International Journal of Impact Engineering 66 (2014) 60–82

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Review

Response of granular media to rapid penetration

Mehdi Omidvar, Magued Iskander*, Stephan Bless

New York University, USA

ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form
22 November 2013
Accepted 9 December 2013
Available online 20 December 2013

Keywords:
Soil
Sand
Impact
Crater
Phenomenology

ABSTRACT

There has been a flurry of interest over the past decade in the study of impact and penetration into granular media. A wealth of knowledge has resulted from these efforts. This review summarizes some of the significant findings of these recent studies, and attempts to bridge the resulting insights with those obtained from earlier findings. The effects of projectile properties as well as soil behavior on penetration are examined at the meso- and macro-scales, and significant insights into the fundamental physics of projectile penetration in sand are outlined. Issues relating to laboratory-scale physical modeling are presented to aid with interpretation of experimental data. Empirical and analytical methods to predict the response of soils to projectile impact are also summarized. Finally, a brief description of the impact-cratering and other transients of penetration is presented for completeness.

1. Introduction

Impact and travel of projectiles in granular media has intrigued engineers and physicists dating as far back as the mid eighteenth century [1]. Initially, interest in the subject stemmed from military applications. Over the past century, research has also been motivated by civilian applications in a number of related areas, including: subsurface investigation of soil and rock, particularly at inaccessible locations and extraterrestrial surfaces [2–14], planetary impact [15], installation of deep sea anchors and foundations [16,17], nuclear waste disposal [18–20], mining [21], and aircraft landing studies [22,23]. Several important reviews of projectile penetration in different materials have been published, addressing penetration into metals [24,25], rocks [26], and soils [27–29]. The travel of projectiles is conventionally divided into exterior ballistics dealing with projectile behavior prior to impact, and terminal ballistics associated with the deceleration of projectiles at impact and penetration. The aim of this review is to provide a summary of published reports on terminal ballistics in granular media, with emphasis on sand. The reader is referred to Refs. [30–32] for an introduction to terminal ballistics in other materials. Finally, this review aims to bridge the language gap between physics and geomechanics, by adopting ideas from both disciplines and employing language that is accessible to both fields.

2. General aspects of rapid penetration into granular media

2.1. Terminology

In this review the following terminology is adopted to refer to the various events and behaviors that take place during penetration:

Length Scale: The behavior of granular materials can be studied on a number of interrelated scales. Although the macro- or continuum scale is the scale of primary interest for practical engineering applications, behavior of the continuum is decidedly influenced by physical phenomena that occur at underlying scales. The structural properties of individual soil particles, as well as intergranular kinetics and kinematics are studied at the micro-scale. Granular interactions such as rotation, translation, and comminution (crushing) of particles are significant phenomena at this scale. Collective behavior including rearrangement, dilation, strain localization, and formation and buckling of force chains, takes place at an intermediate scale, referred to as the meso-scale [33,34].

Velocity Regimes: Penetration can take place over a wide range of velocities, and one or another physical process will dominate depending on the velocity regime. For example, pile driving, ballistic penetration, and planetary impact occur at different velocity scales. In this review, four velocity regimes are adopted to

* Corresponding author. Department of Civil and Urban Engineering, Polytechnic School of Engineering, New York University, 6 MetroTech Center, Brooklyn, NY 11201, USA.

E-mail address: Iskander@poly.edu (M. Iskander).

0734-743X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.12.004

demarcate between the various controlling phenomena during projectile penetration in granular media. Quasi-static penetration refers to penetration at very low velocities, in which inertial effects do not contribute to penetration resistance, and penetration is driven by application of an external load. Subsonic penetration refers to velocities below the speed of propagation of acoustic waves in the medium, which commonly fall in the rage of 250–550 m/s in sand, depending on the mineral composition of the grains, packing porosity, and confining pressure [35]. Penetration in this regime is largely driven by the kinetic energy of the projectile. Supersonic penetration refers to penetration velocities exceeding the sonic wave velocity. Conventionally, this term is restricted to conditions where there is no or little deformation of the penetrator itself, and is upper-bounded by impact velocities in the range of 1–1.5 km/s. Still higher impact velocities are referred to as hypervelocity impact. Hypervelocity projectiles include meteors and shaped charge jets. Ballistic penetration into sand has applications within all velocity regimes. The focus of this review is on subsonic and supersonic penetration, with some of the important aspects of impact at hypervelocities briefly covered for completeness.

Projectile Notations: This review deals primarily with normal impact of ballistic penetrators. Common projectile shapes that have been used as soil penetrators are shown in Fig. 1. The ogive nose is common for small caliber bullets, while other shapes have been employed to investigate projectile-soil interaction mechanisms and penetration characteristics. A common parameter used to describe ogival nose shapes is the caliber radius head (CRH) ratio (Fig. 1), defined as the ratio of the radius of curvature of the nose to the projectile diameter. A blunt nose shape is equivalent to a CRH of zero, while increasing the CRH will result in a sharper nose with longer ballistic length. A conical nose is equivalent to a CRH approaching infinity, and is therefore often described in terms of its apex angle.

Non-normal impact is defined in terms of the obliquity angle and the angle of attack (AoA). The obliquity angle is the angle made by the velocity vector and the normal to the target surface, while AoA refers to the angle between the projectile axis of symmetry and the instantaneous velocity vector (Fig. 2). The impact angle is also occasionally used in the literature, and is defined as the complimentary angle of the obliquity angle, *i.e.*, the angle made by the velocity vector and the target surface. Non-normal impact and penetration can be further described by defining three independent rotation modes for the projectile [36]. The reference plane is set as the plane containing the velocity vector and the normal of the target (Fig. 2). Common terms employed in ballistics including

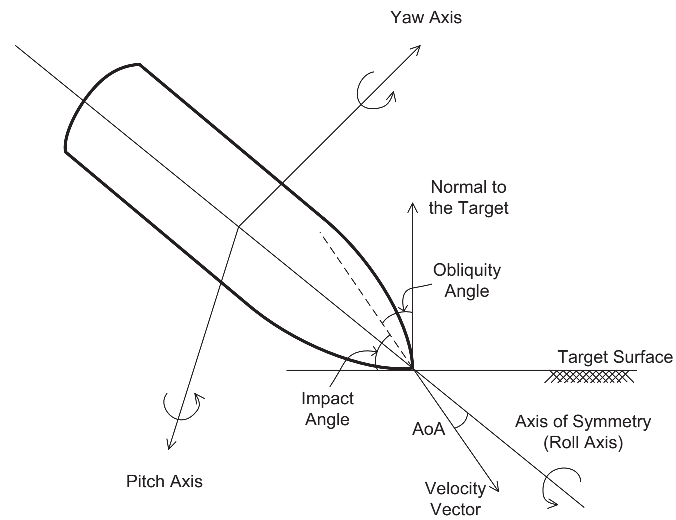

Fig. 2. Definition of projectile notations including the angle of attack (AoA), obliquity angle, pitch, yaw and roll.

pitch, roll, yaw, axis of symmetry, and angle of attack are also defined in the figure.

2.2. Energy dissipation

The impact of a projectile on a soil target generates stress waves that propagate through the soil as well as the projectile. Stress waves are attenuated both through geometric dispersion, and because they deposit energy into the granular medium. The resistance of a granular medium to penetration is related to its ability to dissipate energy. Some of the kinetic energy of the projectile is dissipated upon impact on the soil surface, through which particles are set in motion, and stress waves are generated. The remaining energy is dissipated in the form of work done as the projectile overcomes resisting forces, stemming largely from frictional and collisional dissipation. The physical phenomena occurring as a result of energy transfer to the granular medium depend on the velocity regime and the associated strain rates imposed. For example, small projectiles impacting at the lower end of the subsonic regime cause little change in the grain geometry, whereas supersonic impact produces a high-pressure shock wave, causing

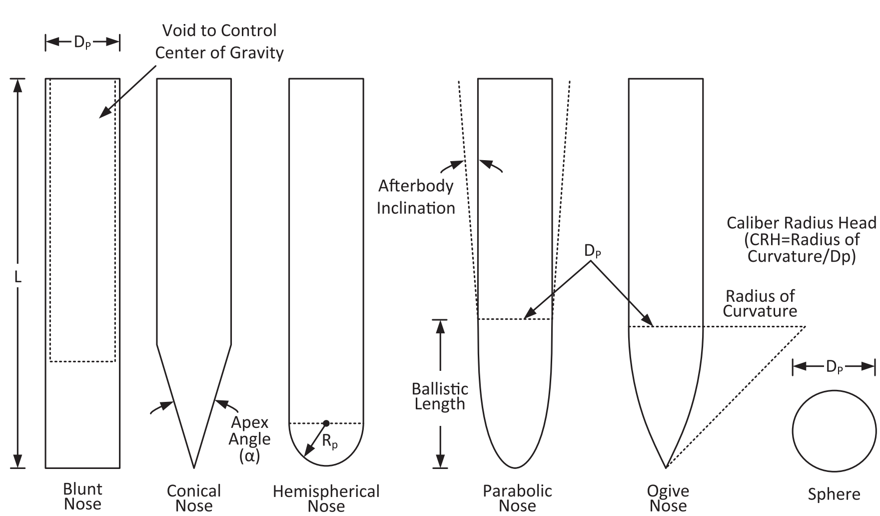

Fig. 1. Common projectile shapes and associated parameters.