A Study on Shock Wave Propagation Process in the Smooth Blasting Technique

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1. ABSTRACT

Explosives can easily generate high energy and ultra-high pressure. In recent years, research on the advanced technological use of explosives is studied in various places. Here we focus on the Smooth Blasting Technique that is applied for tunnel blasting. This technique is performed to fracture concrete and to reduce the quantity of fragments, while avoiding stress concentration of ground pressure during tunnel blasting. When this technique is used, it is important to know what influence it will have.

In our calculation code, the analysis of compressible substances, which cells transform greatly like air, was very difficult. In this study, we use LS-DYNA, an analysis code using a finite-element method. By analyzing the stress state of the air hole circumference, multilayer models such as air, Vinyl Chloride and water are analyzed and it aims to get the propagation process of the shock wave. The Arbitrary Lagrangian Eulerian (ALE) method is based on the arbitrary movement of a reference domain, which additionally to the common material domain and spatial domain, is introduced as a third domain. Three equations of state (EOS) are used in this study. The JWL equation of state is applied for the reaction of the explosive, and has form of a perfect gas equation of state. When the density becomes large, exponential terms modify the perfect gas equation of state. The Mie-Gruneisen equation of state is applied for water and poly vinyl chloride, and the linear polynomial equation of state is applied for air.

2. INTRODUCTION

In tunnel blasting and rock destruction, the noise and damage over the neighborhood cause problems. Various researches are performing in order to raise safety and to mitigate noise. One of these techniques is the Smooth Blasting Technique. This technique arranges explosives of more densely than usual along the most besides of a tunnel. The explosives are used to have small diameter for a hole and loading low density. This explosive softens shocking destructive power, and a natural ground is got using the expansion power of explosion gas. In the case of the smooth blasting, there are various examination matters, such as an interval, a resistance level, the method of explosive charge, and the amount of explosive charge.

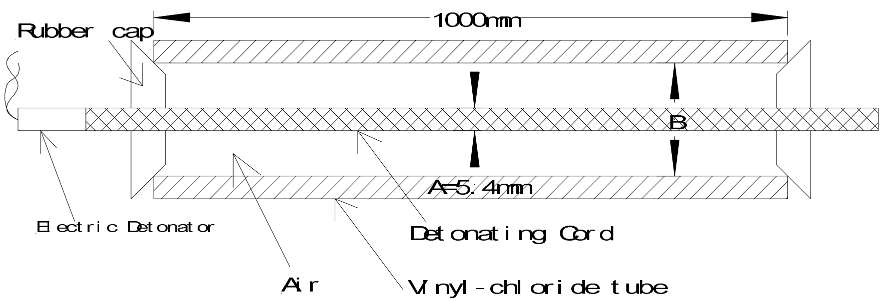
In recent years, these are many requests that it aims at improvement in digging efficiency by enlargement of a tunnel section. The optimization of the smooth blasting is demanded, because we must get the natural ground that changes in connection with tunnel advancing. In an experiment, detailed analysis is difficult. In this study, the shock wave generated from an explosive using LS-DYNA shows clearly how to propagate air, poly vinyl chloride and water.

LS- DYNA is used simulate large deformation material responses and dynamic processes and to solve the continuum equations for nonlinear responses of materials and structures. In this study, in order to check what influence the air between a rock and an explosive does in the case of smooth blasting, easy equipment was made, experiment and analysis were performed. When there are not the cases where there is air, and air, it is the purpose of this study that the shock wave from an explosive verifies what action gives to vinyl chloride and water.

3. EXPERIMENT

3.1 EXPERIMENTAL METHOD

Before performing numerical simulation by LS-DYNA, the experiment that checked how a shock wave propagates from a vinyl chloride tube by optical observation with a high-speed camera was conducted. The experimental setup is shown Figure 1. We have arranged water around this equipment and have observed an underwater shock wave. The tube of vinyl chloride was prepared three kinds and performed optical observation. The length of a tube is as follows and the decoupling ratio was 1.0, 1.9, and 2.4.



Decoupling ratio= Vinyl-chloride tube diameter ***B*** / Detonating cord diameter ***A***

Figure 1. Experimental setup

3-2. OPTICAL OBSERVATION OF UNDERWATER SHOCK WAVE WITH SHADOWGRAPH METHOD[1)]

The photography method used in this study is called shadowgraph method. The shadowgraph method is to observe and project the shadow of the light by density change on a screen or the film of a camera, and is also called direct projective technique. Both transparent medium and opaque medium can be visualized by using X-rays. The shadowgraph method is used for visualization of a shock wave or a motion of wave for many years.

The shadowgraph system and a high-speed camera (IMACON468 of HADLAND PHOTONICS, interframe times 10ns to 1ms in 10ns steps independently variable, number of channels framing:4 streak:1) were used to observe the underwater shockwave. The recorded a framing photograph and also by a streak photograph.

The principle of the shadowgraph method is shown in Fig. 3. We assume that density change is one dimension of vertical line. When a density change part does not exist in an observation medium, a screen is the same brightness. On the other hand, when a density change part exists in an observation medium, refractive index differ in the density change part. Therefore, when parallel light passes the density change part, as shown in Figure. 3, light is refracted and makes the image which has the shade of brightness on a screen. This shade of brightness is recorded on the film of a photograph, and is observed.

The optical system used for the optical observation experiment is shown in Figure. 4. The light source in photography uses the XENON flashlight of 50 microseconds of glint-of-light time. The image converter camera can take a photograph of high-speed phenomena, such as propagation of a shock wave, and high-speed flying plate, it is possible to take a photograph of streak photograph and framing photograph at the same time.

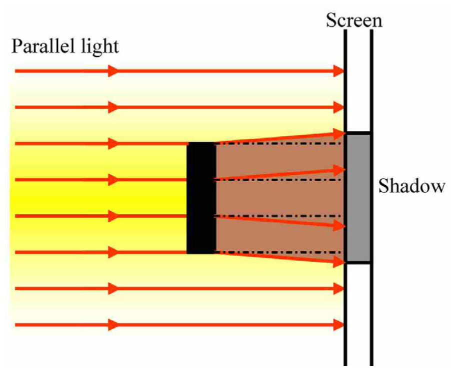


Figure 2. Principle of shadowgraph method

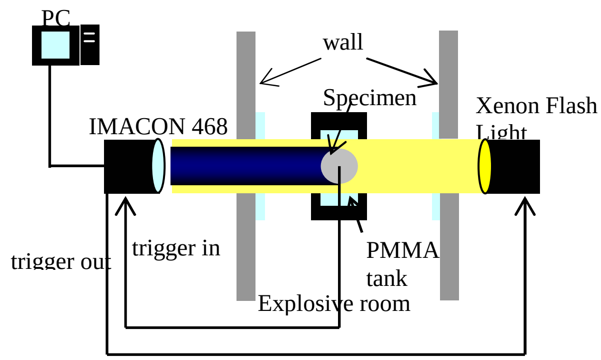


Figure 3. Schematic illustration of optical system

The streak photograph is taken in a streak slit on the center of Figure 1. A horizontal axis is time axis and its right directions is positive, a vertical axis is distance axis and its up direction is positive in the streak photograph of underwater shock wave shown in Figure 4. Figure 5 is the inclination diagram obtained from the streak photograph in the case that the decoupling ratio was 1.0, 1.9 and 2.4. We can get shock wave velocity from Figure 5. Since there is no air layer in ratio1.0, this case has a shock wave velocity larger than ratio1.9. However, although the air layer has spread in ratio2.4, shock wave velocity is increasing. In Figure 4, since the shock wave had not spread symmetrically in the upper part and the lower part of a vinyl chloride tube, it is possible that this have had a problem in the set of detonating cord. In Figure 4, the reflective wave that the shock wave reflected between detonating cord and the vinyl chloride tube can see also in the layer of water.

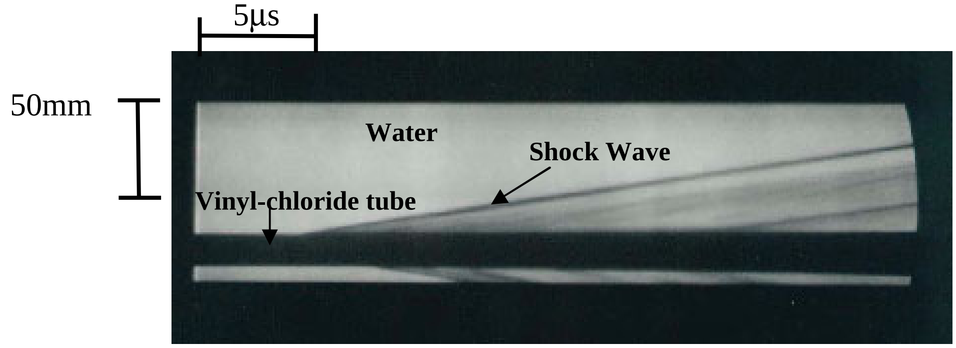


Figure 4. Streak photograph (decoupling ratio = 2.4)

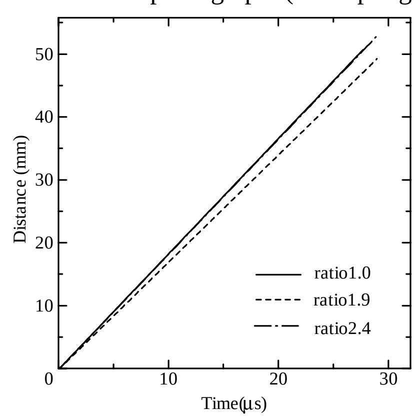


Figure 5. Inclination diagram for underwater shock wave

4. NUMERICAL SIMULATION METHOD

4.1 NUMERICAL SIMULATION MODEL

The Numerical simulation model is shown in Figure 6-1 and Figure 6-2. This model has adopted 1/4 model of a pillar for calculating space reduction. The units for this study were: “millimeters (mm)” for length. “Kilograms (kg)” for mass, “Giga Pascal (GPa)” for pressure, and “milliseconds” (ms) for time. In this numerical analysis, since the parameter of detonating cord was not found, the parameter of PETN (detonation pressure 22.0GPa, detonation velocity 7450m/s, density 1500kg/m^3) was used. PETN is basis explosive of the detonating cord, and the detonating cord is made from binding paper etc. around the surroundings of PETN. The radial direction is set to d_p (PETN part=2.7mm), d_a (air part), d_v (vinyl chloride tube=3mm) and d_w (water part=50mm). The used rubber is density =1300kg/m^3 and shear modulus =0.0005GPa. The air part was changed and numerical analysis was carried out. We evaluated about effect about of air from pressure histories.

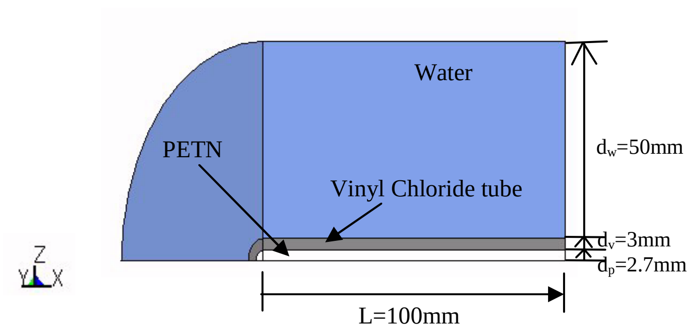


Figure 6-1. Numerical simulation model (ratio=1.0)

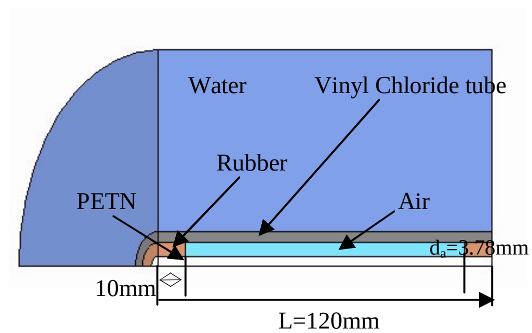


Figure 6-2. Numerical simulation model (ratio=2.4)

4.2 ALE FORMULATION

Numerical analysis was carried out using the Arbitrary Lagrangian Eulerian (ALE) approach. An ALE formulation contains both pure Lagrangian and pure Eulerian formulations. This has combined the Lagrange method which observes change of the velocity, acceleration, etc. paying attention to arbitrary fluid particles, and the Euler method for dealing with change of physical quantity, such as velocity and pressure, as function for the position of the point and time in space. We used the Multi-Material ALE Formulation[2)] to PETN and air. Two levels of ALE technology exist. One allows ALE behavior only within a material (forcing material boundaries to remain Lagrangian). The second level of ALE technology allows multi-material elements to form and is therefore more generally applicable.

4.3 EQUATION OF STATE

The equation of state for an explosive in this study was used Jones-Wilkins–Lee (JWL) equation[3)]. This equation is shown below and each coefficient is shown in Table 1.

JWL equation

$$P_{JWL} = A\left[1-\frac{\omega}{VR_1}\right]\exp(-R_1V) + B\left[1-\frac{\omega}{VR_2}\right]\exp(-R_2V) + \frac{\omega e}{V}$$

V= ρ_0 (Initial density of an explosive) /ρ (Density of detonation gas)
P_{JWL} : Pressure e : Specific internal energy
A,B,R_1,R_2,ω : JWL parameter

Table 1. JWL parameter of PETN

A (GPa)	B (GPa)	R_1	R_2	ω
625.3	23.29	5.25	1.60	0.228

About the handling of the detonation phenomenon in this analysis, "C-J Volume Burn" was used. In C-J Volume Burn, the decomposition rate W of the explosive was calculated with the specific volume of the cell, and the detonation state of a cell determines by the decomposition rate of each cell. The decomposition rate of the explosive was calculated by the following formula.

$$W_{i,j}^{n+1} = 1 - \frac{V_0 - V_{i,j}^{n+1}}{V_0 - V_{CJ}}$$

Where V_0 is initial specific volume of the explosive, and V_{CJ} is specific volume of C-J state of the explosive. Then $P_{i,j}^{n+1}$ that is the pressure in the cell can be found from the following formula using W_j^{n+1} and P_{JWL} given from JWL equation.

$$W_j^{n+1} < W_j^n \quad P_{i,j}^{n+1} = (1 - W_{i,j}^{n+1}) P_{JWL}$$

The equation of state for water and vinyl chloride tube in this study was used Grüneisen equation.

Grüneisen equation

$$P = \frac{\rho_0 c_0^2 \mu \left[1 + (1 - \frac{\gamma_0}{2})\mu - \frac{a}{2}\mu^2 \right]}{\left[1 - (s_1 - 1)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{(\mu + 1)^2} \right]^2} + (\gamma_0 + a\mu)e$$

Deformation of this equation obtains Mie-Grüneisen equation[4].

Mie-Grüneisen equation is shown below and each coefficient is shown in Table 2.

Mie-Grüneisen equation

$$P = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2} \left[1 - \frac{\Gamma_0 \eta}{2} \right] + \Gamma_0 \rho_0 e$$

η= 1-ρ_0 (Initial density of the medium) /ρ (Density of the medium)
P : Pressure e : Specific internal energy
C_0,s : Constant of material Γ_0 : Grüneisen coefficient

Table 2. Mie-Grüneisen parameter of water and vinyl chloride tube

	ρ_0 (kg/m^3)	C_0 (m/s)	S	Γ_0
WATER	1000	1490	1.79	1.65
Vinyl Chloride tube	1380	2300	1.47	0.40

The equation of state for an air in this study was used Linear Polynomial equation. This equation is shown below and each coefficient is shown in Table 3.

Linear Polynomial equation

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E$$

The linear polynomial equation of state may be used model gas with the gamma law equation of state. This may be achieved by setting.

$$C_0 = C_1 = C_2 = C_3 = C_6 = 0$$

and

$$C_4 = C_5 = \gamma - 1$$

Where γ is ratio of specific heats.

Table 2. Linear polynomial parameter of air

	ρ_0(kg/m^3)	γ	C_4	C_5
Air	1.025	1.403	0.403	0.403

5. NUMERICAL SIMULATION RESULTS AND DISCUSSION

The pressure contours in the case that decoupling ratio=1.0 and decoupling ratio= 2.4 are shown in Figure 7.The explosive detonates from the part on the extreme left which gave initial detonation.

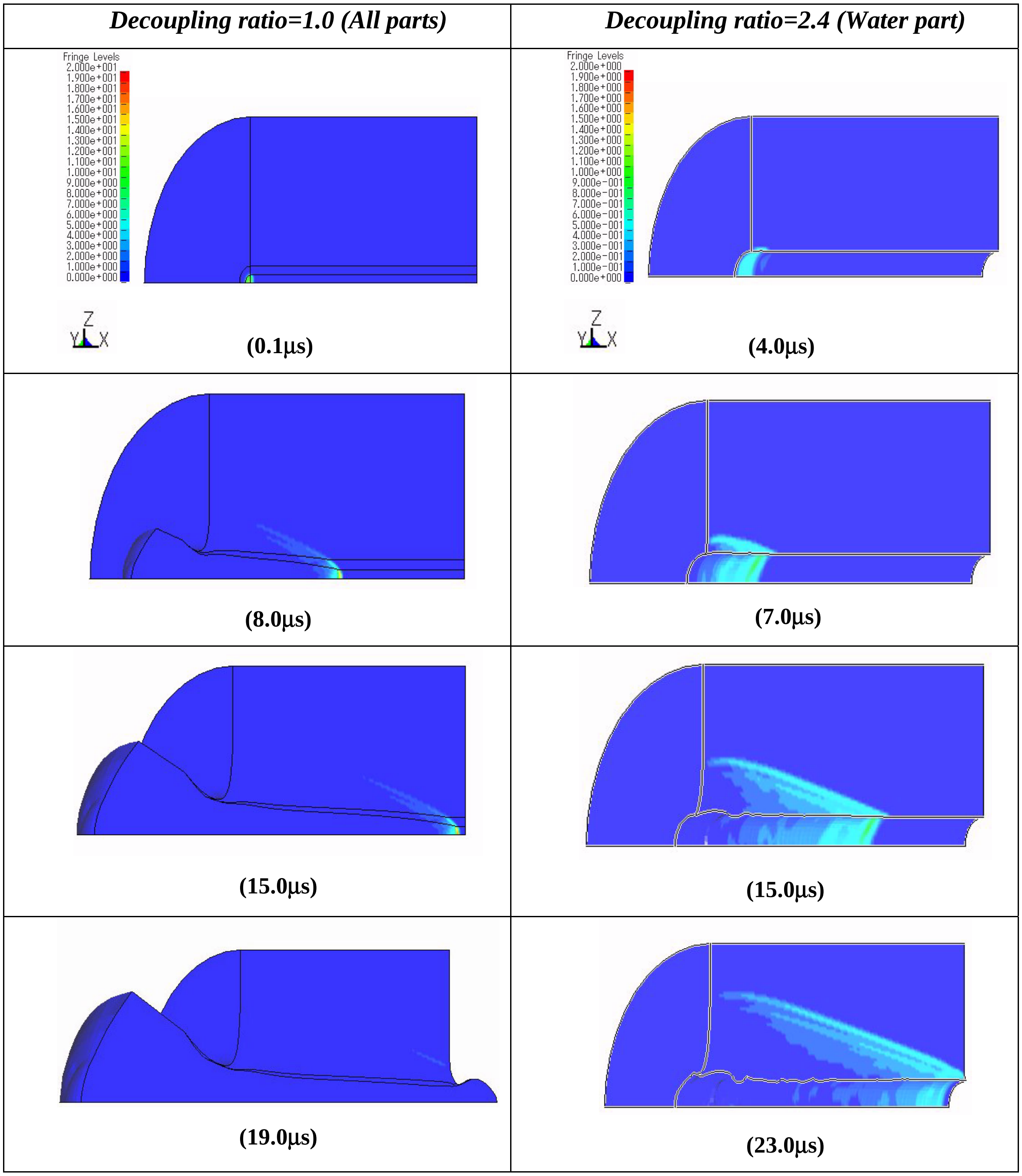
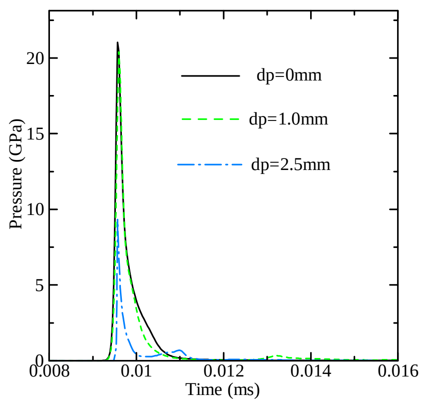
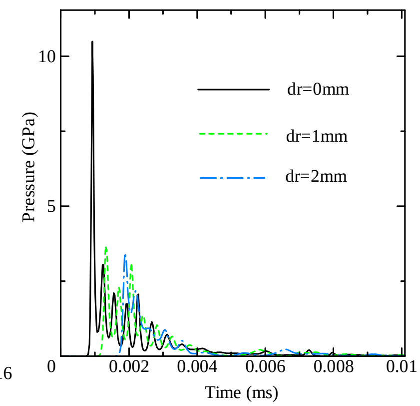


Figure 7. Pressure contours (decoupling ratio=1.0 and decoupling ratio=2.4)

In pressure contours of decoupling ratio 1.0, shock wave propagates to vinyl chloride tube part and water part. The reflective wave can clearly see in water part of decoupling ratio 2.4.

In the decoupling ratio 2.4, the pressure histories of the all parts were shown from Figure 8-1 to Figure 8-5, respectively. The measure points of the pressure history are distance for z-direction of each material. PETN generally propagates about C-J (Chapman-Jouguet) pressure at all portions. The performance of explosive depends on its own chemical property, the pressure is so called C-J pressure. In d_p=0mm and d_p=1.0mm, although PETN detonates by C-J pressure, since d_p=2.5mm is around a boundary with air, it is the pressure below the half of C-J pressure. It is shown that increasing of the pressure value in addition to a peak pressure value by the influence of reflective waves in the vinyl chloride tube and the water.





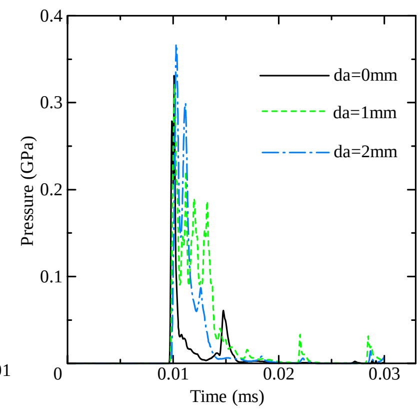


Figure 8-1. Pressure histories (PETN) **Figure 8-2.** Pressure histories (Rubber) **Figure 8-3.**Pressure histories (Air)

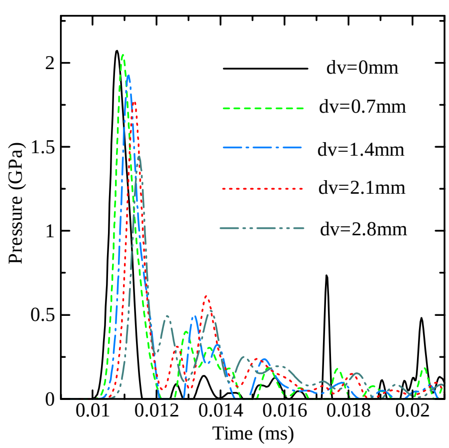


Figure 8-4. Pressure histories (Vinyl Chloride tube)

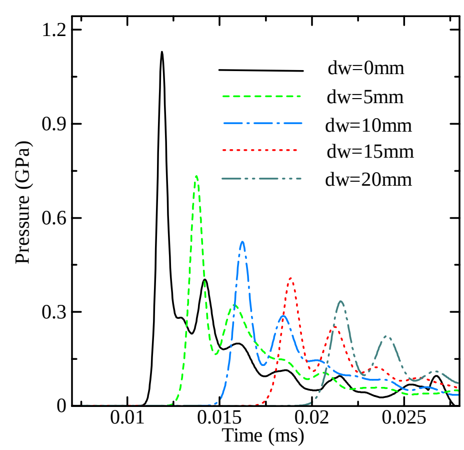


Figure 8-5. Pressure histories (Water)

Table 4 shows the pressure value on each point of PETN, Rubber, Air, Vinyl Chloride tube and Water, respectively. L is the distance (mm) from the extreme left. In the layer of PETN, since the material that has covered the surroundings is different, the difference of pressure value about 1 GPa is proved in the decoupling ratio 1.0, 1.9, and 2.4. When there is an air layer, it turns out well that it influences greatly in the initial pressure value which a vinyl chloride tube and water receive. However, no difference of a pressure value can almost be checked in the point of 40mm on a water layer. In other words, it is possible that the convergence value of pressure does not change so much.

Table 4. Pressure value on each point

	PETN	*Rubber*	*Air*	*Vinyl Chloride*	*Water*	
	$L=60\ d_p=0$	$L=5\ d_r=0$	$L=60\ d_a=0$	$L=60\ d_v=0$	$L=60\ d_w=0$	$L=60\ d_w=40$
ratio 1.0	22.049	-	-	10.118	2.873	0.308
ratio 1.9	21.027	10.494	0.279	2.066	1.130	0.177
ratio 2.4	21.139	10.117	0.247	1.162	0.733	0.126

unit of pressure=GPa

6. CONCLUSION

In this study, when the smooth blasting technique is used, it verified what influence a high explosive would have on water or air. The emulsion explosive is generally used for the smooth blasting technique. But it analyzed not using emulsion explosive but using PETN in this study. The process in which a shock wave propagated water and air using PETN was analyzed. In our calculation code, the analysis of compressible substances, which cells transform greatly like air, was very difficult. But we use LS-DYNA, it succeeded in analyzing multilayer models such as air, vinyl chloride and water.

References

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