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A Novel Predictable Rock Breaker Using Intelligent Hydraulic Control with ICT Convergences

Bok-Joong Yoon [1], Kil-Soo Lee [1] and Jae-Hak Lee [2,*]

[1] Department of Convergence/Green Technology Research, Korea Construction Equipment Technology Institute, Gunsan-si, Jeollabuk-do 54004, Korea

[2] Department of Aircraft Parts Engineering, International University of Korea, 965Dongbu-ro, Munsan-eup, Jinju-si, Gyeongsangnam-do 52833, Korea

* Correspondence: jhleepau@iuk.ac.kr; Tel.: +82-55-751-8253

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Abstract: In this paper, a hydraulic breaker system is suggested with optimized impact forces and with active control to improve the system's energy efficiency. While performing operations such as demolition, rock pulverization, and ground hammering, the consistent breaking force causes energy dissipation due to the various strengths of the bedrock. Moreover, if the ground condition is not monitored, this may lead to catastrophic damage to the whole system. Moreover, frequent part changes can result in fatal malfunction. Therefore, a novel rock breaker is needed that is able to predict target properties of the rock in order to perform at the optimal impact force. The characteristics of rock forecasts obtained by a proximity sensor can determine the depth at which the piston stroke will reach the object. Moreover, a cascade control system for multiple levels of impact points, included operating and monitoring modules, is developed by applying ICT convergence through a wireless communication system. Consequently, adequate results were obtained from the applied field test on the feasibility of the suggested breaking system, thus confirming the possibility of applying this system in conventional heavy industries.

Keywords: cascade control; hydraulic breaker; ICT convergence

1. Introduction

Hydraulic breakers are widely used, typically attached to excavators in heavy industries and construction for the deactivation and removal of building structures, road demolition, water supply and drainage construction, foundation works, and the destruction of quarry stones. The breaking system is composed of the main body and the bracket which houses the system. Figure 1 shows the primary components and assembly of a hydraulic breaker. The main body consists of the head cap, cylinder, front head, and valve housing. The excavators discharge the pressurized hydraulic oil into the main valve, which is located at the top of the hydraulic breaker. The cylinder moves from the top to bottom and back and forth according to the oil pressure due to differences in the cross-sectional area. Lastly, the piston impacts the chisel, which makes direct contact with the rock to break it down.

The means of the impact process have been developed and performed as manual preset strokes—either mechanically manual long strokes or short strokes. Recently, mechanical, automatic long and short strokes have been investigated, and are widely used in heavy industries [1–3].

A few studies have reported the use of electro hydraulic control [4–6] for breaking systems [7,8], as listed in Table 1. Moreover, there in an increasing demand for the improvement of construction equipment efficiency, coinciding with the emergence of new environmental regulation standards in many countries.

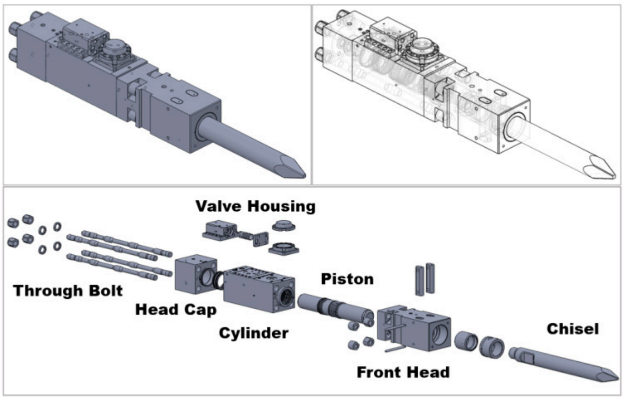


Figure 1. Hydraulic breaker and components.

Table 1. Weaknesses of conventional hydraulic breakers.

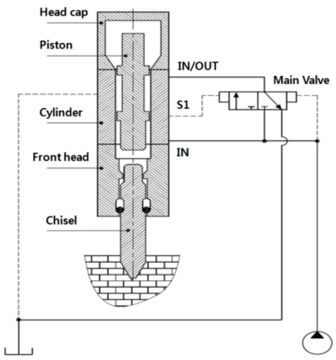
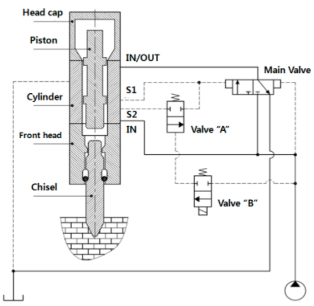
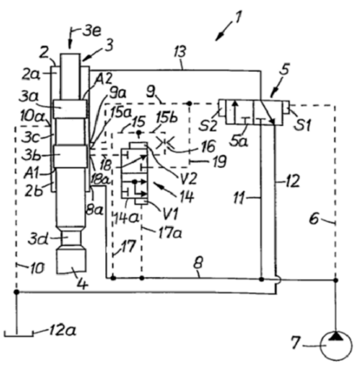
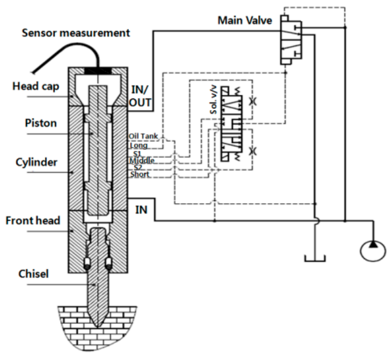
Only Long-Stroke Type	Weakness
	Always uses maximum impact energy, which leads to decreases in the system durability and life time
Manual Long-and Short-Stroke Type	**Weakness**
	Manual change with only ON/OFF switches, thus decreasing the work efficiency and leading to inconvenience in the breaking operation
Auto Long-and Short-Stroke Type	**Weakness**
	Mechanical automatic hard or soft rock mode operation; complicated hydraulic components increase the processing cost

Table 1. *Cont.*

Electric Auto Multi-Stroke Type	Weakness
	The electronic control component has weak durability in construction applications and infrastructure industries

A hydraulic breaker that can predict the strength of rock using an ICT-converged electronic auto-adjusted stroke was investigated and verified by practical operating field tests under conventional conditions so as to validate the proposed system's usability, durability, and efficiency.

2. A Novel Hydraulic Breaker

While operating in the manual stroke condition, the piston strokes deeper than usual since the impact rock may have low strength. Based on this phenomenon, the suggested system was fabricated to detect the piston depth and verify the stroke length automatically. In the case of impacting hard rock, the piston employs longer strokes and retains the position of the chisel to smash the hard enough to break it. Meanwhile, shorter and higher-frequency strokes are employed for weaker substances so as to decrease the amount of unnecessary shocks and vibration for the improvement of productivity and durability.

2.1. System Composition and Analysis

A schematic diagram of the proposed hydraulic breaker is shown in Figure 2. The suggested auto-adjusted stroke system has two proximity sensors (S1, S2) to collect the position data and two signal ports for transferring the control signal to the main and solenoid valves.

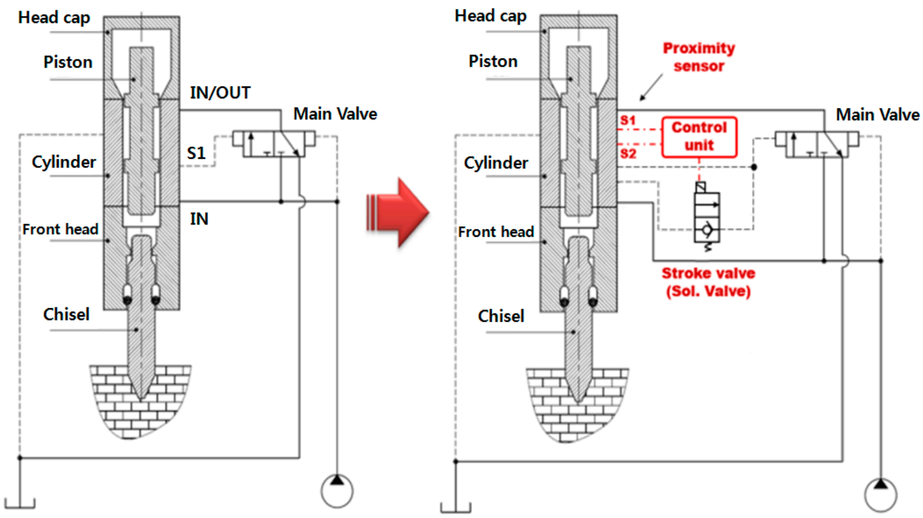


Figure 2. Schematic diagrams of hydraulic breakers (left: conventional/right: developed).

When the proximity sensor detects a shortened position, the data in the breaking system signals for the operation of the multi-port (short middle) solenoid valve. In contrast, when the signal indicates the longer position of the piston, the system works as a conventional hydraulic breaker.

2.2. System Analysis

In order to guarantee a reliable mode of operation for the auto-adjusted stroke hydraulic breaker, modeling and numerical simulations [8] have to be investigated quantitatively and discussed. Figure 3 shows a simplified model of the hydraulic breaker [9]. The piston velocity optimization was carried out using AMEsim using Design of Exploration (DOE) [10,11]. As a result of the DOE analysis, it was found that the significant factors affecting the piston stroke velocity are the flow channel, piston cross-sectional area, and output channel. According to these analyses, the chisel velocity was modified from 8.7 m/s to 10.3 m/s, as indicated by the optimized result shown in Figure 4.

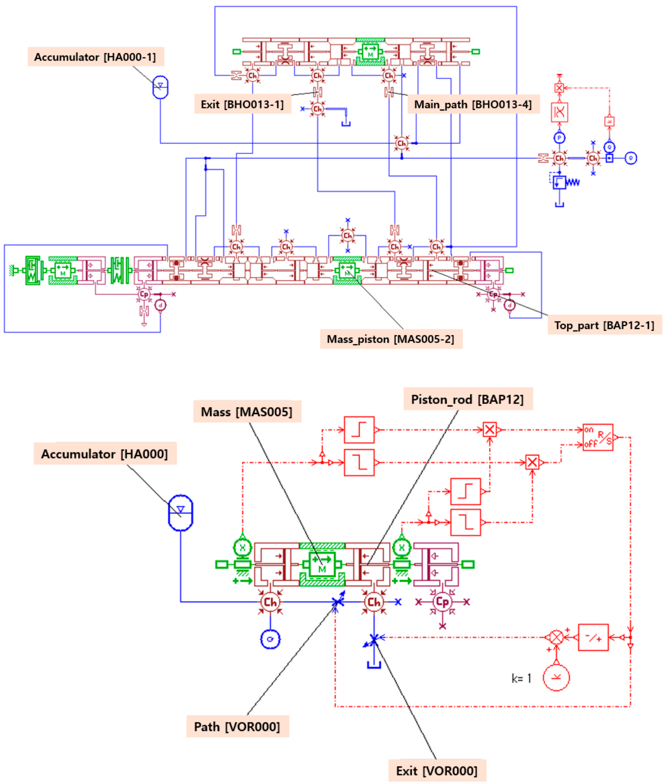
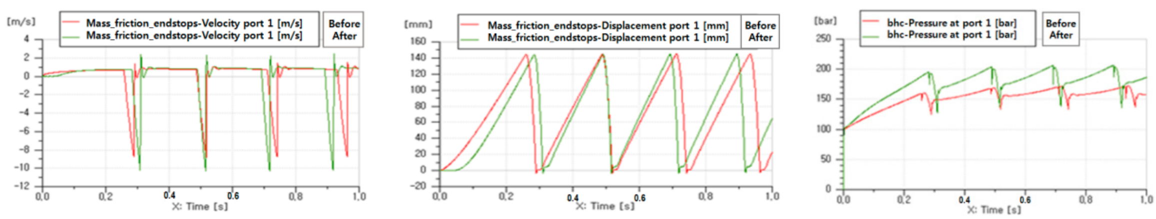


Figure 3. Breaker modeling (top: conventional/bottom: developed).



(a) (b) (c)

Figure 4. Simplified hydraulic breaker model: (**a**) velocity; (**b**) displacement; (**c**) pressure.

2.3. Cascade Control

The suggested adjustable hydraulic control is mainly composed of sensors for measuring the depth of the piston (chisel) (Figure 5) and a solenoid valve for controlling the displacement of the stroke as determined by the algorithm (Figure 6). In addition, the micro control unit (MCU) for the communication and monitoring of the system in real time as well as the operation time after setting the stroke mode are shown in Figure 7.

While impacting the bedrock, signals from the proximity sensor can identify that the flow line is close to the solenoid valve when the system determined that the rock is hard, and the piston is set in the long stoke range mode and retain this position.

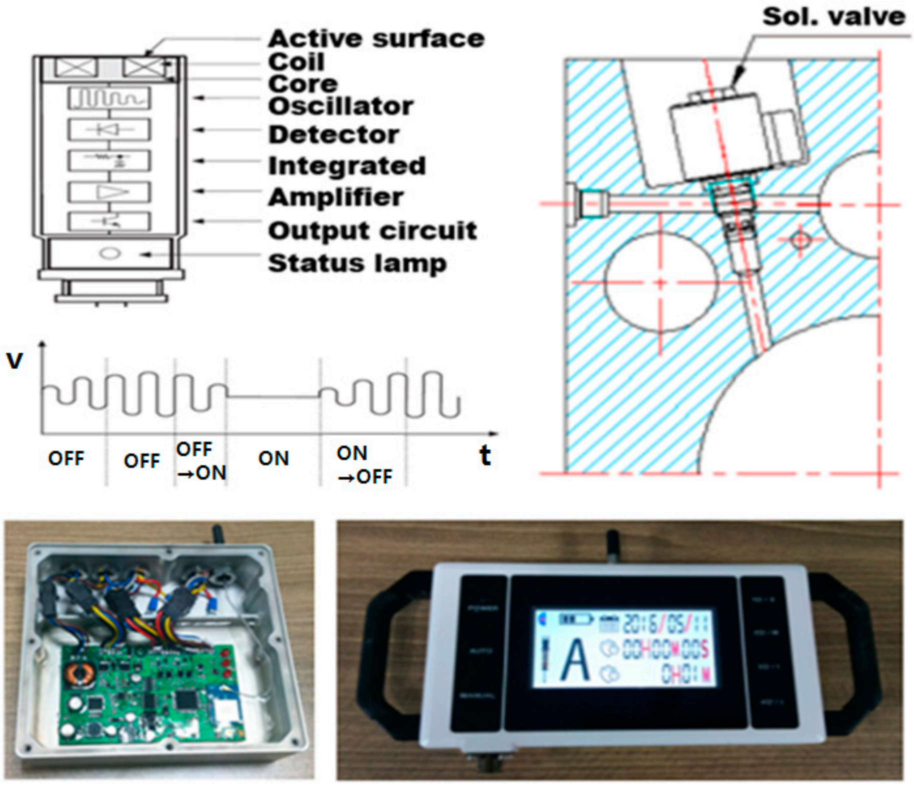


Figure 5. Proximity sensor, solenoid valve, controller, and display panel with control keys.

Figure 6. System of the hydraulic breaker.

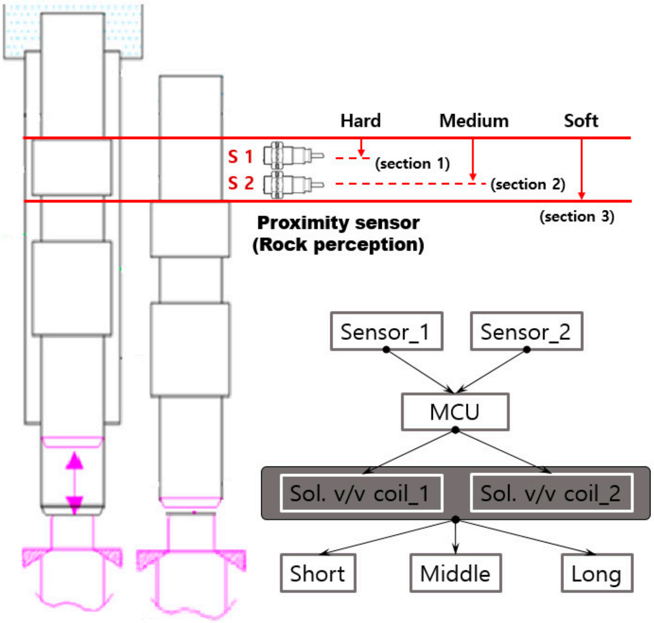


Figure 7. Schematic diagram of the control system logic.

When one sensor is employed for rock property detection, for mid-strength rock it sets a medium stroke with a middle position, controlled from the solenoid valve. When two sensors are used to detect and send the signal, the controller can recognize soft rock to provide the shortest stroke. Figure 8 shows the proximity sensor data for the properties of each rock type.

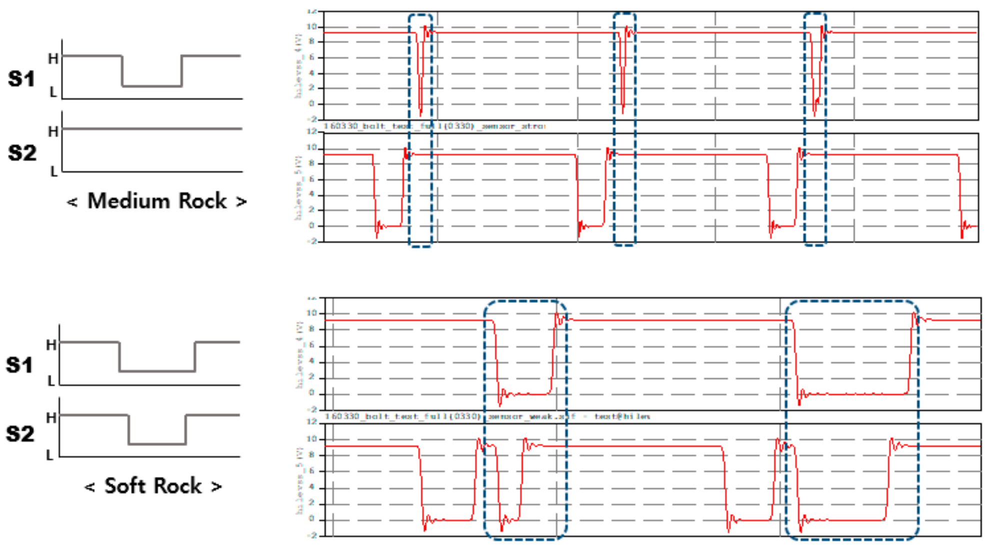


Figure 8. Proximity sensor data of each rock type.

The MCU controls two proximity sensors and two solenoid valves in the adjustable stroke hydraulic breaker. The schematic diagram of the control system logic is shown in Figure 7.

The standard for determining the rock strength used in this investigation is listed in Table 2. The properties conform to criteria of the rock according to the compressive strength, as authorized by the Ministry of Land, Infrastructure, and Transport. The MCU consists of an atmega128 micro controller with ZigBee wireless communication to receive/transmit the status to the display and control panel. The operator can also select the manual mode to maintain the stroke in the control panel, which is shown using an LCD visual indicator.

Table 2. Criteria of the rock according to uniaxial compressive strength.

Strength (MPa)	Weather-ed	Soft	Medium Hard	Hard	Extremely Hard
Construction Association of Korea	30 ~ 70	70 ~ 100	100 ~ 130	130 ~ 160	160 ~
Korea engineering and consulting association	~ 5	5 ~ 30	30 ~ 80	80 ~ 150	150 ~
Korea Expressway Corporation	~ 60	60 ~ 80	80 ~ 100	100 ~	-
Seoul Metro	~ 10	10 ~ 25	25 ~ 50	50 ~ 100	100 ~
Korea Train Express	~ 5	5 ~ 25	25 ~ 50	50 ~ 100	100 ~
Seoul Metropolitan Government	~ 10	10 ~ 25	25 ~ 50	50 ~ 100	100 ~

3. Performance Evaluation and Field Test

To validate the performance of the cascade control system, a flow meter and pressure sensor were installed to measure the impact frequency, energy, and efficiency. Experiments and a field test were performed at the Korea Institute of Machinery and Materials (KIMM).

An adequate field test was operated manually to determine the result of each stroke. The impact frequency was calculated by inversing five consecutive operating cycle times, as in Equation (1). The impact energy (E_i) computed in Equation (2) from the wave over25 operating cycles with constant speed was shown to have pulse shape definiteness with no interference from other data.

$$f_i = \frac{5}{t_i}, \tag{1}$$

$$E_i = \frac{CF^2}{A_t \cdot \sqrt{E_t \cdot \rho_t}} \cdot \int_{t_i}^{t_n} {\varepsilon_i}^2 \cdot dt, \tag{2}$$

$$\varepsilon_i = \frac{4 \cdot U}{2.6 \cdot k \cdot U_B \cdot K_a}, \tag{3}$$

$$\eta_{tot} = \frac{E_i \cdot f_i}{Q \cdot (P_s - P_r)}, \tag{4}$$

The deformation ε_i measured the initial to final operation time from the selected wave, excepting preloading time of equipment, using the arithmetic mean as shown in Equation (3). The specifications of the products used in the experiment are listed in Table 3. The experimental conditions included an environmental temperature of 22 ± 10 °C and 50 ± 30% relative humidity.

The variables of the equations are listed in Table 4, including the units.

Table 3. Specifications of products used in the experiment.

Specification	Unit	B500
Operating weight	kg	3720
Tool(chisel) outer diameter	mm	175
Operating pressure	MPa	13.7–17.6
Oil flow rate	l/min	200–280
Suitable excavator	ton	40–50

Table 4. Description of variables.

Nomenclature	Description	Unit
t_i	operation cycle time	s
E_i	impact energy	J
CF	calibration factor	$\frac{F_{cal}}{\varepsilon_{meas}}$
ε_{meas}	deformation while calibration	
A_t	cross-section area of test chisel	mm^2
E_t	module of direct elasticity	N/mm^2
ρ_t	density of test chisel	kg/m^3
ε_i	measured deformation	
t_i	initial impact time	s
t_n	terminate impact time	s
k	gauge factor	
U	output voltage	V
U_B	input voltage	V
K_α	amplifying factor	
η_{tot}	total efficiency of hydraulic breaker	%
P_s	operating pressure	MPa
P_r	output pressure	MPa
Q	flow rate of hydraulic breaker	l/min

A field test was carried out to confirm the possibility of applying this system in conventional heavy industries, as shown in Figure 9. Attached to the system were the pressure sensor, flow rate sensor, temperature meter, and strain gauge. The actual experiment evaluated the performance of the hydraulic breaker in long and short stroke modes.

Figure 9. Control system and site for the experiment; the blue circle indicates the strain gauge.

Figure 10 shows the impact frequencies. While in the long stroke mode, there were five impacts in 1.2–2.2 s. In the short stoke mode, there were four impacts in 1.5–2 s. Using the strain gauge composed of a Wheatstone bridge, and the measured voltage value is converted into impact energy through Equations (2) and (3), as shown in Figure 11.

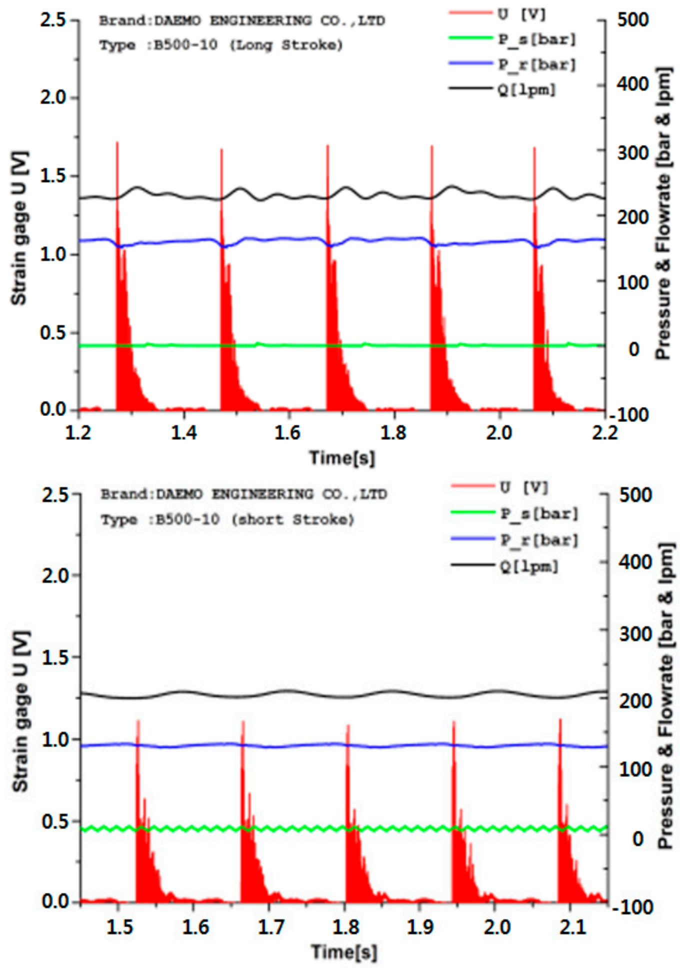


Figure 10. Experiment result graph of the impact frequency (upper: long/lower: short).

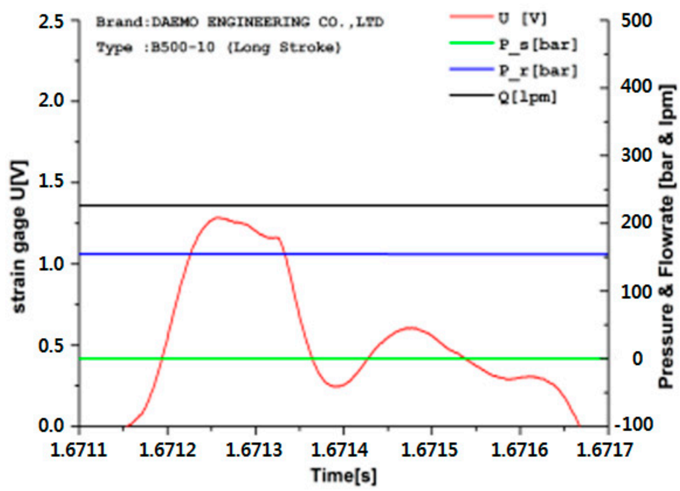


Figure 11. *Cont.*

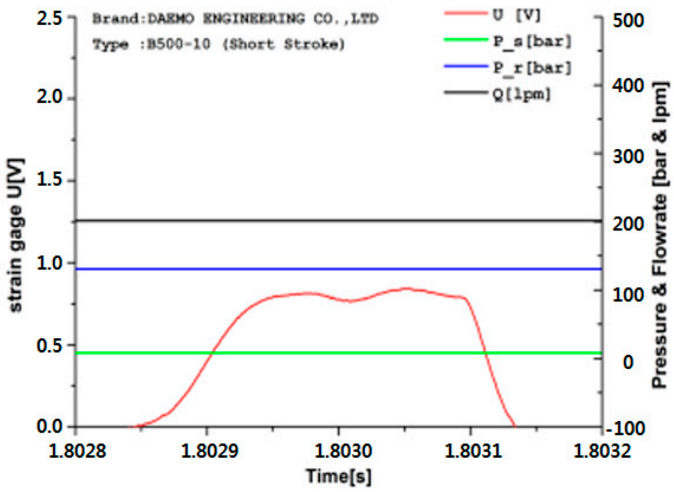


Figure 11. Result graphs of the impact energy (upper: long/lower: short).

In the long stroke mode, the energy was observed to reach about 6583 J, while it reached 3102 J in the short stroke mode. The result shows that the impact efficiency improved 7%, as shown in Table 5. Furthermore, the amount of impact energy in the short stroke mode is suitable for breaking up soft rock with a strength of 70–100 MPa.

Table 5. Results of the impact efficiency.

Specification		Breaker(B500)Working Mode	
Item	**Unit**	**Long Stroke**	**Short Stroke**
Operating pressure	ps/bar	152.86	141.21
Outlet pressure	pR/bar	0.07	7.80
Oil flow rate	Q/l/min	225.08	210.25
Impact energy	E/J	6583.46	3102.45
Impact frequency	f/Hz	4.94	8.60
Impact efficiency	η_{tot},%	57.15	57.06

The ICT convergence system was adapted and verified to transmit between the controller and the hydraulic breaker, due to the harsh conditions of the operation field such as high levels of vibration and impact. An additional test applying wireless communication was certified by Korea Conformity Laboratories (KCL). All of the results qualified for a condition up to 85 °C temperature and 50–150 °C in the thermal shock test, up to 30G in the triaxial shock test, and distances of less than 30 m for the salt spray tests.

4. Conclusions

The novel predictable rock breaker suggested features an adjustable stroke for optimal impact energy with improved efficiency and productivity. The cascade control using ICT convergence wa provided to the electro hydraulic control system to ensure wireless communication between the display panel and the manipulator in both manual and automatic modes. Moreover, the impact frequency range was extended from 5 to 9 Hz in the long stroke mode, and the impact energy increased from 50 to 57%. Consequently, the field test results validated the feasibility of the suggested breaking system and confirmed the possibility of applying the proposed system in conventional heavy industries.

Author Contributions: B.-J.Y. and K.-S.L. designed and performed the experiments and analysis; J.-H.L. built up the research project, contributed to the search process, and wrote the paper.

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Conflicts of Interest: The authors declare no conflict to interest.

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