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Measurement of Borehole Pressure History in Blast Holes in Rock Blocks

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Abstract

Borehole pressure is a measure of the expansion work an explosive can carry out in a blast hole. It is a fundamental parameter indicating energy partitioning and efficiency of the explosive. It is also the most important factor that determines the blasting results such as fragmentation, heaving and damage in remaining rock. However, technically and economically feasible measuring methods were not available. Recently, a method for measurement of pressure history in blast holes, the so-called LHM method, has been developed at SveBeFo and successfully applied in laboratory tests and in model tests in granite blocks. The method has also been involved in field tests in bench blasting.

This paper describes a series of measurements of borehole pressure using the LHM method in blast holes in large blocks of very competent granite. Six test shots have been carried out, in which two types of explosives and three decoupling ratios were studied. The experiments showed that the LHM method worked well. The measured borehole pressure varied from 0.08 to 1.4 GPa, depending on the explosive type and decoupling ratio. However, only a part of the pressure history, 30 to 500 μs could be measured before the gage was damaged. The measured pressure amplitude has been compared to the estimates by empirical formulas. The comparison showed that the empirical formulas for explosion pressure provide quite good estimates while the formulas for borehole pressure in decoupled holes give poor estimates. However, when the decoupling ratio is large, approximately 2.4, Calder's formula can estimate the borehole pressure in decoupled holes well.

Keywords: borehole pressure, explosion pressure, decoupling, pressure gage, LHM

1. Introduction

The history of the borehole pressure in a blast hole in rock describes the expansion work of the explosive during the rock breakage process. This data directly indicates the transfer of the explosive energy into the rock and hence it is a direct measure of the efficiency of the explosive. Furthermore, the borehole pressure determines the blasting results such as fragmentation, heave and damage in the remaining rock[1, 2]. Besides, it is a crucial input or calibration data for various computer simulations. Therefore, this information is the most important one in an evaluation of the explosive performance and in the prediction of blasting results.

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Despite of the importance of this parameter, direct measurements of the borehole pressure have rarely been carried out, owing to the absence of feasible methods. Instead, various empirical formulas or computer codes are used to estimate this pressure[3]. The accuracy of such estimations remains unknown.

There are a number of techniques to measure different pressures associated with a detonation. For example, the manganin gage[4] for measuring of detonation pressure is an established method and commercial products are available. However, this method is mostly suitable in laboratory tests and the accessories are clumsy.

PVDF gages have also been employed in measuring detonation pressure with good success[5]. Since they are a type of piezo electrical gages with limited time constants, they are not suitable for measurement of the history of borehole pressure.

The composite carbon resistor has commonly been used as pressure sensor for detonation pressure since the first application by Watson[6]. This kind of gages can be applied in the measurement of not only strong shock pressures such as detonation pressures[6] and borehole pressure[7], but also weak dynamic pressures such as pressure waves in rock masses[8, 9] or static pressures.

Based on a sensor of a composite carbon resistor, G Persson[10] at SveBeFo has developed another gage design named LHM (In Swedish: Lägesbestämd Hydrostatisk Mätkopp, or Location-fixed Hydrostatic Measuring-cup). The goal was to measure the entire history of the borehole pressure. Details are described in the following section.

This method has been successfully applied in laboratory tests[10]. In order to extend the application of this new method to rock blasting, a series of measurements of borehole pressure using the LHM method have been conducted in blasting holes in large blocks of very competent granite[3]. Some applications of this method in field scale have been carried out. More measurements in bench blasting are under way.

2. The LHM method

The configuration of the LHM method[10] is illustrated in Figure 1. A sensor consisting of a carbon resistor (1/8 W, 470 Ω ± 5 per cent) is mounted at the bottom of a steel cup. A signal cable connects the sensor through the bottom of the cup to an amplifier. The cup is filled with pure water. The size of the cup is 140 mm in length, 27 mm in inner diameter, 5 mm in side wall thickness and 20 mm in bottom thickness.

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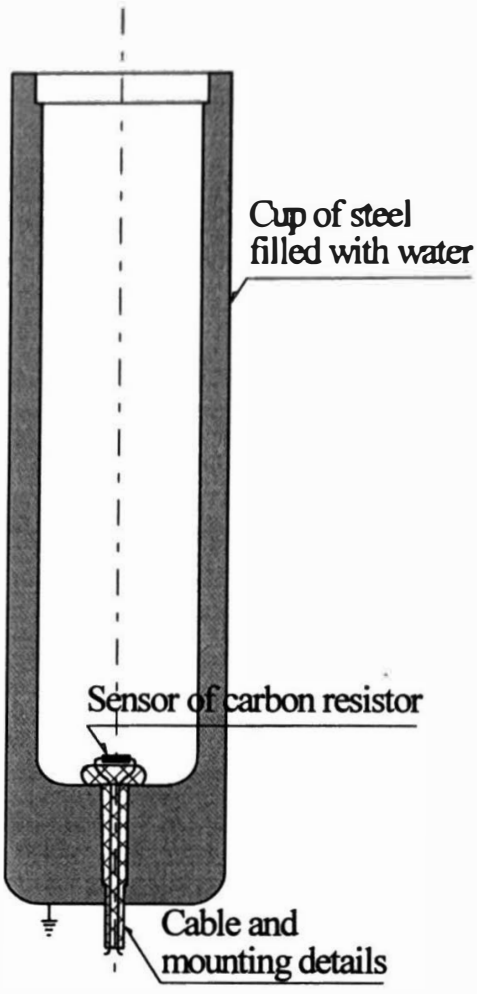

Figure 1: The LHM gage design for measurement of history of borehole pressure.

The pressure sensitivity of the carbon resistor has been calibrated under static pressure up to 2.1 GPa[10] and the pressure-resistance relation can be described by:

$$P = 0.4075\left(\frac{R_0 - R}{R}\right)^{0.8734} \quad \text{when } P \le 1 \text{ GPa} \qquad [1a]$$

$$P = 0.2597\left(\frac{R_0 - R}{R}\right)^{1.3128} \quad \text{when } P \ge 1 \text{ GPa} \qquad [1b]$$

where: P = pressure on the resistor (GPa)
R_0 = resistance of the carbon resistor at 1 atm (Ω), the nominal value is 470 Ω
R = resistance of the carbon resistor under pressure (Ω)

When measuring, the cup is placed at the bottom of a blast hole with the water in contact with the explosive. The water protects the sensor from the high temperature detonation gases and also damps the strong shock wave. In this manner, the gage will

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only measure the pressure of a quasi-static state, corresponding to the borehole pressure. If the cup is fixed in the blast hole, it follows the expansion of the blast hole and monitors the decrease of the borehole pressure during the expansion.

2. Measurements in blast holes in granite blocks

2.1 Geometry of the experiments

Experiments have been carried out in six blocks in Svenneby ornamental stone quarry. The rock there is a competent granite. The blocks used for the experiments were selected from big boulders without visible cracks or joints and the size was 1.5 to 2.8 m in length, 1.0 to 1.4 m in width and around 1 m in thickness.

A blast hole and a cable hole were drilled in the middle part of each block parallel to the thickness dimension, see Figure 2. The diameter of the blast hole was 38 mm and the length was approximately 0.6 m. A cable hole of 19 mm in diameter was drilled, coaxially with the blast hole, from the bottom of the blast hole to the opposite surface of the block. The length of the cable hole was therefore approximately 0.4 m.

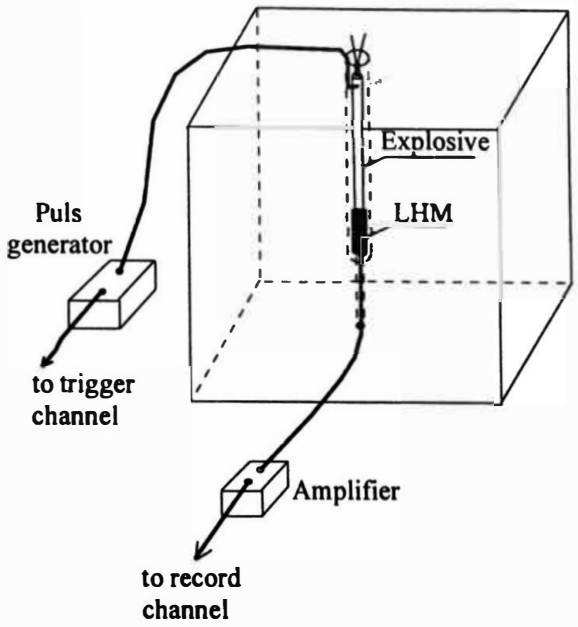

Figure 2: Measuring system for borehole pressure measurements in granite blocks.

2.2 Measuring system

The measuring system is shown in Figure 2. An LHM pressure gage was placed at the bottom of each blast hole. The signal cable ran through this cable hole and connected the sensor to the amplifier. Top initiation with one No. 8 detonator was used. A pair of ionisation pins were placed in the explosive charge in the vicinity of the detonator. The

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ionisation signal was used for two purposes: to trig the recording equipment, a LeCroy 9354A digital oscilloscope, and to identify the initiation time of the explosive.

The reason for the top initiation is the usage of the fuse detonators in order to avoid any possible electric noise, which can deteriorate the measurement[3]. The diameter of the fuse is so large that it may affect the centring of the charge in the hole.

2.3 Tested explosives

Two explosives were studied. One is Gurit B and the other is the so-called "Blue Cartridge" (Blå rör in Swedish). Both are cap sensitive and designed for cautious blasting. The properties of these two explosives are listed in Table I. However, the chemical formulas for the studied explosives are the properties of the manufacturer, Dyno Nobel AB, and hence can not be disclosed. The charge configuration in each test shot are summarized in Table II, together with the test results.

Table I: Properties of the two tested explosives

Explosive	Density in cartridge (kg/m^3)	VOD in ϕ 16 mm charge (m/s)	Heat of detonation* (MJ/kg)	Ideal VOD* (m/s)
Gurit B	1050	2065	3.51	5945
Blue Cartridge	1000	1946	1.94	4221

*: Calculated by program Cheetah[11]

Besides, the relation between the VOD and the charge diameter for the Gurit B has been experimentally determined[3]:

$$VOD = 3857 - 28674/d \qquad [2]$$

where: VOD = VOD of unconfined Gurit B at the density of 1050 kg/m^3 (m/s)
d = charge diameter of Gurit B (mm)

3. Measuring results and analysis

The pressure measurements and VOD estimates from the six shots are summarized in Table II, together with the charge configuration. Pressure signals are shown in Figure 3. The measured peak borehole pressure ranges from 0.08 to 1.4 GPa dependent on the explosive type and the decoupling ratio.

3.1 Comparison of the measured borehole pressures with empirical estimates

In this section the measured borehole pressures are compared with the estimates from the empirical formulas collected in Appendix I.

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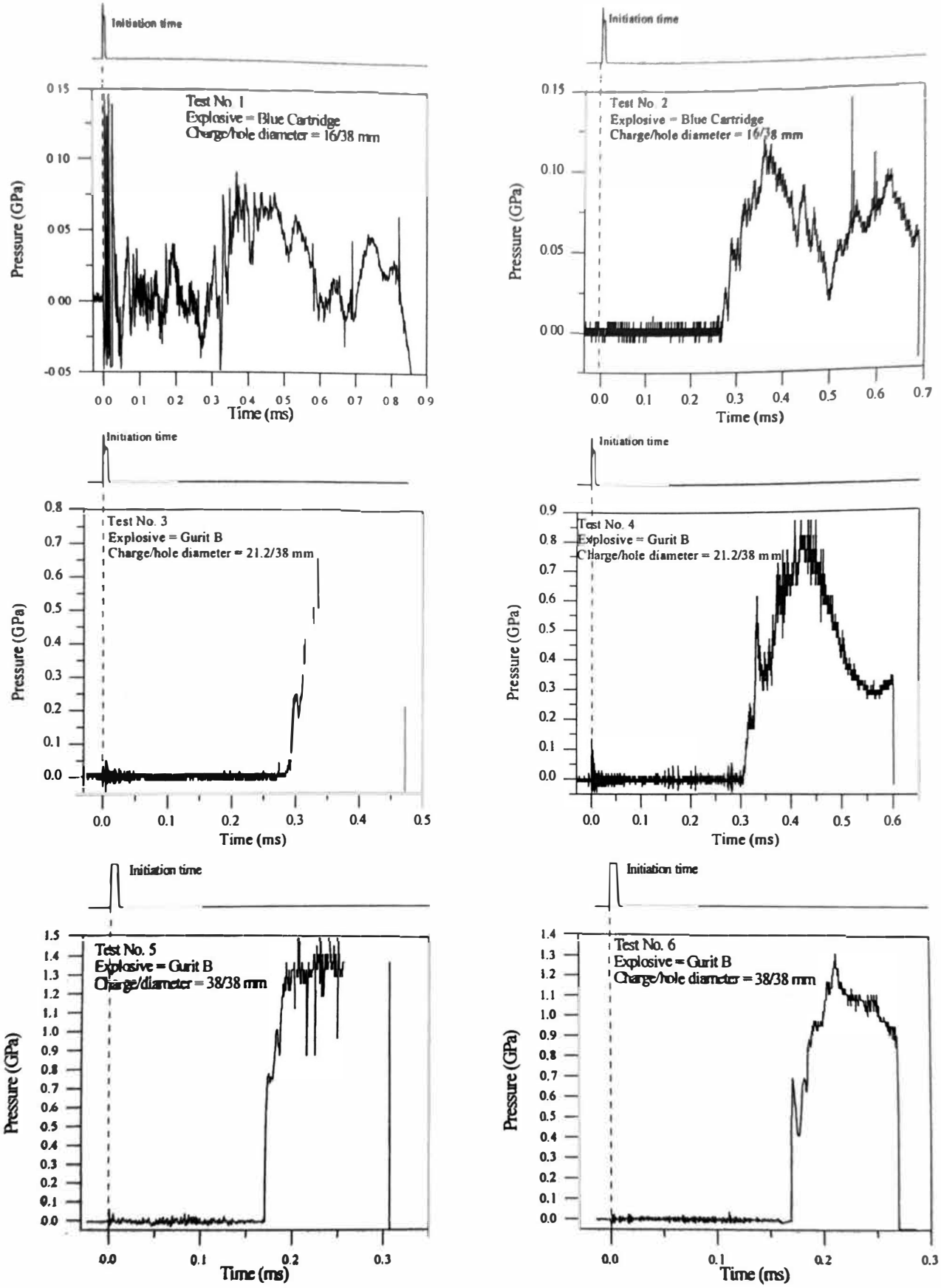

Figure 3: Pressure signals from the six LHM gages mounted in the bottom of the blast holes in granite blocks.

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Table II: Results of borehole pressure measurements in six granite blocks

Test No.	Explosive	Charge		Hole diameter (mm)	Pressure measured		Estimated VOD in hole* (m/s)
		Diameter (mm)	Density (kg/m^3)		Max. (GPa)	Duration (μs)	
1	Blue Cartridge	16	1000	38	0.08	500	1900
2	Blue Cartridge	16	1000	38	0.12	420	2300
3	Gurit B	21.2	1050	38	> 0.60	30	2460
4	Gurit B	21.2	1050	38	0.81	300	2640
5	Gurit B	38	980	38	1.38	86	3090
6	Gurit B	38	1070	38	1.30	100	3470

*: Estimated VOD = VODs in blast holes estimated from the pressure signals[3].

Table III shows the estimates of the constant volume explosion pressure in the studied explosives by four formulas. The variation of the estimated explosion pressures lies within ±17 per cent of the average.

In Test No. 5 and No. 6, the blast holes were fully charged. Thus the borehole pressure should be the same as the explosion pressure. Comparing the measured borehole pressures with the average estimate of the explosion pressure, the agreement for Test No. 5 is good while rather poor for Test No. 6.

Table III: Estimated explosion pressures by empirical formulas in Appendix I and measured explosion pressures from Tests No. 5 and 6.

Eq.	Estimated explosion pressure: P_e (GPa)					
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
A8*	0.50	0.74	0.91	1.04	1.39	1.83
A9	0.56	0.82	0.94	1.09	1.45	1.88
A10	0.41	0.60	0.72	0.82	1.05	1.45
A11	0.46	0.67	0.79	0.91	1.20	1.58
A12	0.47	0.68	0.79	0.91	1.22	1.77
Average	0.48	0.70	0.83	0.95	1.26	1.70
Deviation from the average	-15% ~ +17%	-15% ~ +17%	-13% ~ +13%	-14% ~ +15%	-17% ~ +15%	-15% ~ +11%
Measured explosion pressure					**1.38**	**1.30**
Errors between estimates and measurement					-24% ~ +5%	+11% ~ +45%

*: P_e here is the average value of P_e estimated by $P_e = \frac{1}{2}P_{CJ} = \frac{1}{2}\rho_0 D^2/(1+\gamma_{CJ})$ using different γ_{CJ} values in Table IV.

The borehole pressure in decoupled holes was estimated by two empirical formulas: Calder's formula (Eq. A16) and Atlas Powder formula (Eq. A17). In Table V, the estimates were compared with the measured pressures in Tests No. 1 to 4.

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Table IV: γ_{CJ} for the six tests estimated by empirical formulas in Appendix I.

Eq.	Estimated γ_{CJ}					
	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
A1	—	—	2.49	2.49	—	2.49
A2	—	—	2.53	2.53	2.49	2.54
A3*	2.37	2.37	2.46	2.46	2.36	2.48
A4	—	—	2.18	2.18	2.14	2.20
A6	≈ 3	≈ 3	≈ 3	≈ 3	—	≈ 3
A7	2.48	2.48	2.50	2.50	2.47	2.50

—: condition(s) for the empirical formula not satisfied: either the density or the chemical formula of the explosive is beyond the application conditions.

*: the heat of detonation and the ideal VOD in Eq. A3 were calculated by Cheetah[11], see Table I.

Table V: Measured borehole pressures in decoupled blast holes from Tests No. 1 to 4 and estimates by two empirical formulas.

		Borehole pressure in decoupled holes: P_b (GPa)				
		Test 1	Test 2	Test 3	Test 4	
Measured		**0.08**	**0.12**	**> 0.6**	**0.81**	Eq.
Calder formula	Estimate	0.071	0.103	0.232	0.268	A16
	Error	-11%	-14%	>-61%	-67%	—
Atlas Powder formula	Estimate	0.048	0.070	0.174	0.201	A17
	Error	-40%	-42%	>-71%	-75%	—

Generally speaking, the agreement between the empirical estimates of the borehole pressure and the measurements is poor. The worst agreement is obtained for decoupled charge with small decoupling ratio, i.e. Tests No. 3 and No. 4. Calder's formula estimated quite well the borehole pressure in holes with large decoupling, i.e. Tests No. 1 and No. 2.

From the above analyses, the following conclusions can be drawn for the pressure estimations of the tested explosives:

- Explosion pressure: The variation between different predictions is within ±17 per cent. Compared the estimates with two measurements, the agreement is rather good. Based on Test No. 5, the best agreement is achieved by Eq. A8 combined by Eq. A3, i.e.

  $P_e = \frac{1}{2} \cdot P_{CJ} = \frac{1}{2} \cdot \rho_0 D^2/(\gamma_{CJ}+1)$ and $\gamma_{CJ} = \sqrt{1 + \frac{D_\infty^2}{2(q + e_0)}}$

- Borehole pressure in decoupled hole: At large decoupling (ϕ 16 mm charge in ϕ 38 mm hole), estimates given by Calder's formula agree well with the measurements. However, at smaller decoupling, the agreement between the predictions by the empirical formulas and the measurements is very poor. The error is as large as 75 per cent.

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3.2 Analysis of discrepancies between the measured and estimated borehole pressure

The discrepancies are analyzed in two aspects, the accuracy of the measurements and the principle behind the estimations.

Since the number of the measurements is limited, it is difficult to statistically obtain an accuracy of the measurements. The largest uncertainty lies in the VOD values, since no direct VOD measurement has been carried out and the VOD values have been estimated from the pressure signals[3]. However, judged from the measured VODs in unconfined charges, the estimated VODs seem reasonable[3].

3.2.1 Analysis of the explosion pressure

Generally speaking, the explosion pressure and the borehole pressure increase as the product of explosive density and squared VOD increases ($\rho_0 \cdot D^2$). This general dependence is obeyed in the pressure measurements from Tests No. 1 to 4, but not in Tests No. 5 and No. 6. Both the charge density and the VOD are higher in Test No. 6 than in Test No. 5, while the measured pressure is higher in Test No. 5. This might be an inaccuracy of the pressure measurement, which consequently results in a large discrepancy between the estimated and measured explosion pressures for Test No. 6, see Table III. Otherwise, the agreement is good between the measured and the estimated explosion pressures, see Table III.

3.2.2 Analysis of the borehole pressure in decoupled hole

There are four measurements, Tests No. 1 to 4. The measurements showed that the borehole pressure increases as the VOD increases. Tests No. 3 and 4 showed also that the pressure in decoupled boreholes is lower than that in fully charge holes.

However, compared to the measurements, the empirical formulas did not give good estimates of the borehole pressure in decoupled holes. In fact, the discrepancies are large, especially for the cases of small decoupling. The reason for the discrepancy might originate in the calculation principle behind the formulas.

As described in Appendix I, the empirical formulas calculate the pressure inside the detonation gases when the gases have isentropically expanded to fill the borehole. In other words, the borehole pressure is a point on the gas expansion isentrope corresponding to the volume of the blast hole. However, there are two defects in such an estimation, a) the actual gas expansion in blast holes is not an isentropical process and b) the adiabatic gamma (γ) in the formulas is not a constant during the expansion.

Look at the blasting in a decoupled borehole. First, the detonation gases shock the air in the gap between the explosive and the borehole wall. This results a rarefaction wave back into the detonation gases and a shock wave into the air. When this air shock wave arrives at the borehole wall, a new shock wave will be reflected into the air and further

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into the detonation gases. Due to the cylindrical symmetry, this shock - reflection process will continue long after the borehole wall starts to move.

Nevertheless, if the decoupling is sufficiently large, the reflection from the borehole wall is weak and less significant. The expansion process may be estimated by a pure isentrope. Furthermore, when the decoupling is large and consequently the gas expansion is large before the reflection, the adiabatic gamma of the detonation gases (γ) may be considered as a constant around 1.2 to 1.3. This can partially explain why the Calder's formula (Eq. A16) gives good estimate at large decoupling, see Table V.

3.3 Measured duration of the borehole pressure

The measured pressure period lasts from 30 to 500 μs.

When the LHM gage is placed upon a cable hole and beneath the explosive as in Figure 2, the pressure from the detonating explosive forces the LHM cup into the cable hole. The bottom of the LHM cup is compressed, squeezes the cable inside, causes at first a short-circuit in the cable and then cuts off the cable.

According to Eq. 1, a short-circuit in the cable causes the resistance in the circuit $R = 0$ and the corresponding pressure $P = +\infty$. On the other hand, a cut-off of the cable results in $R = \infty$ and $P = 0$.

As can be seen in Figure 3, all pressure histories were terminated by either a short-circuit or a cut-off of the cable. The measured durations of the borehole pressure were short due to this reason. Had the damage to the cable been less or occurred later, would the measured pressure durations have been longer. Therefore, protection of the cable is the only solution to achieve longer recordings.

4 Conclusions

The following conclusions can be drawn based on the analysis of the pressure measurements in six blast holes in granite blocks.

- The LHM method worked well and good pressure signals have been obtained.
- The signal cable from the LHM cup determines the measured pressure duration. It is believed that a better protection of this cable by e.g. grouting material will result in longer signal durations.
- A number of empirical formulas for explosion pressure and borehole pressure in decoupled holes have been collected. The predictions of those formulas have been compared with the measurements.
- The estimates of explosion pressure by four formulas differed within ±17 per cent around the average and the agreement with two measured explosion pressures is rather good.

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- Two formulas for borehole pressure in decoupled holes have been compared to the measurements. The agreement between the estimates and the measurements is generally very poor with estimation error from -11 to -75 per cent. Nevertheless, when decoupling ratio is large, Calder's formula provided good estimates, error within -14 per cent for a ϕ 16 mm charge in ϕ 38 mm hole.

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APPENDIX I: Empirical formulas for estimation of γ_{CJ}, explosion pressure and borehole pressure

Following symbols are defined:

D = velocity of detonation or VOD (m/s)
D_∞ = ideal VOD (m/s)
e_0 = internal energy of the explosive (J)
L_b = length of the blast hole (m)
L_e = length of the charge in a blast hole (m)
P = pressure (Pa)
P_0 = ambient pressure (Pa) = 1 atm.
P_b = borehole pressure in a decoupled blast hole (Pa) = P_e in a fully charged hole
P_{CJ} = detonation pressure (Pa)
P_e = explosion pressure (Pa)
q = heat of detonation (J/kg)
r_b = radius of the blast hole (m)
r_e = radius of the charge in a blast hole (m)
S = entropy (J)
v = volume (m^3)
v_b = volume of the blast hole (m^3)
v_e = volume of the charge (m^3)
γ = adiabatic coefficient = $-(\partial \ln p/\partial \ln v)_s$
γ_{CJ} = γ at the C-J state
ρ_0 = density of the unreacted explosive (kg/m^3 or otherwise specified)

1 Adiabatic gamma at C-J, γ_{CJ}

In the following, six empirical formulas for γ_{CJ} are presented.

Formula 1: according to Kamlet and Jacobs[A1], Kamlet and Dickinson[A2], Kamlet and Hurwitz[A3] and Kamlet and Short[A4], for ideal CHNO and CHNOF explosives at loading density exceeding 1 g/cm^3:

$$\gamma_{CJ} = 0.655/\rho_0 + 0.702 + 1.107\rho_0 \qquad [A1]$$

Here: ρ_0 in g/cm^3

Formula 2: according to Defourneaux[A5], for a CHNO high explosive:

$$\gamma_{CJ} = 1.9 + 0.6\rho_0 \qquad [A2]$$

Here: ρ_0 in g/cm^3

Formula 3: assuming that the detonation is ideal and the detonation gases follow the polytropic gas law with a constant γ value[A6]:

$$\gamma_{CJ} = \sqrt{1 + \frac{D_\infty^2}{2(q + e_0)}} \qquad [A3]$$

Formula 4: according to Wu[A7], for a high explosive having a chemical formula of $C_aH_bN_cO_d$:

$$\gamma_{CJ} = 1.25 + \gamma_0\left(1 - e^{-0.546\rho_0}\right) \qquad [A4]$$

Here: ρ_0 in g/cm^3 and

$$\gamma_0 = \frac{0.5b + c + d}{0.0482a + 0.446b + 0.2632c + 0.298d} \quad \text{when } d - \tfrac{1}{2}b - 2a \geq 0 \qquad [A5a]$$

$$\gamma_0 = \frac{a + 0.43b + 0.5c}{0.2857a + 0.2549b + 0.1316c + 0.018d} \quad \text{when } d - \tfrac{1}{2}b - 2a < 0 \qquad [A5b]$$

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$$\gamma_0 = \frac{a + 0.35b + 0.5c}{0.2857a + 0.2166b + 0.1316c + 0.018d} \quad \text{when } d\text{-}\tfrac{1}{2}b\text{-}a \le 0 \qquad [A5c]$$

$$\gamma_0 = \frac{a + 0.5b + 0.5c - 0.46d}{0.2857a + 0.147b + 0.1316c + 0.081d} \quad \text{when } d\text{-}\tfrac{1}{2}b \le 0 \text{ and } a \ge d \qquad [A5d]$$

$$\gamma_0 = \frac{a + 0.5b + 0.5c}{0.0734a + 0.147b + 0.1316c + 0.3d} \quad \text{when } d\text{-}\tfrac{1}{2}b \le 0 \text{ and } a < d \qquad [A5e]$$

Formula 5: for high explosive with $\rho_0 = 1 \sim 1.8$ g/cm^3 [A8]:

$$\gamma_{CJ} \approx 3 \qquad [A6]$$

Formula 6: according to Cooper[A8]:

$$\gamma_{CJ} = 1/(1.4035\rho_0^{-0.04} - 1) \qquad [A7]$$

Here: ρ_0 in g/cm^3

2 Explosion pressure or the borehole pressure in a fully charged blast hole, P_e

If the expansion of the detonating explosive from the C-J plane to the original explosive volume is assumed to obey the polytropic gas equation of state (EOS) or the γ-law EOS with a constant γ value and the ambient pressure P_0 is neglected, then the explosion pressure is exactly a half of the detonation pressure[A6], i.e.

$$P_e = \tfrac{1}{2} \cdot P_{CJ} = \tfrac{1}{2} \cdot \rho_0 D^2/(1+\gamma_{CJ}) \qquad [A8]$$

Besides this, further three empirical formulas are presented below.

Formula 1: according to Calder[A9]:

$$P_e = N(\rho_0)\, \rho_0\, D^2 \qquad [A9]$$

Here: $N(\rho_0)$ = a coefficient varying with ρ_0 [A9]

$= 0.235(\rho_0/1000)^{-0.57} - 0.08$ for $800 \le \rho_0 \le 2000$ [A10]

Formula 2: Gulf Oil Chemicals Company formula[A11]:

$$P_e = 0.1125\, \rho_0\, D^2 \qquad [A10]$$

Formula 3: according to Sanchidrian et al.[A12]:

$$P_e = 228\, \rho_0\, D^2/(1+0.8\rho_0) \qquad [A11]$$

Here: ρ_0 in g/cm^3

Formula 4: according to Ouchterlony[A10]:

$$P_e = \gamma^{\gamma}/(\gamma+1)^{(\gamma+1)} \cdot \rho_0\, D^2 \qquad [A12]$$

Here: $\gamma = \gamma_{CJ}$ and is calculated by Eq. A3.

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3 Borehole pressure in a decoupled blast hole, P_b

Assuming that the expansion of the detonating explosive from the original explosive volume to the borehole volume a) is an isentropic process and b) the adiabatic gamma (γ) is a constant along the isentrope, then the relation between the borehole pressure in a fully charge blast hole, P_e, and in a decoupled blast hole, P_b, can be reduced, as described below.

$\gamma = -\left(\frac{\partial \ln P}{\partial \ln v}\right)_s$ = constant, can be transformed to

Pv^γ = constant [A13]

Applying Eq. A13 to the expansion in a blast hole from P_e to P_b:

$$P_e v_e^\gamma = P_b v_b^\gamma \qquad [A14]$$

That is:

$$P_b = P_e \cdot \left(\sqrt{\frac{L_e}{L_b}} \cdot \frac{r_e}{r_b}\right)^{2\gamma} \qquad [A15]$$

It is difficult to assign an adequate γ value to this equation, since γ is really not a constant in the reality. It varies, among other factors, with the species of the detonation gases. However, it is known that when the detonation gases are expanded into a very large volume, approximately 20 times the original explosive volume, γ approaches a value of 1.2 to 1.3.

These two γ values, namely 1.2 and 1.3, have been used in empirical formulas as in Eqs. A16 and A17.

$$P_b = P_e \cdot \left(\sqrt{\frac{L_e}{L_b}} \cdot \frac{r_e}{r_b}\right)^{2.4} \qquad [A16]$$

Here: P_e is calculated by Eq. A9, according to Workman and Calder[A13].

$$P_b = P_e \cdot \left(\sqrt{\frac{L_e}{L_b}} \cdot \frac{r_e}{r_b}\right)^{2.6} \qquad [A17]$$

Here: $P_e = \rho_0 D^2/8$, according to Atlas Powder[A14].

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