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A numerical study on the ricochet of ogive-nosed projectiles from concrete targets

Jihoon Han[1], Hwangki Cho[2], Min Kuk Choi[3], Sangjin Park[3], Woo Jin An[3], and Dongwoo Sohn[2*]

[1]Department of Mechanical Engineering, Chonbuk National University, Jeonju-si, Republic of Korea
[2]Department of Mechanical Engineering, Korea Maritime & Ocean University, Busan, Republic of Korea
[3]The 4th R&D Institute-3rd Directorate, Agency for Defense Development (ADD), Daejeon, Republic of Korea

*Corresponding author: dsohn@kmou.ac.kr

1. Introduction

A ricochet phenomenon, which refers to the rebound of a projectile from a target surface without penetrating or perforating the target, is an important consideration in ballistics. It is necessary to understand the ricochet of warheads not only in order to design and develop the defense facility for anti-missile protection such as hard and deeply buried targets, but also in order to enhance the penetration performance of warheads. However, it is not straightforward because the ricochet is governed by various complex factors such as the geometry, material properties, incident angle, and striking velocity of the projectiles. In addition, target materials affect a trend in the projectile trajectory, such as the penetration into the target or ricochet from the target surface. For the construction of defense facilities, concrete is widely used due to its high cost-effectiveness ratio and high compressive strength. In this study, we thus focused on the investigation of the ricochet of projectiles obliquely impacting on the concrete targets.

Although numerical and experimental studies [1-5] have been conducted until recently on the projectiles penetrating into the target materials with oblique incidence angles, an investigation of the correlation of various factors that affect the projectile trajectories has not been completed yet. In the current work, we developed a semi-empirical model to predict the dynamic behavior of projectiles penetrating into concrete targets in a simple and efficient manner. Setting the nose shape, striking velocity, and oblique incidence angle as key parameters, we then investigated the effects of various combinations of the key parameters. In particular, we found critical conditions to prevent the ricochet of ogive-nosed projectiles.

2. Prediction method for oblique penetration of ogive-nosed projectiles

For a projectile penetrating into a concrete target, the normal stress acting on the projectile surface, which was formulated based on the spherical cavity expansion approximation [6], can be expressed as

$$\sigma_n = Sf_c' + \rho v_n^2 \tag{1}$$

where S is the dimensionless empirical constant that can be estimated from experimental results; f_c' and ρ are the unconfined compressive strength and density of the concrete target, respectively; and v_n is the normal velocity defined at a point on the projectile surface. In the current study, the frictional effect was not considered additionally because the frictional resistance can be regarded as being lumped into the empirical constant [7].

When a projectile penetrates the semi-infinite target with an oblique incidence angle, the resistance toward the free surface of the target is much lower than that toward the opposite infinite domain. Therefore, the free surface effect should be considered in order to obtain the normal stress that depends on the distance from a point on the projectile surface to the free surface of the target, as follows:

$$\sigma_n^f = f\left(r_a, r_d, v_n\right)\sigma_n = f\left(r_a, r_d, v_n\right)\left(Sf_c' + \rho v_n^2\right) \tag{2}$$

where r_a is a radius depending on the point of the projectile surface and d^* is a distance from that point of the projectile surface to the target free surface in the normal direction of the projectile surface. As shown in Fig. 1, r_d is given as the summation of r_a and d^* (i.e. $r_d = r_a + d^*$). The decay function $f(r_a, r_d, v_n)$, which is based on the solution of a dynamically expanding spherical cavity [7, 8], can be defined for the incompressible Mohr-Coulomb materials, as follows:

$$f\left(r_a, r_d, v_n\right) = \frac{\sigma_a(r_a)}{\sigma_a(r_a)_{r_d \to \infty}} \tag{3}$$

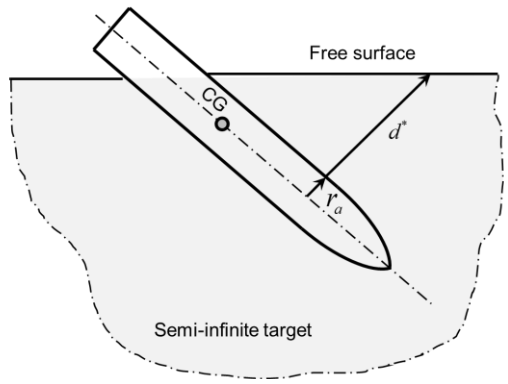

Fig.1 Oblique penetration of an ogive-nosed projectile into the semi-infinite concrete target

where the radial stress $\sigma_a(r_a)$ is given analytically considering the cavity, plastic, elastic, and free-surface regions around the projectile surface [7] and is normalized to the value for $r_d \rightarrow \infty$.

In the current study, the surface integral of the normal stress given in Eq. (2) was calculated by performing an element-wise numerical integration as in the finite element method. The stresses evaluated at the Gauss integration points were converted to the nodal forces. The forces and moments at the center of mass were then calculated based on the nodal forces. The kinematic quantities of the projectile, such as the position, velocity, and acceleration, were updated at each time increment using the 4th-order Runge-Kutta method for Newton's equations of motion.

3. Results and Discussion

The ogive-nosed shapes of projectiles can be defined with the caliber-radius-head (CRH). Here we considered two different CRH values, ψ = 1 and 3. With a given oblique incidence angle of 36°, the projectile trajectories were predicted using the semi-empirical model at different striking velocity v_0 ranged from 10 to 1000 m/s. Fig. 2(a) and (b) show the results for $\psi = 1$ and 3, respectively. The maximum striking velocity, termed the critical striking velocity below which the ricochet occurs, increased as the nose shape became sharper. The ricochet of the sharp-nosed projectile occurred at a relatively high speed because a penetration ability of projectiles with a sharp nose was greater than that with a blunt nose. As such, the critical striking velocity can be given in the function of the nose shape and oblique incidence angle. Similarly, a minimum incidence angle, termed the critical incidence angle above which the ricochet occurs, can depend upon the nose shape and striking velocity of projectiles.

As mentioned above, it is important to find critical conditions of ogive-nosed projectiles to prevent the ricochet. Our work will be used as an efficient analysis platform to predict the dynamic behavior of projectiles and will provide a basis for the effective design and development of warheads and defense facilities.

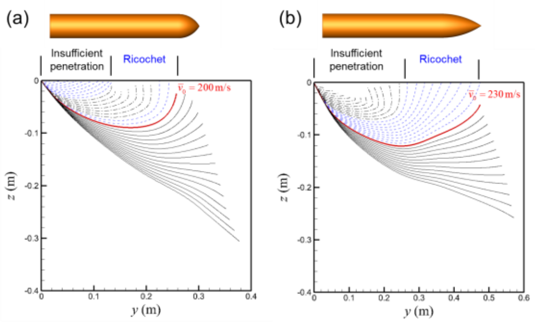

Fig.2 Trajectories of ogive-nosed projectiles obliquely penetrating into the concrete targets with various striking velocities: (a) ψ = 1 and (b) ψ = 3

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