827. Influence of concave groove on transmission of blasting vibration wave

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Abstract. With the extensive application of blasting techniques, the prediction and hazard control of explosion-induced vibration is an important issue which cannot be ignored in blasting engineering. A numerical approach is presented to study the explosion-induced pressure load on the surface of C-4 explosives in a semi-infinite space, in order to explore the effectiveness of concave grooves in ground vibration wave barrier. Numerical simulations are carried out by using a widely applied explicit dynamic nonlinear finite element software LS-DYNA and adopted the Arbitrary Lagrangian-Eulerian method for numerical analysis to simulate the propagation of blast waves. The analysis shows that the concave grooves have a significant effect on attenuating the propagation of detonation waves. The vibration control is related to the width and depth of the groove, and the impact of the depth is greater than that of the width. This study can be used as a reference in hazard control of explosion-induced vibration.

Keywords: blast, concave groove, wave barrier, vibration control, ground vibration.

1. Introduction

Blasting is the main construction method for rock and soil excavation. With the extensive application of blasting techniques, the prediction and hazard control of explosion-induced vibration play a very important part in engineering design and construction, and they have become important issues for experts, scholars and engineering technicians. To ensure that the vibration cannot affect the structural safety of buildings, there is an urgent demand for hazard control of explosion-induced vibration. The following are 3 general methods for the hazard control of explosion-induced vibration [1]:

(1) Control the explosive source.
(2) Control the protected object and fit it with dampers.
(3) Take measures for the propagation of seismic wave by excavating the damping groove to interrupt the propagation path.

When explosives explode on or near the ground surface, the seismic waves will be triggered by the air shock wave. Blast waves are first transmitted in the form of underground shock waves, and then transformed into elastic seismic waves, inducing the vibration of the surface mass point. In addition, the soil stress waves generated from the compression of the air shock wave on the ground surface also convert into elastic seismic waves [2]. Therefore, when there is an explosion on the ground surface, these two types of blast waves can be detected in the soil simultaneously. Near the explosive point, the velocity and intensity of the air shock waves are higher. Relatively, the velocity and intensity of the corresponding soil stress waves are also higher. These are the key parameters affecting ground vibrations [3].

The propagation of blast waves in the soil/rock medium is subject to the medium characteristics and charge parameters. But the impact of surface grooves on the propagation of blast waves is very great. Currently, the foundation for investigating the parameters of explosion-induced vibration in blasting engineering lies on the perspective of energy conversion in the explosion, as well as the theory of conservation of mass, energy and momentum in the propagation of detonation and shock waves. Based on the aforementioned engineering properties, the analysis of impact and damage of the explosion-induced vibration on the protected object can be evaluated from the velocity, acceleration, stress and displacement of the vibration. In engineering constructions, the peak of vibration velocity at the vertical mass point is often considered as the highest intensity of the explosion-induced vibration. Therefore, for explosions on or near ground surface, the analysis of hazard scale is mainly based on the propagation characteristics of the air shock wave and the vibration intensity of the ground surface. Varghese and Shankar (2011) [4] combined power flow balance and conventional acceleration matching has been used for the identification of structural parameters in the time domain. The results demonstrate that the proposed combined method is more accurate in identifying the structural parameters of a system compared to conventional acceleration based matching methods. Spyros and Fotis (2004) [5] used the finite element method to analyze the propagation of blast waves in the undulating terrain and discovered that the mass point vibrations were strong in protruding landforms, but weak in concave landforms. By exploring methods for reducing the explosion-induced vibrations, the damping rate of concave landforms was found to be up to 30~50 % [6]. However, the damping effect decreased with the increasing distance to the explosive source. From field experiments, Zhang (2000) [7] discovered that when the blast waves passed through the concave landforms, the attenuation coefficient of peak velocity was between 4.7 % and 87.0 %, and the attenuation degree was related to the scale of concave topography. Li Weixue et al. (1998) [8] looked into actual engineering cases to analyze the relationship between the attenuation of blast waves and the concave topography and geological structure. Real et al. (2012) [9] demonstrate the most relevant parameters in a trench are its width, depth and in-filled material or trench typology.

Hazard control of explosion-induced vibration is an important issue in blasting engineering. When the scale of blasting vibration exceeds the safe range, it will cause damage to buildings in the strata layer or on the ground surface; thus, it is necessary to master and control its patterns in order to reduce the hazard scale. In order to understand the vibration isolation effect of concave grooves, the hydrodynamic code-LS-DYNA was used as the analysis tool in this study to simulate the impact of blast waves on the ground surface when the explosives explode on the ground surface. The objectives were to provide relevant vibration reduction measures for engineering, control the vibration effect of explosion, ensure the safety of nearby protected objects, and provide references to future studies and engineering applications.

2. Numerical methods

In order to carry out a thorough investigation on the influence of concave grooves on the propagation and vibration of blast waves, the Finite Element Method (FEM) in LS-DYNA was adopted in this study. FEM can compute both explicit and implicit solutions based on the fluid-solid coupling Arbitrary Lagrangian-Eulerian (ALE) numerical model which adopts both Lagrangian and Eulerian algorithms. The ALE model can adequately describe the hydrodynamic behavior of the explosion-induced gases, effectively analyze their coupling with solids, and resolve the dynamic analysis problem of geometric nonlinearity, material nonlinearity and contact nonlinear for structural materials. The empirical formulas in the U.S. Army Technical Manual TM5-855-1 [10] are also used to simulate the explosion of explosives on the ground surface and verify the isolation effectiveness of concave grooves.

2. 1. Arbitrary Lagrangian-Eulerian (ALE) technique

This study used the Arbitrary Lagrangian-Eulerian (ALE) technique for numerical analysis to investigate the coupling of explosives, air and soil in an explosion. ALE description uses

Eulerian (spatial description) description for fluids and Lagrangian (material description) for solids, to avoid any severe distortion of mesh elements which can interrupt the numerical computation. It can effectively control boundary activities to facilitate the dynamic analysis of fluid and solid coupling. Hirt, Amsden, Cook (1974) proposed ALE description and solved the following equations [11]:

Mass conservation equation

$$\frac{d}{dt}\int_{s(t)} pdv = -\int_{\partial s(t)} \rho(u - v_w)\cdot nds. \tag{1}$$

Momentum conservation equation

$$\frac{d}{dt}\int_{s(t)} pudv = -\int_{\partial s(t)} \rho u(u - v_w)\cdot nds - \int_{s(t)} \nabla \cdot pdv. \tag{2}$$

Energy conservation equation

$$\frac{d}{dt}\int_{s(t)} pIdv = -\int_{\partial s(t)} \rho I(u - v_w)\cdot nds - \int_{s(t)} pu\cdot nds. \tag{3}$$

where $S(t)$ is an active area in space, $\partial s(t)$ is its boundary and v_w is the velocity of $\partial s(t)$.

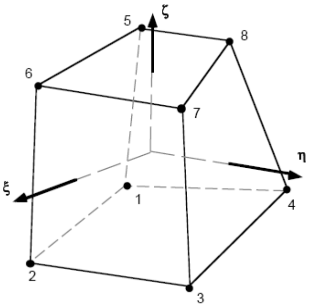
For Eqs. (1) ~ (3), when the mesh velocity is 0 ($v_W(t) = 0$), it is a Eulerian description; when the mesh velocity equals the material velocity ($v_W(t) = u$), it is a Lagrangian description; otherwise, the equations are between Eulerian and Lagrangian descriptions. The characteristic of ALE description lies in the construction of a suitable mesh according to the boundary of the material region, in order to avoid computations on meshes with severe distortion. ALE description resolves the individual drawbacks of Eulerian and Lagrangian descriptions and can handle problems such as explosions and high velocity impact.

2. 2. Element type

The analysis of the finite element method has to use different element types based on the characteristics of the problem. In this study, the analysis is done by using the ALE method with three-dimensional 8-node solid elements. Elements are defined as 8-Node. In *X*, *Y* and *Z* directions, there is a degree of freedom in translation. Together with degrees of freedom in velocity and acceleration, there are in total nine degrees of freedom for each node. The volume cannot be zero in case of compressive stress or drastic distortion. The shape function of 8-Node solid elements is defined as in Eq. (4) [12]; Fig. 1 is the demonstration of a solid element:

$$\phi_j = \frac{1}{8}\left(1 + \xi\xi_j\right)\left(1 + \eta\eta_j\right)\left(1 + \zeta\zeta_j\right), \tag{4}$$

where ξ_j, η_j and ζ_j are the natural coordinates of the unit, and depending on the location, the node values are ± 1.



Node	ξ	η	ζ
1	-1	-1	-1
2	1	-1	-1
3	1	1	-1
4	-1	1	-1
5	-1	-1	1
6	1	-1	1
7	1	1	1
8	-1	1	1

Fig. 1. Schematic diagram of a solid element [12]

2. 3. Time integration

Analyzing explosion-induced vibration is a transient dynamic problem. Its differential equations are related to the derivatives of time and space, and the numerical solution must be able to deal properly with time integration. Such integral methods can be roughly divided into two categories: explicit time integration and implicit time integration. The explicit approach uses the solution of the previous time point to derive the solution of the next time point; the implicit approach uses iterative methods to find the solution.

In general, the time interval Δt used in explicit time integration requires small time increments to avoid large calculation error. LS-DYNA software mainly uses explicit time integration, which is a conditional stability; the numerical integration is based on two basic concepts [13]:

(1) Only equations in a discrete time interval Δt can meet the equation of motion.

(2) The changes of translation, velocity and acceleration are given in time interval Δt : between t_j and t_{j+n} , time interval Δt is divided into n parts. That is, $t_j = t_j + T$, $T = n\Delta t$ and the solution of time t at any point will be the initial condition of the next time point $t + \Delta t$. The overall time integration is built on the approximate solution of individual time.

Analysis of explosion-induced vibration is a transient dynamic problem, and explicit time integration is more suitable for solving this problem. In the finite element method, Δt is related to the geometric conditions of elements and material velocity. The stability conditions of Δt for 8-Node Solid Element are as follows:

$$\Delta t_e = \frac{L_e}{\left\{\left[Q + \left(Q^2 + c^2\right)^{1/2}\right]\right\}}, \tag{5}$$

where $L_e = \dfrac{v_e}{A_{e\max}}$,

$$c = \left[\frac{4G}{3\rho_0} + \left(\frac{\partial p}{\partial \rho}\right)_s\right]^{1/2}. \tag{6}$$

The wave propagation velocity of regular elastic materials is defined as:

$$c = \sqrt{\frac{E\left(1-\upsilon\right)}{\left(1+\upsilon\right)\left(1-2\upsilon\right)\rho}}. \tag{7}$$

where Q is the bulk viscosity coefficient; L_e is a characteristic length; v_e is the element volume; $A_{e\max}$ is the area of the largest side; c is the material wave velocity; ρ is the specific mass density; E is Young's modulus; and υ is Poission's ratio.

The minimum time interval (Eq. 8) of the element, i.e., the smallest mesh unit is used in the solving process and determines the calculation accuracy, stability and computation time. For stability, usually $\alpha \le 0.9$ is used. In explosion simulations, $\alpha \le 0.67$ is used [14]:

$$\Delta t^{n+1} = \alpha \cdot \min\left\{\Delta t_1, \Delta t_2, \Delta t_3, \cdots, \Delta t_N\right\}, \tag{8}$$

where N : number of elements.

3. Implementation of the numerical simulation

The objective of this study was to investigate the vibration isolation effect of concave grooves in Surface Blasts. LS-DYNA was used as the analysis tool to investigate the impact of blast waves on the ground surface when C-4 explosives explode on ground surface. The fluid-solid coupling method was used to simulate the explosion experiment. The explosives and air were set as Eulerian meshes, and soil was the Lagrangian mesh to construct the fluid-solid coupling numerical analysis model in order to analyze the explosion-induced shock wave and acceleration of the ground surface.

3. 1. Analysis model

The analysis model was built on 8-Node Solid Element and adopted the ALE algorithm. The units were cm, g, μs. Air dimensions were $450 \times 350 \times 450\ (\text{cm})$. The boundary was defined as non-reflecting to simulate the explosion in the infinite zone; for rectangle C-4 explosives, weight was $1600\ \text{g}$, density was $1.601\ \text{g/cm}^3$, dimensions were $5 \times 10 \times 5\ (\text{cm})$ and the model center contacted the ground surface; soil dimensions were $450 \times 250 \times 450\ (\text{cm})$. Because of the model symmetry, only a 1/4-size model was used in the analysis. The finite element mesh dimensions of air, explosive and soil were $5\ \text{cm}$, $5\ \text{cm}$ and $10\ \text{cm}$, respectively. The width and depth of the concave groove were $50 \times 50\ (\text{cm})$, $50 \times 75\ (\text{cm})$, $50 \times 100\ (\text{cm})$, $25 \times 50\ (\text{cm})$, $25 \times 75\ (\text{cm})$, $25 \times 100\ (\text{cm})$ and $25 \times 120\ (\text{cm})$, respectively, to measure the blast pressure in free field and the acceleration before and after the grooves in order to investigate its vibration isolation effectiveness. Fig. 2 is an illustration of the analysis model.

3. 2. Overall material models and equation of state

An equation relating the pressure, specific volume and temperature of a substance is known as an equation of state (EOS). In order to effectively simulate the explosion, in addition to basic parameters of material type, equations of state also need to be set at the same time.

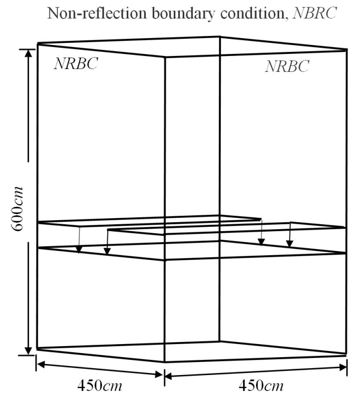


Fig. 2. Schematic diagram of the 1/4 analysis model

3. 2. 1. Soil

The selection of soil composition should take into account the material porosity and its crushing or compacting behavior. The soil composition model of this study was proposed by Krieg (1972) [15], and was also called Simple Elastic-Plastic. Taking isotropic plasticity theory as the starting point, there is compressible plasticity in the material. This model can be used in porous material, such as soil, rock and concrete. Based on the above description, the experimental parameters of [16] were used for analysis, and the relevant parameters are given in Table 1.

Table 1. Main parameters in the soil model

ρ (g/cm^3)	G (MPa)	K_u (MPa)	a_0	a_1	a_2	p_{cut} (MPa)
1.8	0.000639	0.3	3.4×10^{-13}	7.03×10^{-7}	0.3	-6.9×10^{-8}

3. 2. 2. Air

This study used the LS-DYNA's No. 9 *MAT_NULL material model to simulate air, and equations of state *EOS_LINEAR_POLYNOMIAL were used to describe the material model as in Eq. (9) [12]:

$$P = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + \left(C_4 + C_5\mu + C_6\mu^2\right)E, \tag{9}$$

$$\mu = \frac{1}{V} - 1,$$

where E is the internal energy per initial volume, μ is the coefficient of dynamic viscosity, C_1, C_2, C_3, C_4, C_5, C_6 are constants, and V is the relative volume. The relevant parameters are given in Table 2.

Table 2. Main parameters in the air model

ρ (g/cm^3)	E_0 (J/m^3)	v_0 (g/cm^3)
1.29	2.5×10^5	1.0

The ideal-gas equation can be simplified as Eq. (10) (set C_1, C_2, C_3, C_4, C_5, $C_6 = 0$, and let $C_4 = C_5 = \gamma - 1$):

$$P = (\gamma - 1)\frac{\rho}{\rho_0}E, \tag{10}$$

where γ is the ratio of specific heats of air, ρ_0 is the initial value of air density and ρ is the current air density.

3. 2. 3. Explosive

The No. 8 *MAT_HIGH_EXPLOSIVE_BURN material model was used to simulate the high explosive model. Eq. (11) is the JWL (Jones Wilkins Lee) EOS for high explosives [17]:

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}, \tag{11}$$

where A, B, R_1, R_2 and ω are constants pertaining to the explosive, V is the relative volume and E_0 is the initial energy per initial volume. The relevant parameters are shown in Table 3.

Table 3. Main parameters in the C-4 model

ρ (g/cm^3)	v_D (cm/μsec)	P_{CJ} (Mbar)	A (Mbar)	B (Mbar)
1.601	0.8193	0.28	5.0977	0.1295
R_1	R_2	ω	V	E_0 (J/m^3)
4.5	1.4	0.25	1.0	0.09

4. Numerical results and discussion

4. 1. Comparison of numerical results by the TM5-855-1 manual

In general, ground vibration induced by Surface Burst consists of two parts: (1) the blast wave passes through air by air stress, and is called air-induced ground motion; (2) the blast wave propagates directly from the explosive point to the ground surface, and is called direct-transmitted ground shock [2]. The U.S. Army Corps of Engineers in the regulations of TM5-855-1 manual undertook a series of field explosion tests. Based on the data obtained from the explosion tests, the numerical simulation concluded the empirical formulas of the propagation behavior of the blast wave induced by the surface explosion in soil. Therefore, this study used the calculated value of the empirical formulas in the manual as a reference to verify the reliability of the simulation.

Figs. 3-6 show the variation of blast wave over time in the semi-infinite soil medium. Fig. 7 show the pressure-time histories curves under different distances conditions. In order to understand the propagation pattern of the blast wave, the peak detonation pressure values at locations with $100\,\mathrm{cm}$, $200\,\mathrm{cm}$, $300\,\mathrm{cm}$ and $400\,\mathrm{cm}$ horizontal distance to the explosive center point were investigated, respectively. Fig. 8 presents the correlation between the peak detonation pressure and the horizontal distance; it is clear that the peak detonation pressure decreases with the increasing of propagation distance. The simulation results are very similar to the empirical formulas in TM5-855-1. The difference is caused by the different experiment media but as a whole, the energy attenuation characteristic of the blast wave is consistent. Therefore the credibility of the analysis model in this study can be verified to further investigate the vibration isolation effectiveness of concave groove to Surface Blast.

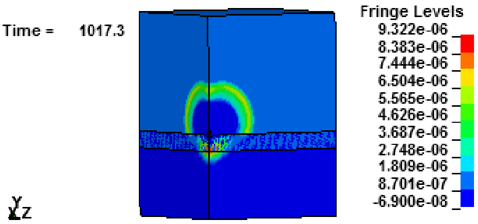


Fig. 3. Contours of pressure in $t = 1017.3$ μs

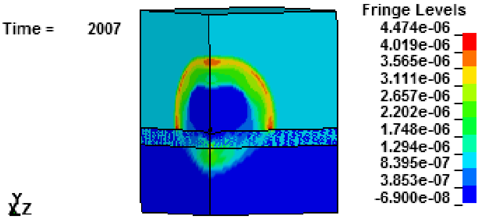


Fig. 4. Contours of pressure in $t = 2007$ μs

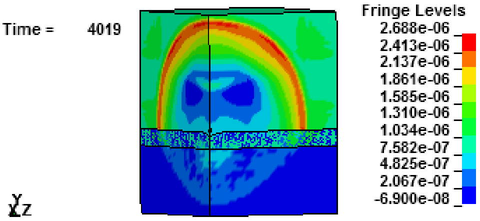


Fig. 5. Contours of pressure in $t = 4019$ μs

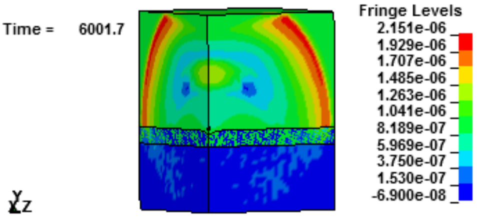


Fig. 6. Contours of pressure in $t = 6001.7$ μs

4. 2. Influence of concave groove width and depth on blast wave propagation and ground acceleration

The simulation results of different cases are listed in Table 4. In cases 1-3, with certain blasting energy, fixed model depth and proportionally increasing model width, the detonation pressure decreases with the increasing width. In cases 4-6, with fixed model width and proportionally increasing depth, the detonation pressure decreases with the increasing depth, and the decreasing scale is larger than in cases 1-3. The experimental model of case 7 has greater depth and smaller width compared to the previous 3 cases, but its decreasing scale of detonation pressure is the largest. From the above results, the depth of concave grooves has a larger impact on the attenuation of detonation pressure, which is consistent with the conclusions of Zhang et al (2000) [7]. In conclusion, the concave groove has a significant impact on the attenuation of the blast wave propagation, and the attenuation degree correlates with the width and depth of the groove. Also, the attenuation effect of depth is larger than width.

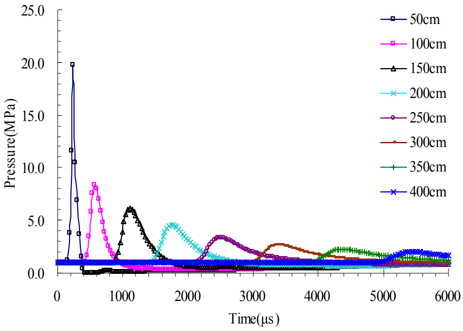


Fig. 7. Pressure-time histories curves under different distances condition

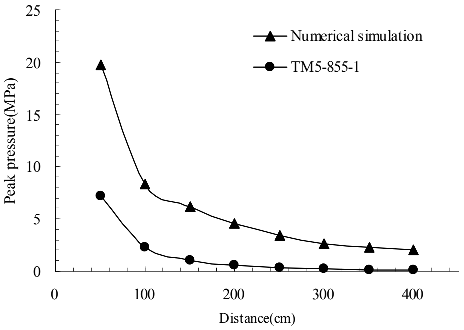


Fig. 8. Comparison of the peak pressure in the numerical simulation and TM5-855-1 empirical

Table 4. The simulation results of different cases listed

	Concave groove					
	Depth (cm)	Width (cm)	Peak pressure (MPa)		Peak acceleration ($cm/\mu s^2$)	
			Before (10 cm)	After (10 cm)	Before (10 cm)	After (10 cm)
Case 1	50	50	4.56	2.67	22.5292	6.9521
Case 2	50	75		2.41		6.3715
Case 3	50	100		2.17		4.8592
Case 4	50	25		3.32		11.3379
Case 5	75	25		3.31		3.2297
Case 6	100	25		3.21		0.0444
Case 7	120	25		2.05		0.0292

5. Conclusions

The propagation and attenuation of explosion-induced blast waves in the stratum medium depend mainly on the geological characteristics and blasting parameters. However, in highly undulating terrains, the propagation of the blast waves is affected by the local topography. This study used numerical simulation to analyze the attenuation of blast waves according to the changes of concave grooves, in order to explore the propagation patterns of blast waves. The results show that the finite element method can properly simulate the dynamic characteristics of soil in an explosion. From the dynamic characteristics of soil after an explosion, we can know that when moving away from the explosive source, the propagation of the blast wave gradually attenuates. This gives a preliminary understanding of the explosive phenomenon of C-4 explosives on the ground surface. Moreover, the concave groove has a significant impact on the attenuation of blast wave propagation, and the attenuation scale is related to the width and depth of the groove; depth has a larger impact on attenuation than width. This study can be used as a reference in blasting protection design and damping operation for relevant engineering.

Acknowledgements

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