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Penetration of granular materials by small-arms bullets

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ABSTRACT

This paper presents an experimental and numerical study on the penetration of granular materials by small-arms bullets. In the experimental tests, five different types of granular material (0–2 mm wet sand, 0–2 mm dry sand, 2–8 mm gravel, 8–16 mm crushed stone and 16–22 mm crushed rock) were impacted by four different types of small-arms bullets (7.62 mm Ball with a soft lead core, 7.62 mm AP with a hard steel core, 12.7 mm Ball with a soft steel core and 12.7 mm AP with a tungsten carbide core). The tests were carried out using different rifles to fire the projectiles, while the granular materials were randomly packed in a 320 mm diameter specially-designed steel tube. In all tests, the initial projectile velocity and the depth of penetration in the granular material were measured for each bullet type. In the numerical simulations, a discrete particle-based approach was used to model the behaviour of sand during bullet impact. The method works with discrete particles that transfer forces between each other through contact and elastic collisions, allowing for a simple and robust treatment of the interaction between the sand particles and the bullet which is represented by finite elements. An important observation from this study is that the penetration depth is strongly influenced by deviation of the bullet from its original trajectory. Good agreement between the available experimental results and the numerical predictions is also in general obtained.

1. Introduction

In international operations, long-distance transportation of protective elements is often necessary, and the weight of the system becomes a critical parameter. This limits the use of traditional structures made of steel or concrete, and a main challenge is to design barriers that have sufficiently low mass to be transported while at the same time having enough strength to defeat the threat. Børvik et al. [1,2] proposed to use extruded aluminium panels as a light-weight and mobile shelters. Such systems constitute a cheap, low-weight solution that quickly can be installed in camps out-of-area. To increase the ballistic perforation resistance of the protection, a local granular material is filled in the empty cavities between the panels. At repatriation or if the protection has to be moved, the mass is simply emptied through a hatch beneath the panels, and the system retains its low mass. However, ballistic tests have revealed that the relation between the grain size of the granular material and the calibre of the bullet significantly affects the perforation resistance of the protection, so a proper filling material is crucial [1]. Thus, to understand the behaviour of granular materials during impact by small-arms bullets is important for the design of such light-weight protective structures.

The study of projectile penetration in granular materials can be traced back to 1742 with the Robin–Euler penetration depth formula. Since then, a number of empirical models, some of which are still used today, have been proposed (see e.g. Young [3] and Corbett et al. [4]). Even though the problem has been studied for centuries, the number of systematic and detailed experimental studies available in the open literature is few. Allen et al. [5,6] presented some test data and a theoretical model for the penetration of nonrotating projectiles in sand, while Bai and Johnson [7] proposed a model to investigate the effects of impact velocity and sand resistance during ricochet. Forrestal et al. [8–10] developed closed-form analytical equations based on the cavity expansion theory and experimental tests for nonrotating pointed-nose projectiles that penetrated soil targets after normal impact. However, these and similar methods require tri-axial material data from samples cored

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from the actual target to give an accurate prediction of the depth of penetration, and such test data are not readily available. A comprehensive review of the response of granular media to rapid penetration was recently published by Omidvar et al. [11].

During the last decade, there have been numerous attempts at describing the constitutive behaviour (e.g. Refs. [12–20]) and to develop numerical methods (e.g. Refs. [21–32]) for granular materials under extreme dynamic loading conditions, partly motivated by impact cratering in geophysics and landmine explosions in international operations. A review on the stress–strain behaviour of sand at high strain rates has been given by Omidvar et al. [33]. Although advanced numerical techniques like the coupled Lagrangian–Eulerian approach have allowed new insight into the complex process of soil-structure interaction, their ability to describe sand particle–particle contact and loose soil ejecta are very limited [16]. However, the recent approach of using discrete particles to model real sand behaviour has shown to be promising (see e.g. Ref. [25,32,34]). This method, which is based on a Lagrangian formulation, has several advantages over coupled Lagrangian–Eulerian approaches as both numerical advection errors and severe contact problems are avoided, while at the same time keeping the computational time at a reasonable level.

The purpose of this study is two-fold. Firstly, a rather comprehensive experimental study on the penetration of granular materials by small-arms bullets was carried out. In the experimental tests, five different types of granular material (0–2 mm wet sand, 0–2 mm dry sand, 2–8 mm gravel, 8–16 mm crushed stone and 16–22 mm crushed rock) were impacted by four different types of small-arms bullets (7.62 mm Ball with a soft lead core, 7.62 mm AP with a hard steel core, 12.7 mm Ball with a soft steel core and 12.7 mm AP with a tungsten carbide core). A number of tests were conducted for each combination of granular material and projectile type, giving a total of 126 tests. The tests were carried out using different rifles to fire the projectiles, while the granular materials were randomly packed in a 320 mm diameter specially-designed steel tube. In all tests, the initial bullet velocity and the depth of penetration in the granular material were measured, and the penetration depth was plotted as a function of bullet type and filling material. This was done to study the behaviour of granular materials during bullet impact, and at the same time establish an experimental database for validation of numerical methods. Secondly, a discrete particle-based approach [35] was used to model sand and its interaction with the bullet during penetration. The method has been implemented in the non-linear finite element code IMPETUS Afea Solver [36]. It works with discrete, rigid, spherical particles that transfer forces between each other through a penalty-based contact formulation. Modelling the sand as discrete particles allows for a numerically simple and robust treatment of its interaction with structural parts represented by finite elements (see Refs. [25,34]), and several parametric studies for increased understanding of this particular penetration problem have been carried out. As will be shown, good agreement between the experimental and predicted results is in general obtained, especially when the complexity of the problem and the simplicity of the approach are taken into account.

2. Experimental set-up

2.1. Test rig

The ballistic set-up used in the experimental study is similar to that described in Børvik et al. [37,38]. Here, a 7.62 × 63 mm smooth-bore Mauser gun or a 12.7 × 99 mm McMillan sniper rifle with barrel lengths of about 1 m was used to fire the different bullets. Note that the McMillan rifle gives gyroscopic stability to the bullet by spinning it around its own axis of symmetry, while spin is absent when using the smooth-bore Mauser gun. During testing, the stock was removed and the weapon was mounted in a rigid rack inside a 16 m^3 impact chamber. This fixture guaranteed a well-defined impact point in all tests, and the various rifles could be fired by a magnetic trigger from safe distance. Several independently operating optical velocity measurement systems, shown to be accurate to within 1–2% [38], were used to measure the initial velocity of the bullets just before impact with the target. Due to the opaque nature of the granular materials, no high-speed cameras were used in these tests.

To be able to confine the granular materials during impact and to measure the penetration depth after impact, the jig shown in Fig. 1 was designed. It consists of a thick-walled steel tube with inner diameter $D_t = 320$ mm, wall thickness $H_t = 12.5$ mm and length $L_t = 1000$ mm. The tube was mounted in a frame, making it possible to turn the tube around its own midpoint into an upright position. In the upright position the tube was randomly packed with the granular material to be tested. A steel disc (with a central hole of 30 mm) was used to close the tube. The hole was sealed by a thin plastic film to hold the granular material in place before testing. Due to the disc the granular material was marginally compressed inside the tube. The distance from the muzzle of the rifle to the front of the tube was 500 mm in all tests.

After firing, the penetration depth was carefully determined by removing the granular masses along the penetration channel. In most of the tests, the bullet left a trail of compressed and partly fractured material that could be followed. Due to difficulties in finding all the embedded bullet parts after a test, the granular material was filtered as it was removed. This procedure was in several of the tests rather tedious, and even though this was done with great care some experimental uncertainty must be expected. Advanced digital diagnostic techniques for measurements during ballistic penetration of sand have been proposed (see e.g. Refs. [28–30]), but such sophisticated approaches were not considered in these tests. After each test, the tube was filled with new masses and a new test could be conducted.

It should finally be noticed that due to the limited diameter of the tube, the granular material will be confined inside the rigid steel tube during penetration. The effect of this confinement compared to naturally confined materials is not known. However, since the impact velocity is high and the tube diameter is significantly larger than the diameter of the bullets this effect is assumed negligible. In this study, all tests were carried out under identical impact conditions using well-defined boundary conditions. The effect of the boundary conditions will be studied numerically in Section 4.

2.2. Granular materials

Four different fractions of the same granular material have been used in this study, i.e. 0–2 mm wet and dry sand, 2–8 mm gravel, 8–16 mm crushed stone and 16–22 mm crushed rock. The grading curves and medians of the various granular materials are given in Fig. 2. All materials used in the tests are based on concrete aggregates from Årdal in Sogn, Norway, and the mineral composition is feldspar (49%), granite (40%), quartzite (6%) and dark rock (5%). These numbers are collected from samples taken from 1 to 2 mm and 2–4 mm masses. Table 1 shows some material properties for the different fractions of the granular materials with respect to the bulk material. The fineness modulus is obtained by adding the total percentage of the sample of an aggregate retained on each of the specified sieves, and then dividing the sum by 100 [39]. The density of the granular material is as seen decreasing as the fineness modulus and consequently the void-volume fraction increases.