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Long-rod penetration: the transition zone between rigid and hydrodynamic penetration modes

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Abstract

Long-rod penetration in a wide range of velocity means that the initial impact velocity varies in a range from tens of meters per second to several kilometers per second. The long rods maintain rigid state when the impact velocity is low, the nose of rod deforms and even is blunted when the velocity gets higher, and the nose erodes and fails to lead to the consumption of long projectile when the velocity is very high due to instantaneous high pressure. That is, from low velocity to high velocity, the projectile undergoes rigid rods, deforming non-erosive rods, and erosive rods. Because of the complicated changes of the projectile, no well-established theoretical model and numerical simulation have been used to study the transition zone. Based on the analysis of penetration behavior in the transition zone, a phenomenological model to describe target resistance and a formula to calculate penetration depth in transition zone are proposed, and a method to obtain the boundary velocity of transition zone is determined. A combined theoretical analysis model for three response regions is built by analyzing the characteristics in these regions. The penetration depth predicted by this combined model is in good agreement with experimental result.

Keywords: Penetration; Theoretical analysis model; Transition zone; Threshold velocity; Long rod

1. Introduction

Long-rod penetration in a wide range of velocity means that the initial impact velocity varies in a range from tens of meters per second to several kilometers per second. Forrestal [1,2] conducted the penetration experiments with spherical-nose or ogive-nose steel projectiles and 6061-T6511 aluminum targets at striking velocities between 0.5 km/s and 3.0 km/s. Wickert [3] performed the experiments with tungsten penetrator and aluminum alloy target in the velocity range from 0.25 km/s to 1.9 km/s. These experiments indicate that there are three response regions for long-rod penetration in a wide range of velocity, it is found that there are three response regions as shown in Fig. 1.

(I) In low-speed range, the long rod projectile maintains rigid state, and the penetration depth increases with striking velocity.
(II) In medium-speed range, the nose of rod deforms and even is blunted, and then the penetration depth decreases. It will suddenly draw down if erosion or fracture happens.
(III) In high-speed range, the nose erodes and fails to lead to the consumption of long projectile due to instantaneous high pressure. If striking velocity keeps on increase, the penetration depth will increase again, and tend to reach a steady value finally.

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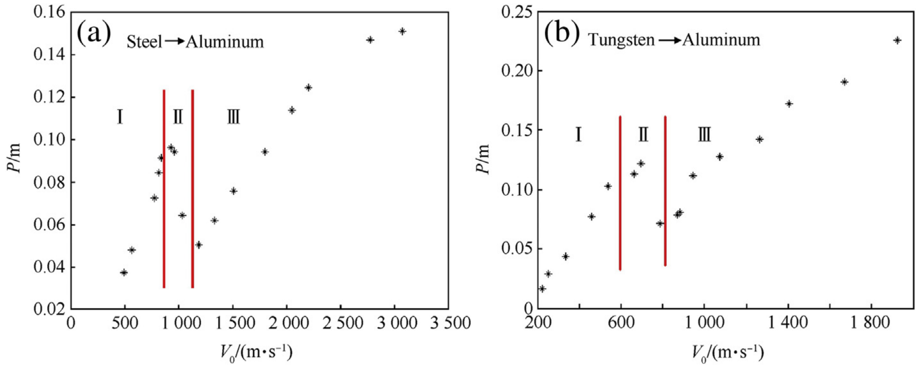

Fig. 1. Three response regions for penetration in a wide range of velocity. (a) The response regions of steel rods penetrating aluminum targets [1]. (b) The response regions of tungsten penetrators penetrating aluminum targets [3].

So far, the theoretical study has focused on the first and the third response regions. There has been little known about the second response region due to the complexity of this problem. The transition zone was discussed in Refs. [4] and [5], but it was simplified as a strong discontinuity, which means that the penetration depth is assumed to decline suddenly when the impact velocity exceeds a critical velocity. For most numerical simulation studies, the same material model was used throughout the entire velocity range [6,7], or it was simplified into two response zones [8]. Lan tried to use a unified model to discuss this issue [9], however, the result is far from been satisfied.

In this paper, we put forward the idea of dividing the velocity range into three regions and building independent theoretical model for each region to address this issue. Herein, the first problem is how to determine the limits of each region. According to the experimental results from Forrestal et al. [11] and Wickert [3], the penetration mechanism is rigid penetration in the first region and erosion penetration in the third region. Thus, to better analyze this problem, two velocities, V_r and V_{th}, are defined. V_r is critical rigid velocity, below which the projectile remains rigid penetration; V_{th} represents critical erosion velocity, above which erosion occurs. Accordingly, the entire velocity range can be divided into three regions, and the second region with the boundary velocities (V_r and V_{th}) is the transition zone.

Another major problem is how to build the theoretical model for each region. For the velocities within low-velocity range ($V_0 \le V_r$) and high-velocity range ($V_0 > V_{th}$), a lot of analytic models, as reviewed in Ref. [10], have been proposed. Here, the appropriate models are chosen for these two regions by comparing the characteristics and applicability of these models. The model proposed in Ref. [11] is used to calculate the depth of rigid penetration in low-velocity region. A comparative analysis of the popular high-velocity penetration models was presented in Ref. [15]. One of them is the Tate model [12–14], in which the target resistance is set to be constant. Another one is Anderson–Walker model [16], in which the target resistance varies with penetrating velocity, making it more close to real situation. Thus, the Anderson–Walker model is chosen to calculate the penetration depth of the third region.

The difficulty of this work is to construct an appropriate theoretical model for the second region (transition zone). This is due to the complicated penetration mechanism in this region involving large plastic deformation in projectile head leading to the reduction of its length, blunted head resulting in the increase of target resistance and the weakening of penetration capability. If erosion happens, the penetration depth will decline sharply, almost halved. What's more, it is a relatively narrow velocity range, almost 100 m/s–200 m/s, in which penetrator head changes easily from large deformation to erosion. As shown in Ref. [1], such velocity range is 892 m/s–1042 m/s, 967 m/s–1037 m/s and 1086 m/s–1174 m/s for the average Rockwell hardness R_c of 36.6, 39.5, and 46.2, respectively, in the experiments of spherical nosed steel rods impacting the aluminum targets. In the case of penetration by tungsten projectiles [3], the velocity range is 695 m/s–785 m/s. In this paper, a phenomenological model to calculate the penetration depth in the transition zone is constructed based on the analysis of penetration behavior in the transition zone.

2. Method to determine boundary velocity of transition zone

2.1. Critical rigid velocity V_r

To achieve the critical rigid velocity V_r at which the projectile changing from rigid to deforming rod, it is necessary to know the stresses acting on the rod/target interface at the threshold velocity. On the side of rod the stress is the effective strength Y_{eff}, and on the side of target it is resistance to penetration H.

During the early stages of penetration, the rod nose experiences a transient lateral stress H_{lat}, which resists the process of crater formation due to the target strength. Once the rod is embedded in the target, the lateral stress like an effective lateral support prevents the rod nose from deforming and eroding. The direct consequence of this support is to increase the strength of the rod from Y_p to an effective strength Y_{eff}, with the Tresca yield condition, $Y_{eff} = Y_p + H_{lat}$, as was done by Segletes [5].