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Analyses of the penetration process considering mass loss

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ABSTRACT

Based on the dynamic cavity-expansion theory and momentum theorem, the key parameters of projectile penetrating into concrete target, i.e., the penetration time and time histories of DOP, deceleration, mass loss, instant mass loss rate and nose shape, are obtained by incremental calculation considering mass loss of projectile. The calculation results are consistent with the experimental results. Due to the mass loss and thus nose blunting effects, the pulse shape of deceleration may be quite different from that obtained in the analysis of a rigid projectile, and then the dissimilarity is analyzed. It is found that the pulse shape of deceleration is determined by the drag force and essentially determined by the performances of target and projectile, i.e., the shear strength of target, the Moh's hardness of aggregate in concrete and the CRH value of projectile nose. Further analysis indicates that the pulse shape of deceleration is more sensitive to the performance of target than that of projectile.

1. Introduction

Since the protective structure is usually consisted of concrete and/or rocks, the penetration process of high-speed Kinetic Energy (KE) penetrator into concrete (or rock) target should be well understood in order to optimize the protection or destruction of the target. The performance of the projectile can be denoted by several parameters, such as the penetration duration time, time histories of Depth of Penetration (DOP), deceleration, penetration velocity, mass loss, mass loss rate and nose shape of projectile, etc.

There has been much effort directed toward understanding the penetration process by experiments. The instant DOP may be experimentally detected by X-ray photograph. The penetration ability of X-ray increases with density of piercing material decreasing, which limits the combination of target and projectile as the density of projectile should be larger enough than that of target (Orphal and Anderson, 2006). Forrestal et al. (2003) and Frew et al. (2006) embedded a single-channel acceleration data recorder into projectile and recorded the time history of deceleration. Unfortunately, the rigorous demands to the performance of the acceleration data recorder, such as the measurement, precision, etc., limit its application. Besides, there is not a reliable way to collect the time history of mass loss and mass loss rate of projectile yet. Hereby, it is pretty difficult to obtain most of the characteristic parameters for penetration.

Hence, we hope these characteristic parameters can be derived in theoretical analysis and numerical simulation. Forrestal et al. (2003) theoretically derived the DOP and time history of deceleration of the projectile at comparatively low impact velocity, ignoring the mass loss of projectile and target inertia effect. The predictions agree well with the experimental results. However, the mass loss of the projectile cannot be ignored any more and the inertia term plays an important role in the axial drag force during high-speed penetration, and thus the complete and also complicated form of the momentum theorem should be adopted in the analysis of the motion of projectile. Generally, the mass loss of projectile mainly comes from peeling of the molten surface layer in its nose and scratching on its whole surface (Klepaczko and Hughes, 2005). Assuming all the frictional heat is absorbed by the penetrator and the peeling of molten surface layer in projectile nose is the primary cause of mass loss, Jones et al. (2002) gave an estimation of mass loss of projectile. They found that the total mass loss of projectile was proportional to the cross-section area of its shank, dimensionless longitudinal cross-section area of its nose and its ultimate DOP as well as the shear strength of target whilst inverse proportional to the melting heat of the projectile material per unit mass. Since Jones et al. (2002) did not take account of the scratch effect, Davis et al. (2003) introduced an empirical coefficient η for modification, and recently L.L. He et al. (2010) suggested its empirical expression. Unfortunately, the nose shape of projectile is

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Nomenclature

a	instant deceleration of projectile
b	length of projectile nose
c	constant, related to axial drag force of projectile in crater stage
dN^*/dt	nose factor rate
dN_1^*/dt	rate of N_1^*
f_1, f_2, f_3, f_4	functions for respectively calculating N^*, N_1^*, dN^*/dt and dN_1^*/dt
f_c	unconfined compressive strength of target
F_n	axial drag force of projectile
g	function for calculating nose volume of projectile
H	Moh's hardness of aggregate in concrete target
H_0	reference value of Moh's hardness of aggregate in concrete target
k	dimensionless depth of crater
m	instant mass of projectile
M_0	initial projectile mass
$\dot{m}$	mass loss rate of projectile
mt	mass of projectile nose
N^*	nose factor of projectile
N_1^*	dimensionless longitudinal cross-section area of projectile nose
Q	melting heat of projectile material per unit mass
r	radius of projectile shank
R	dynamic strength of target
S	empirical constant, only related to f_c (unit in MPa)
t	instant penetration time
T	duration time of penetration
v	instant penetration velocity of projectile
V	volume of ogival projectile nose
V_0	initial impact velocity of projectile
V_{0c}	critical initial impact velocity of projectile
V_1	penetration velocity of projectile at the transition point from crater stage to tunnel stage
x, y	coordinates as shown in Fig. 1
z	instant DOP of projectile
Z	ultimate DOP of projectile
Δm	increment of projectile mass
ΔM	total mass loss of projectile
Δt	time step size
Δv	increment of penetration velocity of projectile
Δz	increment of DOP of projectile
γ	instant relative mass loss of projectile
η	modification coefficient
φ	effective longitudinal cross-section area of projectile nose
κ	mechanical equivalent of heat
ρ_p	density of projectile
ρ_t	density of target
τ_0	shear strength of target
ψ	CRH value of projectile nose
ζ	coefficient defined as Eq. (11)

assumed unchanged during penetration in all of the above analyses, which is in contradiction to the reality, especially when the impact velocity is relatively high.

Since the nose geometry of projectile may has significant influence on its performance (Jones and Rule, 2000), it is not reasonable to ignore the nose blunting effect, especially at high impact velocity. Therefore, the blunting law for projectile nose attracts more and more attention. Several blunting models are constructed empirically in summary of the experimental results, such as Jones et al. (2001), Davis et al. (2004) , Zhao et al. (2010), Chen et al. (2010a,b), etc.. They all adopted the same assumption as Jones et al. (2002) to explain the primary cause of mass loss of projectile. Specifically, Jones et al. (2001) assumed that the length of instant projectile nose is proportional to its instant DOP, which may be too crude compared to the test. Moreover, they did not illustrate the residual projectile shape. Davis et al. (2004) fitted the generatrix contour of projectile nose by polynomial and brought nose blunting in by iterating the coefficients of the polynomial. The description of the nose was very versatile and allowed for some fairly complicated geometry to be easily modeled. The iterative algorithm of coefficients is only related to the nose length of projectile, which has the similar shortcoming to Jones et al. (2001). Zhao et al. (2010) found that each combination of projectile and semi-infinite target had its available maximum DOP considering nose blunting. They constructed a linear relationship between the instant nose shape factor and kinetic energy of projectile and introduced a nose blunting law by varying nose factor with instant penetration velocity of projectile. However, they did not show any specific illustration of projectile nose shape and only focused on DOP of the projectile. In numerical simulation, the variation of the nose shape is pretty easy to obtain by establishing an abrasion model and inserting it into certain commercial software (Beissel and Johnson, 2000, 2002; Silling and Forrestal, 2007). In general, the uniform abrasion model is still in absence and a simple and effective method is in demand.

Chen et al. (2010a) summarized the test results and then proposed a nose blunting law of ogival projectile, i.e., the nose of the residual projectile is still ogival but with a smaller CRH value compared to its prototype. Inserting this blunting law into Jones et al. (2002), the dominant parameters for the performance of projectile are obtained by means of incremental calculation in the present manuscript. The calculation results are validated by experimental results. Furthermore, discussions of these parameters are carried out and the dissimilarity of the deceleration obtained, respectively, by incremental calculation and analysis of penetration of a rigid projectile is especially denoted.

2. Fundamental formulae

Generally, the penetration process of a high-speed penetrator into a semi-infinite concrete target is divided into two stages: crater stage and tunnel stage. Since the projectile keeps losing mass during penetration and the target is semi-infinite, it is assumed that the velocity of the lost mass portion of projectile is decelerated to zero immediately when it departs from the projectile. There is an underlying assumption that the projectile is rigid except the mass abrasion, which implies that the velocity of projectile equals to the penetration velocity. According to the momentum theorem, we have

$$\frac{d}{dt}(mv) = \frac{dm}{dt}v + m\frac{dv}{dt} = F_n \quad (1)$$

for projectile, where m, v and F_n are the current mass, penetration velocity and axial drag force of projectile, respectively. The axial drag force is (Chen, 2003; Forrestal et al., 1994; Frew et al., 2000)