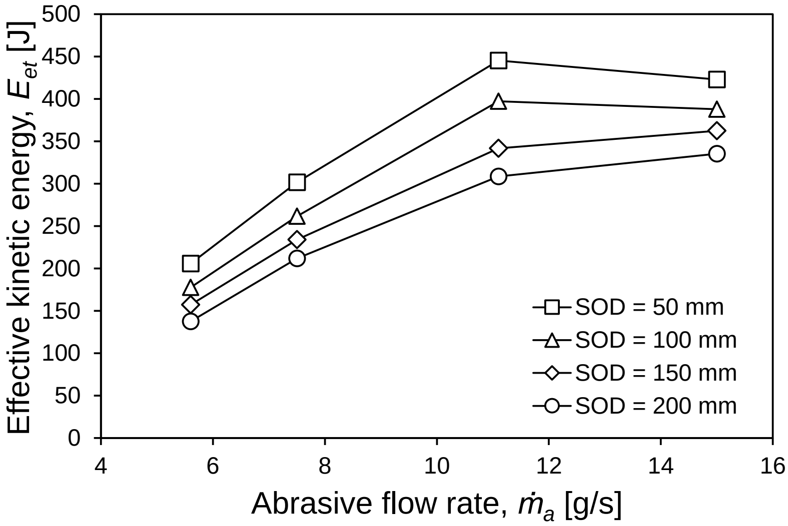

Fig. 7 Effective kinetic energy depending on the standoff distance and abrasive flow rate

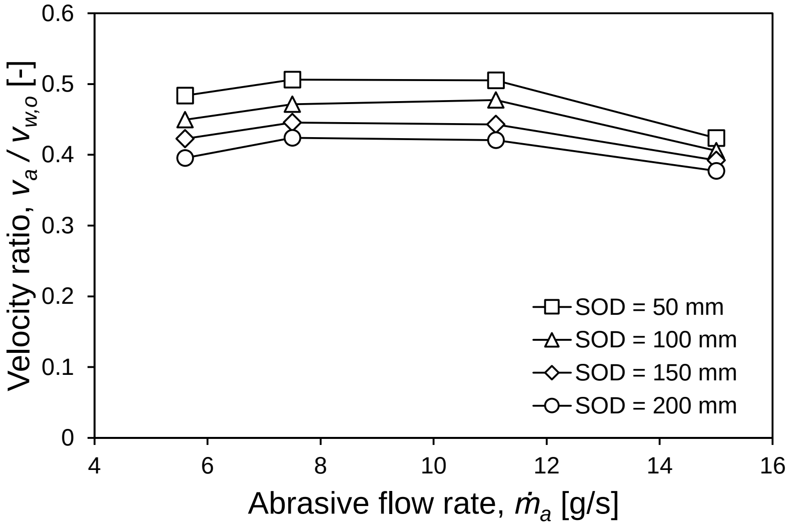

Fig. 8 Velocity ratio depending on the standoff distance and abrasive flow rate

In most abrasive flow rate conditions, the turbulence showed a difference according to the standoff distance ratio, and it was confirmed that it had a minimum value around 70 (Fig. 9). However, it should be noted that the location of the minimum value of turbulence is different under certain abrasive flow rate conditions. When the abrasive flow rate was 15.0 g/s, the turbulence had a minimum value near the standoff distance ratio of about 150. It was found that the acceleration efficiency of the abrasive varies according to the abrasive flow rate when the same energy is input.

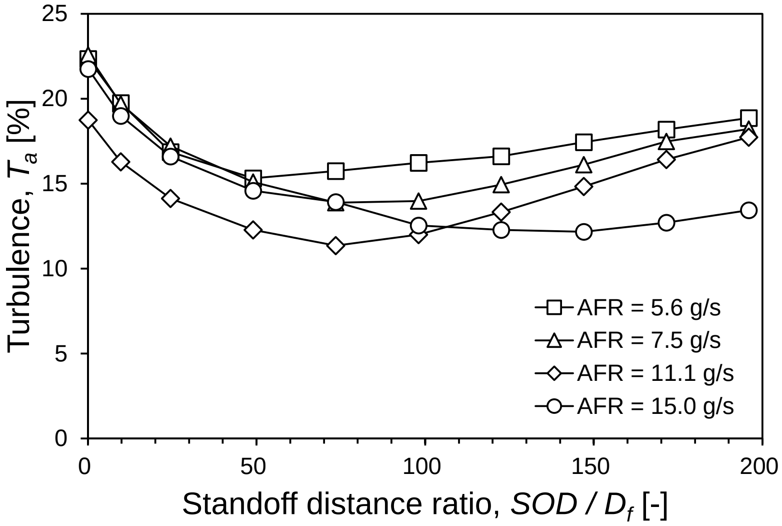

Fig. 9 Effect of abrasive flow rate on turbulence according to standoff distance ratio

5. CONCLUSION

In this study, an abrasive waterjet system was implemented using numerical analysis. By applying different water pump pressure and abrasive flow rate, we observed how the speed of the abrasive, which is essential for rock drilling, changes according to the standoff distance. The results are summarized as follows.

- The higher the water pump pressure, the more energy the water generates under the same orifice condition, which ultimately accelerates the abrasive more.
- An abrasive flow rate of about 10 g/s is optimal in terms of acceleration of the abrasive under the same water pump pressure condition.
- In terms of turbulence, although it depends on the abrasive flow rate, in general, the acceleration of the abrasive was effective when the standoff distance ratio was around 70 ~ 100.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2017R1A5A1014883) and the technical support from ANSYS Korea.

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