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Projectile penetration into sand: Relative density of sand and projectile nose shape and mass

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ABSTRACT

Compacted granular materials, like sand, have a tendency to dilate and expand under shear loading. Such tendency of dilation is beneficial to inhibit projectile penetration. Furthermore, the higher the striking velocity of a given projectile, the higher is the peak strength of the sand sample. Different nose shapes (spherical, flat, hemispherical, conical and ogival) and mass (7 g, 15 g and 20 g) of projectiles were fired into sand samples of relative densities ranging from medium dense to very dense state (60%, 75% and 90%). Results showed that the pointed ogival head projectile had the lowest ballistic limit, whereas the blunt flat head projectile required the highest ballistic energy to defeat the sand block. Despite visible effect of nose shape, the mass of projectile has a larger influence on the amount of absorbed energy. On the other hand, initial compaction of the sand alters the depth of penetration marginally. This is attributed to the projectile impact which compacts the sand as the projectile penetrates through the sand sample. A strong linear correlation between projectile nose shape, mass and ballistic impact energy was established in this study, which allows protective engineers to easily design sand barriers to defeat a range of projectiles. Furthermore, it was found that the energy absorption of sand remains high even when subjected to striking velocities way beyond its ballistic limit. This opens up avenues for sand barriers to be used as sacrificial layer of a composite lightweight protective barrier.

1. Introduction

In soil mechanics, it is a common knowledge that compacted granular materials, like sand, have a tendency to dilate (expand in volume) under shear loading [9]. This occurs when there are low void spaces between the sand grains and the interlocking grains do not have the freedom to rearrange themselves to a denser state. As such, when the sand sample is sheared, a lever motion occurs between the neighbouring grains and the layers of sand grains have to roll over adjacent layers of sand grains, thereby producing a bulk expansion of the material as shown in Fig. 1. Such tendency of dilation is high if the relative density of the sand sample (i.e. how compact is the sand) is high. Furthermore, the larger the strain rate or loading rate, the higher is the peak strength of the sand sample [18]. This is especially useful for high velocity impact. In the process of dilation, the discrete sand grains inhibit penetration and distribute the intense point pressure impact to a wider area. This is in contrast to conventional materials such as metals which undergo deformation. Moreover, the higher damping of sand as compared to metals also helps to dissipate energy passing through the sand layer. This was inferred by the Canadian Military Training Pamphlet which prescribed that 20 in (510 mm) of sand in bags is effective as proof against both armour piercing small arms bullets up to 7.92 mm calibre and bomb fragments [8]. An independent field testing by Turner [23] also showed similar findings where loosely placed sand blocks of less than 15 cm thickness prevented complete penetration of bullets from a revolver, FN FAL rifle and 12 gauge slug shotgun. Furthermore, they observed some bullets fragmenting due to extreme frictional forces offered by the sand. This is attributed to the dilative behaviour of sand under impact. In addition to its unique dilative response, compacted sand behaves like a non-brittle material in general and possesses fairly high level of residual stress even at large strains. Compacted sand can therefore offer an effective and low-cost solution to defence protection capabilities.

Given the possible benefits of sand dilation against ballistic penetration, an extensive suite of ballistic experiments with a smooth gas gun were conducted. The variables studied were: 1) relative density (i.e. compactness) of sand, 2) striking velocity, 3) mass of projectile, and 4) nose shape of projectile. Although the ultimate aim is to stop complete penetration of projectiles into the medium, this study

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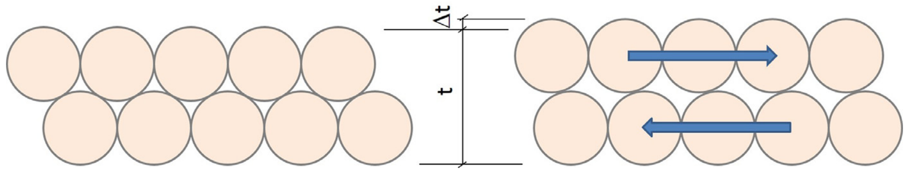

Fig. 1. Volume expansion of compacted sand due to shearing (a) Prior to shearing (b) After shearing.

seeks to explore the energy absorption of the sand medium with intention of extending to a composite material in the near future.

2. Impact testing on sand

Instrumented ballistic testing of soil has been carried out over the past 4 decades [4,5,10,11,13,14,20–22, 24,26]. Alike to other conventional materials, early works were endeavoured towards development of empirical methods of estimating the performance of soil targets. However up till the mid-90s, the classification of soil in these methods were still quantified with constants or coefficients as a function of velocity [22,26]. At later stage, more advanced analytical concepts such as cavity-expansion and Mohr–Coulomb Tresca limit yield models were introduced which account for the effects of modulus and density of the soil target [4,14,20,21]. Shi et al. [21] underlined that the assumption of locked hydrostatic material in Forrestal and Luk's [14] model does not reflect the soil's compressibility well. Boguslavskii et al. [5] mentioned that the penetration analysis carried out by Thompson [22] was not coherent. These demonstrate the challenge of estimating the ballistic performance of sand unlike more homogeneous and controlled materials such as steel and concrete.

Sand is inherently a dilative material made up of discrete particles of various grain sizes and shapes, rather than a continuum material. A sand column cannot maintain its own shape without confining support. When a projectile impacts onto sand, the sand grains rearrange and displaces around the projectile head towards the sides of the projectile body, similar to classic theories of bearing shear failure of foundations as shown in Fig. 2. The initial impact of a projectile onto sand is alike to the shallow foundation example where the sand grains in front of the foundation is pushed downwards (Zone I) and gradually displaced outward (Zone II) and upward to the sand surface as penetration progresses (Zone III). This explains Van Vooren et al.'s [24] observation that sand grains are displaced as a dart progresses through the sand medium, and there is little rotation in front of the dart. Measurements of sand grain displacement using digital speckle radiography by Addiss et al. [1] further substantiate that sand grains move in directions other than the applied force of the incoming projectile, exhibiting a shearing response. Hence, resistance to shear is therefore a suitable representative of the resistance of the sand medium against projectile penetration. In making the problem more complex, the sand's shear modulus increases with higher shear strain rate, confining stress and lower void ratio (Hardin and Drnevich, 1972). This explains

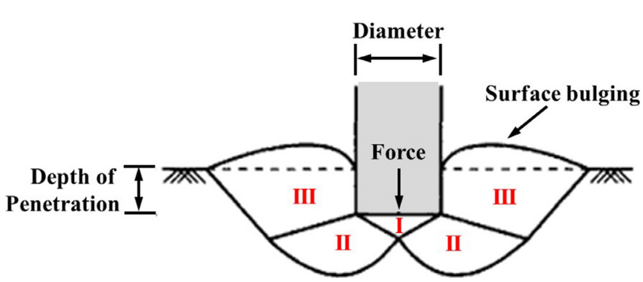

Fig. 2. General shear failure of foundation (after [25]).

Boguslavskii et al.'s [5] observation that the resistance force offered by sand increases dramatically with higher strain, similar to common knowledge of soil mechanics.

Despite the presence of several studies on sand as mentioned above, most empirical and analytical models are generally limited to ogival and conical projectile. With limited projectile nose shapes, a thorough understanding of the effect of nose shape may be inadequate. The influence of degree of compaction on projectile penetration has not been thoroughly understood either. Since sand is not a continuum material, its bulk density does not necessarily exemplify its ballistic performance. A more angular (i.e. sharper edged sand grains) sand composition would yield a lower bulk density than one with rounded grains, but the former possesses a higher internal friction angle and therefore higher shear strength according to the well-known Mohr–Columb equation:

$$\tau_f = \sigma_n \tan\phi \quad (1)$$

where τ_f is the shear strength of the sand at failure, σ_n is the normal stress applied, and ϕ is the internal friction angle of the sand. Instead of bulk density, relative density is a more representative parameter to account for the performance of sand. In soil mechanics, a relative density of 100% implies that the sand grains are arranged such that the volume of voids within the grains is the minimum. Conversely, a relative density of 0% means that the sand grains are arranged such that the total volume of voids is the maximum. These are measured according to the ASTM standards D4253-16 and D4254-16 [2,3]. It should be noted that the maximum and minimum volume of voids differ between types of sand. For sands with different angularity, the minimum and maximum volume of voids differ. The rationale of using the relative density rather than the bulk density of the sand block for analysis in this study is due to the fact that dilatancy of sand is dependent on the relative density [6]. A very high relative density of sand infers that the sand grains can no longer be re-orientated to a denser state and therefore the layer of sand grains displaced by the oncoming projectile must roll-over adjacent layers of sand grains, which invokes the dilative response.

It is well understood that the ballistic performance of sand is lower than that of conventional armour materials such as steel. The technology in steel fabrication has also made steel readily accessible in the market. However, given its lower material density and cost, sand may pose as an alternative lightweight supplemental layer since it is also an effective energy absorption medium. This is especially useful for striking velocities beyond the critical limit of a target where hydrodynamic effect dominates. In view of the ability of sand to fracture and fragment tungsten projectiles to as much as 1000 small pieces beyond the sand's critical limit of 774 m/s to 2000 m/s [4], sand is an effective energy absorber and projectile impeder which should be capitalised.

In view of the limited experimental data on the influence of relative density, projectile nose shape, a suite of experiments was carried out to provide some preliminary understanding of the effect of relative density of sand subjected to projectile impact with different nose shapes. This study also measures the energy absorptivity of sand to assess its suitability as a sacrificial layer of a composite armour.