Article ID: 1000-5773(2007)03-0242-07

Study on Penetration of Concrete Targets by Ogive-Nose Steel Projectile*

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Abstract: We conducted acceleration-time measurement of penetration experiments in targets with 100 mm diameter, 4.0 caliber-radius-head, 25 kg projectiles. The 3 m×3 m×3m and 2 m×2 m×2m concrete targets had an nominal unconfined compressive strength of 35 MPa and density 2 450 kg/m^3. Projectiles were designed to contain a single-channel acceleration data recorder, so we recorded accelerations in the bore of the gun and accelerations during the penetration event. A 100 mm diameter powder gun launched the 25 kg projectiles to striking velocities between 310 and 632 m/s. We compared the measured penetration depths and acceleration-time data with the calculated results using Forrestal formula. The calculated results are in good agreement with rigid-body acceleration measurements for the rise times and peak plateau responses. The acceleration-time data of projectiles can be helpful for devising armour-piercing projectile and defense engineering.

Key words: explosion mechanics; penetration; concrete target; ogive-nose projectile; acceleration-time measurement

CLC number: O385 **Document code**: A

1 Introduction

The penetration experiments attempt to provide a fundamental understanding of the penetration processes for concrete targets. The acceleration of projectile during penetrating is very important for high-powered Earth Penetrating Weapon. First, to develop explosive and fuse that can endure high overload we should acquaint the acceleration value of projectile during penetrating. Second, to develop exactly time-lapse fuse which insures the projectile explosion at optimal depth we should known the relation of projectile displacement and penetrating time. Third, to study the acceleration of projectile during penetrating is able to reveal the detail of projectile penetrating process. So we want through this study to reveal the acceleration characteristic of projectile during penetrating. For our experiments, the projectiles lost small amounts of mass through abrasion and experienced relatively small deformations. Therefore, rigid-body acceleration data provide a measure for net force on the projectile nose during the penetration event. However, most experimental studies[1-4] only provide penetration depth versus striking velocity data, and acceleration data are limited. Forrestal and Luk[5] reported acceleration data for six experiments into soil targets with peak rigid-body accelerations of about $-1\,200g$ (acceleration of gravity). Forrestal and Frew[6] reported acceleration data for penetration into concrete targets with peak rigid-body accelerations between $-6\,000g$ and $-13\,000g$. Zhou Ning, Ren Hui-qi, et

* **Received date**: 2006-10-08; **Revised date**: 2007-01-23
Foundation Item: Sponsored by National Basic Research Program of China, 973 Program(51309-1-6)
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al.[7] reported acceleration data for penetration into reinforced concrete targets with peak rigid-body accelerations are $-17\,500g$ and $-25\,000g$. For this penetration tests with concrete targets, the peak rigid-body accelerations are between $-12\,000g$ and $-22\,000g$.

In this study, we conducted penetration experiments that had a single-channel acceleration data recorder structurally mounted within the projectiles. Thus, we were able to record launch accelerations in the bore of the gun and accelerations during the penetration event. A 100 mm diameter powder gun launched 25 kg, 100 mm diameter projectiles to striking velocities between 310 m/s and 632 m/s. While the projectiles used in this study were large enough to carry a data recorder that measured acceleration during penetration, the 100 mm diameter gun could endure 525 MPa chamber pressure.

2 Experimental System

We conducted two sets of penetration experiments into concrete targets with shape of 3 m×3 m×3 m and 2 m×2 m×2 m. The Targets' average compressive strength is 35 MPa. In addition, 150 mm×150 mm×150 mm cubes were cast for material properties tests. The projectiles dimensioned in Fig. 1 had a nominal mass of 25 kg, and were designed to contain a single-channel acceleration data recorder. Schematic diagram of acceleration data recorder is shown in Fig. 2. Circuit module is made up of power controller, charge enlarge circuit, instant signal recorder and interface. Piezoelectricity acceleration sensor transform acceleration signal into electrical signal, then charge enlarge circuit transform the charge signal into voltage signal and this signal saved by instant signal recorder. After experiment, we took out the acceleration recorder system and linked it with computer, then we can read the launch accelerations in the bore of the gun and acceleration during the penetration event.

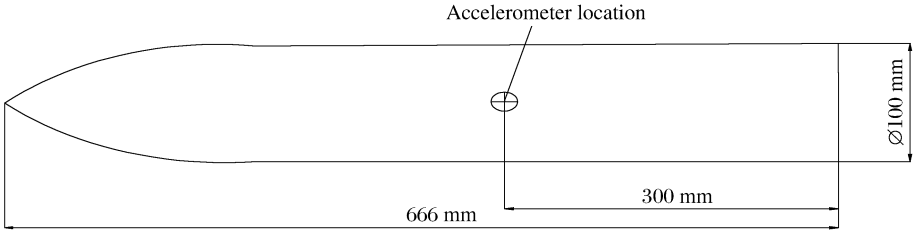


Fig. 1　Projectile geometries and accelerometer locations

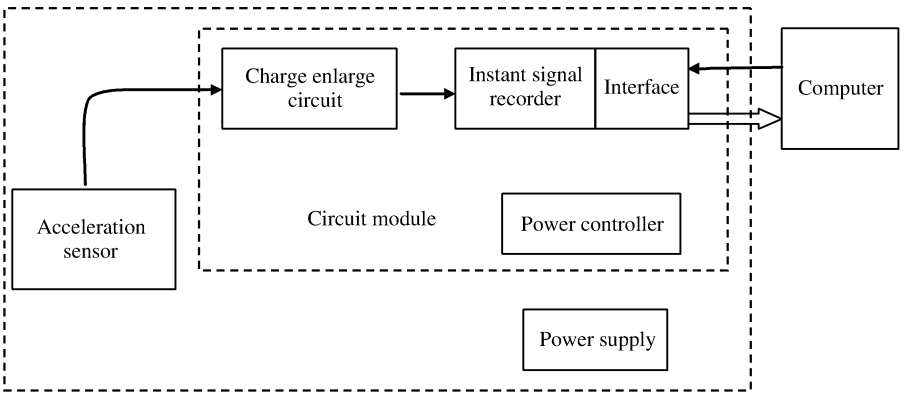


Fig. 2　Schematic diagram of acceleration data recorder

The test set-up sketch-map is shown in Fig. 3. The experimental system includes launch system, projectile pose testing system, projectile velocity testing system and target. Wire netting target was used to test the projectile velocity, while the projectile perforated the wire netting, the circuit became

open, multicenter recorder automatically recorded the time that every circuit cutoff. So we can get the projectile velocity by using the space of wire netting target divided interval of the two circuit cutoff.

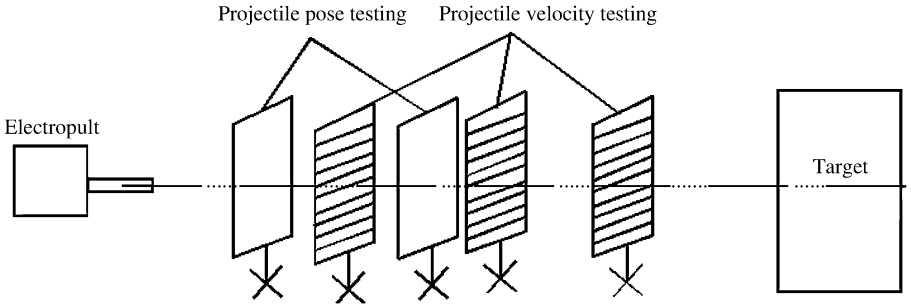


Fig. 3 Experimental system sketch-map

3 Experimental Results

Penetration experiments with concrete targets that had average compressive strengths of 35 MPa have been conducted. The 100 mm diameter, 666 mm long, ogive-nose projectiles were machined from 42GrM steel and designed to contain a single-channel acceleration data recorder. A 100 mm diameter powder gun launched the 25 kg projectiles to striking velocities between 310 m/s and 624 m/s.

3.1 Forrestal Empirical Penetration Equation

In Ref. [8] Forrestal, Altman et al. presented empirical concrete penetration equation. If the target strength parameter R is determined, we can use those equations to calculate penetration position, rigid-body velocity, and acceleration versus time.

Force on the projectile nose is given by

$$F = cz \qquad 0 < z < 4r \tag{1a}$$

$$F_z = m\frac{\mathrm{d}v}{\mathrm{d}t} = -\pi r^2(R + N\rho v_1^2) \qquad 4r < z < P \tag{1b}$$

Where

$$R = Sf_c \tag{2}$$

$$S = 82.6 f_c^{-0.544}, \quad \text{or} \quad S = 72.0 f_c^{-0.5} \tag{3}$$

Where z is current penetration depth and P is the final penetration depth. The projectile has diameter $2r$; mass m; shape parameter N; and the target is described by density ρ and the target resistance parameter R.

Acceleration versus time is

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\tilde{\omega}v_0\sin(\tilde{\omega}t) \qquad 0 < z < 4r \tag{4a}$$

$$\alpha = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{-(\pi r^2 R/m)}{\cos^2\left\{\tan^{-1}\left[\left(\frac{N\rho}{R}\right)^{1/2}v_1\right] - \frac{\pi r^2}{m}(RN\rho)^{1/2}(t-t_1)\right\}} \qquad 4r < z < P \tag{4b}$$

Rigid-body velocity versus time is

$$v = v_0\cos(\tilde{\omega}t), \qquad 0 < z < 4r \tag{5a}$$

$$v = \left(\frac{R}{N\rho}\right)^{1/2}\tan\left\{\tan^{-1}\left[\left(\frac{N\rho}{R}\right)^{1/2}v_1\right] - \frac{\pi r^2}{m}(RN\rho)^{1/2}(t-t_1)\right\} \qquad 4r < z < P \tag{5b}$$

Where v is projectile velocity; v_0 is initial projectile velocity.

Position versus time is

$$z = \frac{v_0}{\tilde{\omega}}\sin(\omega t) \qquad 0 < z < 4r \tag{6a}$$

$$z=\frac{m}{\pi a^2 N\rho}\ln\left\{\frac{\cos\left\{\tan^{-1}\left[\left(\frac{N\rho}{R}\right)^{1/2}v_1\right]-\frac{\pi r^2}{m}(RN\rho)^{1/2}(t-t_1)\right\}}{\cos\left\{\tan^{-1}\left[\left(\frac{N\rho}{R}\right)^{1/2}v_1\right]\right\}}\right\}+4r \quad 4r<z<P \tag{6b}$$

In these equations

$$\tilde{\omega}^2=\frac{c}{m},\quad c=\frac{\pi rR}{4} \tag{7a}$$

$$t_1=\frac{\cos^{-1}(v_1/v_0)}{(\pi aR/4m)^{1/2}} \tag{7b}$$

$$v_1^2=v_0^2-\frac{4\pi r^3 R}{m} \tag{7c}$$

Where the t_1 is the time at $z=4r$.

Those equations have been used to calculation the penetration depth and penetration position, rigid-body velocity, and acceleration versus time data.

3.2 Result Analyze

Table 1 shows a summary of results for five experiments. The first column in Table 1 gives the shot and projectile numbers, the second column records the mass of the projectile, the fourth column records the striking velocity, the fifth column records the penetration depth and the last two record the max. and min. crater diameter. Fig. 4 shows the comparison of penetration depths given by Eq. (6b) and measured. The penetration depth given by Eq. (6b) is less than those measured, but the tendencies of the curves are uniform.

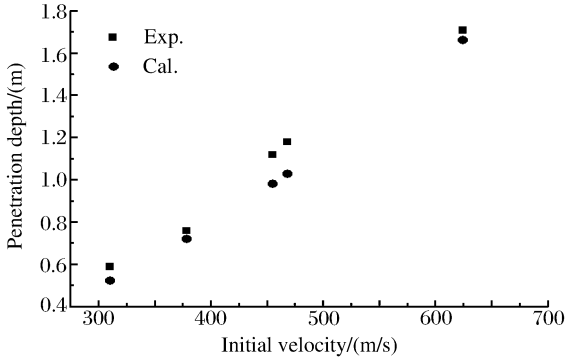


Fig. 4　Comparison of calculate and test penetration depth

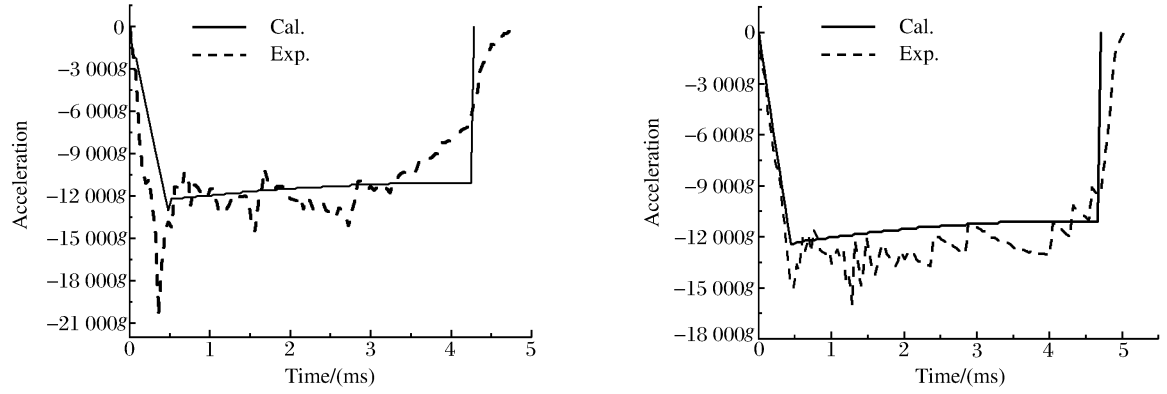
Table 1　Experimental results

Shot No.	m/(kg)	Pitch yaw /(°)	v_0/(m/s)	$P_{Exp.}$/(m)	d_c/(m)	
					Max.	Min.
1	25	0	310	0.59	1.32	1.02
2	25	0	387	0.76	1.77	1.03
3	25	0	455	1.12	1.81	1.60
4	25	0	468	1.18	1.77	1.33
5	25	0	624	1.71	2.21	1.35

As previously discussed, most experimental studies on penetration are limited to final penetration depth versus striking velocity data. However, for this study, we conducted penetration experiments that had a single-channel acceleration data recorder structurally mounted within the projectiles. The acceleration recorder is designed to digitize and record accelerations during launch and acceleration during penetration. After the penetration event, the projectile is recovered from the target and the recorded digital data are retrieved. Through Fig. 5 we can see that, for most cases, the calculation results are in good agreement with the rigid-body responses for the rise times and peak plateau responses. However, the calculation results deviate from the data towards the end of the penetration events.

Since the projectiles lost small amounts of mass through abrasion and experienced relatively small deformation, rigid-body acceleration data provide a time-resolved measure for net axial force on the

projectile during the penetration events. These acceleration-time data represent the major contribution of this study, so we now discuss the accuracy of these measurements. We perform integrations of the acceleration-time data to obtain striking velocity and final penetration depth. Thus, we can compare the measured striking velocities and an integration of the acceleration-time data, and we can compare final penetration depth with a double integration of the acceleration-time data. Fig. 6 shows single and double integrations of acceleration versus time for penetration experiment shot No. 3 in Table 1. These integrations calculate a striking velocity of 461 m/s and penetration depth of 1.03 m; whereas, the data in Table 1 give 455 m/s and 1.12 m. These integrations show good agreement with independent measurements. So, the tested acceleration-time data really reflected the overload of projectile during penetration.



(a) v_0 = 455 m/s (b) v_0 = 488 m/s

Fig. 5 Acceleration versus time data and calculated

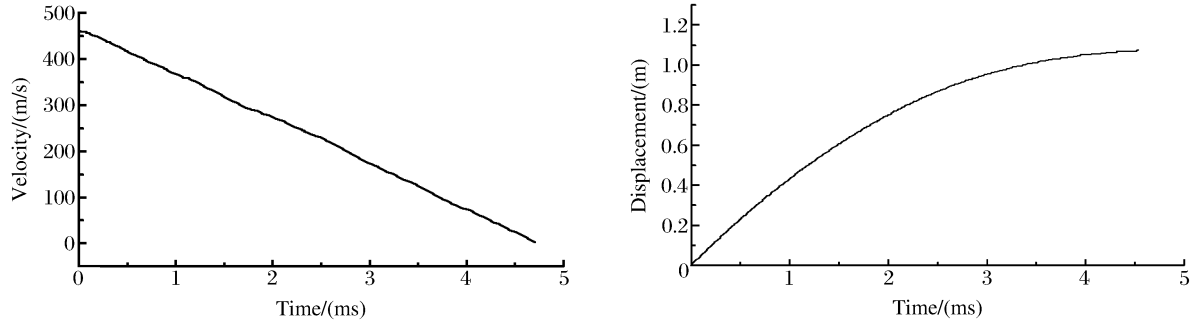
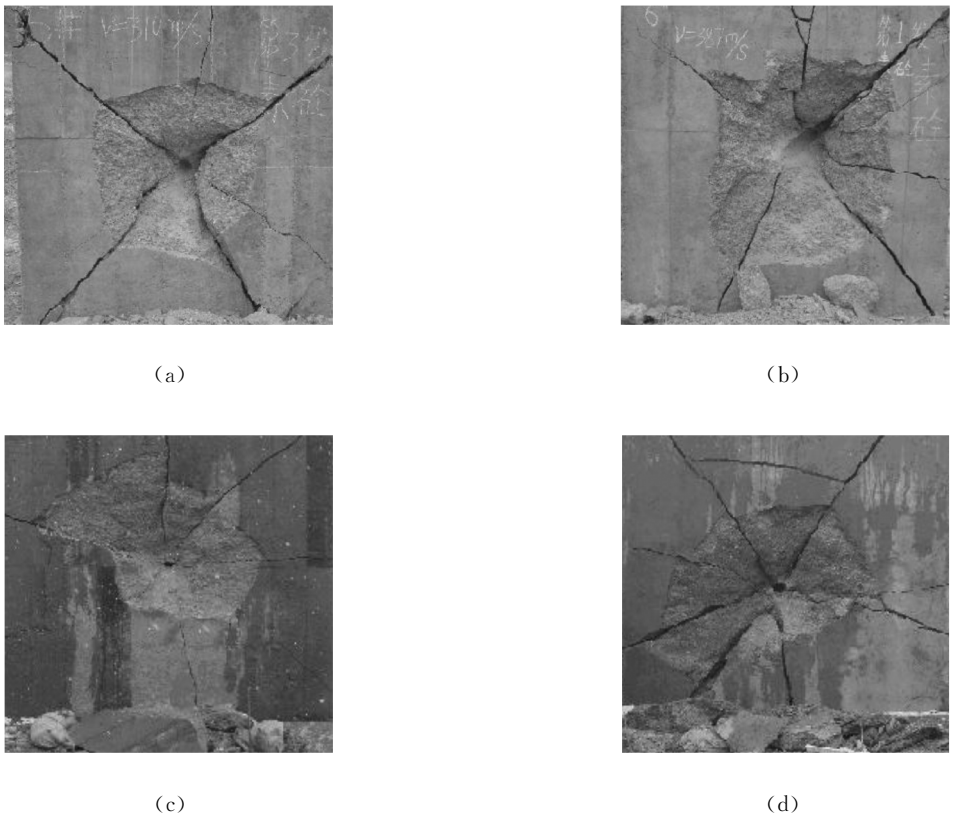


Fig. 6 Velocity versus time and displacement versus time integrated from shot No. 3

3.3 The Damage Effect of Concrete Targets at Different Striking Velocity

Fig. 7 shows the damage effect of 2 m×2 m×2 m and 3 m×3 m×3 m concrete targets at different striking velocities. Fig. 7(a) and Fig. 7(b) are 2 m×2 m×2 m, while Fig. 7(c) and Fig. 7(d) are 3 m×3 m×3 m. The striking velocity of Fig. 7(a) is 310 m/s, Fig. 7(b) is 387 m/s, Fig. 7(c) is 468 m/s, Fig. 7(d) is 624 m/s. Concrete targets have a conical shaped entry crater followed by a tunnel with nearly the same projectile diameter. All concrete targets have symmetrical radial crack.



(a)　(b)

(c)　(d)

Fig. 7　Post-test photographs of concrete targets by different velocity projectiles

4　Summary

We conducted penetration experiments with 3 m×3 m×3 m and 2 m×2 m×2 m concrete targets that had an average compressive strength of 35 MPa and 100 mm diameter, 4.0 caliber-radius-head, 25 kg projectiles. A 100 mm diameter powder gun launched the 25 kg projectile to striking velocities between 310 m/s and 624 m/s. The projectiles were designed to contain a single-channel acceleration data recorder. Thus, we recorded launch accelerations in the bore of the gun and accelerations during the penetration event. We compared the measured penetration depths and acceleration-time data with the calculated results using Forrestal formula. The calculated results are in good agreement with rigid-body acceleration measurements for the rise times and peak plateau responses. The tested acceleration-time data of projectiles can be helpful for devising armour-piercing projectile and defense engineering.

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卵形头部弹丸侵彻混凝土的研究

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摘要： 用头部曲率半径为 4.0、直径 100 mm、质量为 25 kg 的卵形弹丸对混凝土进行侵彻实验，并测试了炮膛内和侵彻过程中弹丸的加速度时程曲线。实验用混凝土靶的抗压强度为 35 MPa，密度为 2 450 kg/m^3，有 3 m×3 m×3 m 和 2 m×2 m×2 m 两种尺寸。测试弹丸发射和侵彻过程加速度的记录系统刚性固结于弹丸内部。弹丸侵彻初速在 310 m/s 至 632 m/s 之间，弹丸的峰值过载在 12 000g 到 22 000g 之间。实验后将测试的侵彻深度、侵彻过程弹丸的加速度时程曲线与用 Forrestal 的理论模型计算得到的结果进行了比较分析。实验结果对认识侵彻的整个过程和相关弹药的设计有重大意义。

关键词： 爆炸力学；侵彻；混凝土靶；卵形头部弹丸；加速度时程曲线测试

中图分类号： O385 **文献标识码：** A