High-Precision Simulator for Hydraulic Percussion Rock Drills

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Received 16 06 2017; accepted 14 07 2017

ABSTRACT

This article summarizes the authors’ studies on a high-precision simulator for hydraulic percussion rock drills, which received a technical award from the Japanese Society for Rock Mechanics in the fiscal year of 2016. Hydraulic percussion rock drills are widely used for blast hole drilling in mines, quarries, and tunnel construction sites. The performance and efficiency of rock drills affect the time and expense necessary for rock excavation, and therefore advancement in rock drills has been required. The design and development of rock drills based on experimental results require much time and effort. Alternatively, computer simulation is an effective method, but the computational models in previous studies were too simple to implement recent rock drill mechanisms. In a series of studies by the authors, precise computational models for stress wave propagation, bit penetration into rock, and the behavior of a rock drill body were proposed based on experimental results. A high-precision simulator for hydraulic percussion rock drills was then constructed by combining the proposed component models. The simulator was able to precisely reproduce consecutive percussive drilling into granite with a rock drill.

Keywords: Rock drill, Percussive drilling, Stress wave propagation, Force-penetration relationship, Computer simulation

1. INTRODUCTION

This article summarizes the authors’ studies on a high-precision simulator for hydraulic percussion rock drills, which received a technical award from the Japanese Society for Rock Mechanics in the fiscal year of 2016. Hydraulic percussion rock drills are widely used for blast hole drilling in mines, quarries, and tunnel construction sites. The performance and efficiency of rock drills affect the time and expense necessary for rock excavation, and therefore advancement in rock drills has been required. During percussive drilling, a rock drill body, rods, a bit, and rock affect each other, and accordingly the drilling rate and efficiency are determined by various factors, including the hydraulic pressure, the thrust force, the number of rods, and the mechanical properties of the rock. Hence, the design and development of rock drills based on experimental results require much time and effort. Alternatively, computer simulation is an effective method, but the computational models used in a previous study (Okubo & Nishimatsu, 1991) were too simple to implement recent rock drill mechanisms.

In a series of studies by the authors, precise computational models for stress wave propagation, bit penetration into rock, and the behavior of a rock drill body were proposed. A high-precision simulator for hydraulic percussion rock drills was then constructed by combining the proposed component models.

2. STRESS WAVE PROPAGATION IN A PISTON, RODS, AND ROD JOINTS

An impact penetration tester was developed to obtain the experimental results needed to construct the computational models of stress wave propagation (Fukui et al., 2010). The tester was composed of an actual piston, shank rod, sleeve-type rod joint, rod, and button bit. In the tests, the piston was made to impact the shank rod, and the generated stress waves were measured with strain gauges attached to the rod. The measured stress waves had high-frequency oscillations in a nearly half sine curve with a wavelength of 5 m, generated by the complex shapes and interactions of the piston, shank rod, rod joint, and rod. The authors constructed the precise computational models for each component and then simulated the stress wave propagation.

The models for the piston, shank rod, and rod were one-dimensional and divided into small elements of the same length. The length was changed to 1 mm from the 20 mm of the previous study (Okubo & Nishimatsu, 1991) in order to better represent the complex shapes of the actual components. The same acoustic impedance (=Young’s modulus × cross-sectional area / wave velocity) as the actual components...
was input into each element, and then stress wave propagation was computed using the discretized one-dimensional wave equation. In the computation, stress between the piston and the shank rod was transmitted through a spring model, because the contact area between the two components was assumed to change gradually. In addition, a new spring model including the mass and length of the sleeve-type rod joint was proposed. A computer simulation with these precise models was able to reproduce the stress wave propagation measured in experimental tests (Hashiba et al., 2015b).

3. BIT PENETRATION INTO ROCK

To construct the computational model for bit penetration into rock, impact penetration tests were conducted with granite using the tester described in section 2 (Fukui et al., 2010). In the tests, a button bit in which spherical tungsten carbide tips were embedded was brought into contact with the rock surface by applying a thrust force on the tester. Then, the piston in the tester was made to impact the shank rod, and consequently the bit penetrated into the rock. After each test, rock debris in the drilled hole was removed, the threads were tightened, and the bit was rotated. The tests were repeated about 50 times, corresponding to three rotations of the bit.

Modeling the force-penetration relationship at the bit is essential for computer simulation of percussive drilling. Previous studies attempted to obtain the relationship from the stress waves measured at two locations on the rod, using inverse calculation of the discretized wave equation. However, it was impossible to precisely calculate the relationship, because of slight differences between the two measured stress waves and a mismatch between the actual button bit and the model in the inverse calculation. The authors developed a new calculation method for the force-penetration relationship using both the experimental and simulated results of an impact test without a rock block (Hashiba et al., 2015a). In the method, the bit forces $F_1$, $F_2$, and $F_3$, which correspond to the impact penetration test, the impact test without a rock block, and the simulation of the impact test without a rock block, respectively, were calculated from the stress waves on the rod. Then, $F_1$–$F_2$ and $F_1$–$F_3$ were considered to be the low and high bit forces, respectively. This method eliminated the errors in the inverse calculation and therefore improved the accuracy of calculating the force-penetration relationship.

The obtained force-penetration relationship was found to be represented by two downward-convex curves in the loading and unloading phases. Hence, the power function for each curve was proposed as the computational model of the force-penetration relationship for the button bit. In addition, the authors formulated the relationships and distributions of the constants in the proposed functions as well as the change in a contact location between the bit and a rock surface (Hashiba et al., 2017).

4. SIMULATOR FOR HYDRAULIC PERCUSSION ROCK DRILLS

The authors constructed the computational model of a rock drill body in which hydraulic pressure in the front chamber is always high and hydraulic pressure in the rear chamber is switched between high and low. The piston is moved forward by the high pressure in the rear chamber and made to impact the shank rod. At that time, the pressure in the rear chamber is switched to low, and then the piston is moved backward. Just after the piston passes through the predetermined position, the pressure in the rear chamber is switched to high, and the piston is decelerated. After reaching dead center of the back, the piston is moved forward. The piston is reciprocated by itself in this manner and made to impact the shank rod 2000–4000 times per minute. The rock drill body implements high and low accumulators to eliminate pressure oscillations as well as to compensate pressure shortage.

These mechanisms were modeled by combining the component models of a pump and accumulators, circuits, and valves in commercial 1D-CAE software (Hirano et al., 2014). The relationship between pressure and flow in the complex circuits was calculated with fluid analysis and implemented in the model. In addition, a damper system to absorb the energy of reflected stress waves and compensate the thrust force was also implemented in the model.

Finally, the authors constructed a high-precision simulator for hydraulic percussion rock drills by combining the component models of the stress wave propagation in section 2, the bit penetration into rock in section 3, and the rock drill body in this section. The simulator was able to precisely reproduce consecutive percussive drilling into granite with a rock drill (Liang, 2017).

5. CONCLUSIONS

In a series of studies by the authors, the precise computational models for stress wave propagation, bit penetration into rock, and the behavior of a rock drill body were proposed, and a high-precision simulator for hydraulic percussion rock drills was constructed. In the future, the accuracy of the simulator should be improved by comparing the computed and experimental results under various drilling conditions. The authors wish to use the simulator for the design and development of future rock drills. Please refer the relevant articles listed below for the details of the mentioned studies.

REFERENCES


Liang, Y. Z., 2017. Study on the drilling process with the hydraulic percussion rock drill, PhD thesis, the University of Tokyo, Chapter 6.