Impact of Projectile Weight and Apex Angle on Penetration Depth in Sandy Soils

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Abstract. This study investigates the influence of projectile weight and apex angle on penetration resistance in sand. Controlled experiments were conducted using conical-nosed projectiles with apex angles of 10°, 30°, 60°, and 90°, and weights ranging from 2.445 kg to 6.81 kg. The penetration depth was measured for each configuration to evaluate the individual and combined effects of these parameters. The results revealed that both projectile weight and apex angle significantly affect penetration depth. Increased projectile weight resulted in deeper penetration due to the greater kinetic energy upon impact. Apex angle also played a critical role: where projectiles with sharp apex angles ranging between (10° and 30°) concentrated the impact force, resulting in deeper penetration, whereas those with blunt angles, i.e. (60° and 90°) dissipated energy over a larger area, reducing penetration depth. These findings have practical implications for designing protective systems and buried infrastructure in high-density soils. By isolating the effects of weight and apex angle, this study provides foundational insights that can be applied to optimize penetration resistance strategies for military and civil engineering applications.

1. Introduction

The study of projectile penetration into granular media, such as sand, is vital in the fields of military defence, civil engineering, and geotechnical applications. Sand's granular structure and inherent energy-absorbing capabilities make it an effective medium for mitigating the effects of projectile impacts [1]. However, the resistance offered by sand to penetration is influenced by several factors, including its density, grain composition, and the properties of the impacting projectile—particularly its weight and apex angle [2-4]. Heavier projectiles generate more kinetic energy, which typically results in deeper penetration. However, this effect can be moderated by the density of the sand, which influences the dissipation of kinetic energy during impact. The apex angle of a projectile, on the other hand, dictates how this energy is distributed upon contact. Sharper angles (e.g., 10° or 30°) focus the energy at relatively small area, leading to deeper penetration, while blunter angles (e.g., 60° or 90°) spread the force over a larger surface area, reducing the depth of penetration.

Many researchers have investigated the effect of different types of projectiles and explosions on soils and investigated the crater formation and penetration depth experimentally and numerically such as: Omidvar et al. [5] developed a predictive model for high-speed penetration into layered sand, demonstrating that relative density significantly alters penetration depth, with denser layers providing greater resistance to penetration. Similarly, Omidvar et al. [6] analysed the dynamic response of sand to rapid penetration by rigid projectiles, concluding that the shape and mass of the projectile had diminishing effects as the relative density of the sand increased. Further studies have explored the role of projectile geometry in penetration mechanics. Dinotte et al. [2] investigated the influence of nose shape on penetration in dry sand, emphasizing that variations in apex angle can significantly impact penetration depth, especially in high-density sand environments. Additionally, Giacomo et al. [7] utilized a vertical projectile launcher to study rapid penetration into soil targets, highlighting the combined effects of apex angle and mass on penetration outcomes. Other studies have explored additional variables that influence penetration behavior. Zhang et al. [8] suggests that projectile penetration into granular materials follows a resistive force model, where grain properties significantly affect energy dissipation. Similarly, Birch et al. [9] examined the effects of moisture content in granular media, finding that water saturation can alter penetration resistance. Further studies on penetration mechanics have explored the role of projectile shape and velocity, with insights from Archimedes' law helping to explain resistive forces encountered in sand [10]. Nagy [11] conducted a numerical evaluation of craters produced by explosions on soil surfaces, demonstrating how blast-induced deformations impact soil mechanics and penetration depth. Nagy et al. [12] presented a numerical investigation of surface explosion effects on clay soils, emphasizing soil-structure interaction and deformation characteristics under explosive loading. They further extended their research by performing a comprehensive nonlinear finite element analysis to assess surface explosion effects on buried structures [13]. Also, Nagy et al. [14] developed a nonlinear numerical model to investigate the impact of surface explosions on buried reinforced concrete structures, highlighting the role of blast wave propagation in subsurface environments. Additionally, studies have demonstrated that ricochet effects at low impact velocities can influence penetration depth, particularly in loose granular formations [15].

Despite these advancements, there remains a gap in the literature concerning the isolated effects of projectile weight and apex angle on penetration depth in very dense sand, particularly at a relative density of 95%. Most existing studies consider multiple variables, such as velocity, material composition, and soil reinforcement, which complicates the understanding of the individual contributions of weight and apex angle. This study aims to fill that gap by systematically investigating the influence of those two parameters on penetration resistance in very dense sand. By maintaining consistent conditions for other variables, this research provides foundational insights that can enhance the design of more effective protective systems in both military and civil engineering contexts.

2. Methodology

This section, clearly describes the experimental setup, materials, procedures, and measurement techniques used in the investigation. It ensures the reproducibility of the results and allows readers to understand the influence of varying the weight and apex angle of the projectile on the penetration of the projectile.

2.1. Experimental Setup

The experiments were conducted using a wooden test tank with internal dimensions of 50 × 50 × 50 cm as shown in figure 1. Dimensions were selected to eliminate boundary effects while providing sufficient depth for projectile penetration without interference with the tank walls [16].

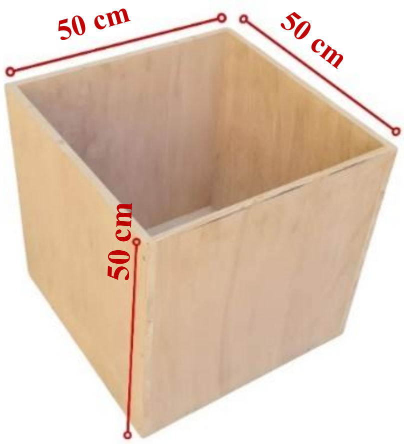

Figure 1: Experimental wooden tank dimensions.

2.1.1. Target Material. The sand used in the study consisted of 97.3% sand, 2.3% gravel, and 0.4% fines, aligning with the properties outlined in figure 2 and table 1. To achieve a relative density of 95%, the volume of sand deposit is selected to be 50 x 50 x 40 cm, then from volume and density the calculated weight of sand deposit is compacted in layers of approximately 10 cm for each layer until reach the selected volume to validate the sand density.

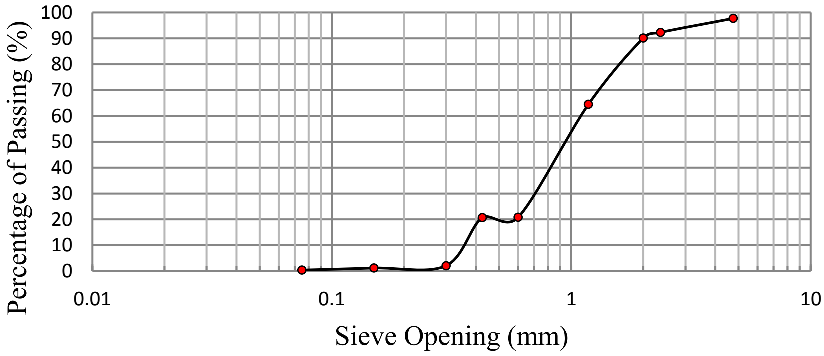

Figure 2: Particle size distribution of sand.

The laboratory tests: sieve analysis, standard proctor test, and direct shear tests are performed, and the resulted soil key properties are as given in table 1.

Table 1: Sand soil properties.

Key properties	Value
Uniformity Coefficient (Cu)	3.371
Coefficient of Curvature (Cc)	1.186
D10	0.35 mm
D30	0.7 mm

D60	1.18 mm
Angle of internal friction (φ)	37°
Cohesion	0
Maximum dry density ($\gamma_{d,max}$)	1.8 gm/cm^3
Optimum Moisture Content (OMC)	8.7%
Young's Modulus (E)	35 MPa
Poisson's ratio (v)	0.3

2.1.2. Projectiles. Conical-nosed projectiles made of mild steel were used to maintain consistent material properties and eliminate variability due to deformation. Four different apex angles were tested: 10°, 30°, 60°, and 90° as presented in figure 3 (a). For the weight variation study, the projectile with a 90° apex angle was used as the baseline. Additional extensions were added to incrementally increase the total projectile weight to 2.445 kg, 3.87 kg, 5.33 kg, and 6.81 kg. This allowed for a systematic study of how projectile mass affects penetration depth. To address stability issues during free fall, tail wings showed in figure 3 (b) were attached to all projectiles to maintain a straight trajectory and accurate impact point

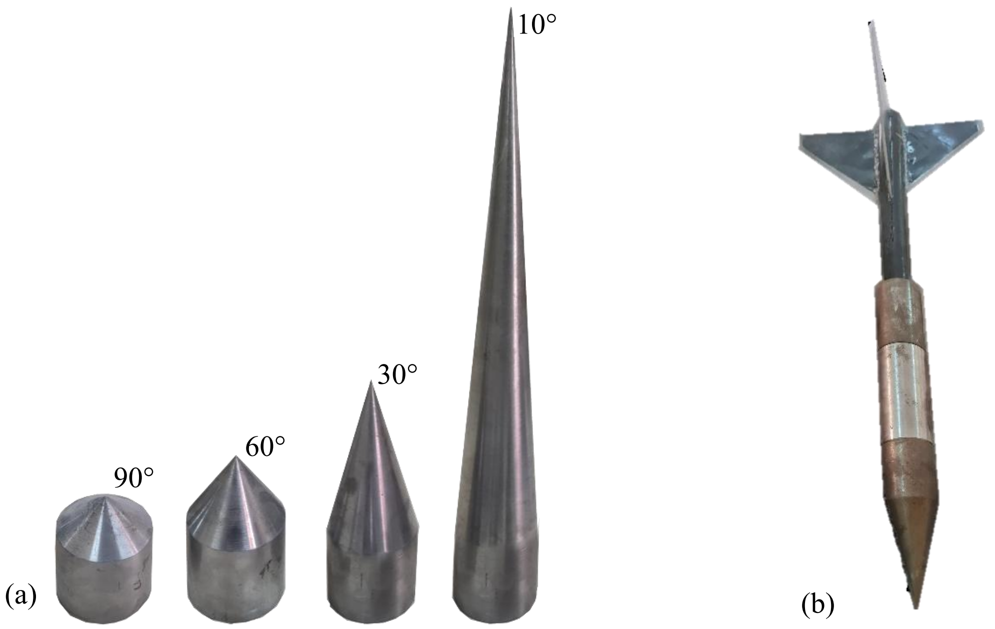

Figure 3: (a) Different apex angles used in experiments (b) Extension tail wings.

2.1.3. Projectile Release Mechanism. A free-fall setup was used to release the projectiles from a consistent height of 4.295 meters, ensuring uniform impact velocity across all tests. This setup ensured that the projectiles impacted the sand surface perpendicularly, and precisely in the centre of the sand surface, providing consistent and repeatable results (see figure 4).

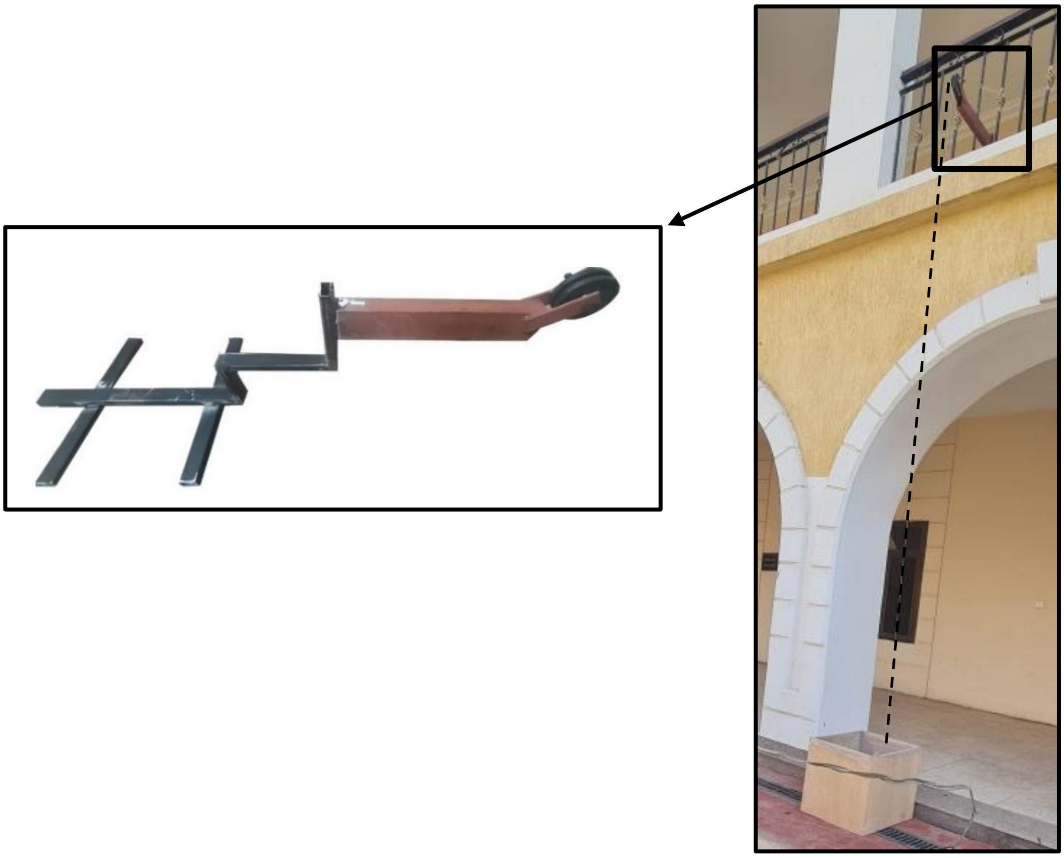

Figure 4: Experimental setup.

2.1.4. Measurement of Penetration Depth. Penetration depth was measured directly after each test. The projectiles were marked with a painted ruler to enable precise measurement of penetration depth, while the tank was also fitted with a calibrated paper ruler to cross-check the recorded values as shown in figure 5. To ensure reliability and consistency, each test condition was repeated three times, and the average penetration depth was recorded.

Figure 5: Measurement rulers adhered to tank walls and painted on projectiles.

3. Results and Discussion

3.1. Influence of Projectile Weight on Penetration Depth

Testing program is presented in table 2. The first set of experiments (Test numbers 1 – 4) focused on examining the influence of increasing projectile weight on penetration depth while using a projectile of a fixed apex angle of 90°. The weights of the tested projectiles were 2.445 kg, 3.87 kg, 5.33 kg, and 6.81 kg. The penetration depths corresponding to each projectile was measured and plotted. Figure 6 demonstrated that increasing the weight of the projectile significantly contributed to increasing the penetration depth of the projectile. Such behaviour could be attributed to the increase of the kinetic energy of the projectile, which lead to deeper penetration in the very dense soil. The dense sand's tightly packed grains create significant friction and energy dissipation, reducing the extent to which additional weight contributes to deeper penetration.

Table 2: Parametric study tests data.

Test #	RD (%)	Soil Type	γ_d (g/cm^3)	α (°)	W_{ptotal} (kg)	d_p (cm)	Notes
1	95	Very Dense Sand	1.781	90	2.445	16.2	Different weights.
2				90	3.87	18	
3				90	5.33	18.9	
4				90	6.81	21.5	
5				60	2.48	20.2	-
6				30	2.76	23.3	Repeatability.
7				30	2.76	23.1	
8				30	2.76	23.5	
9				10	3.665	34	-

Where (RD) is relative density of sand target, (γ_d) is the dry density of sand target, (α) is the apex angle of projectile's conical nose, (W_{ptotal}) is the total weight of the projectile, and (d_p) is the penetration depth of the projectile in the sand target.

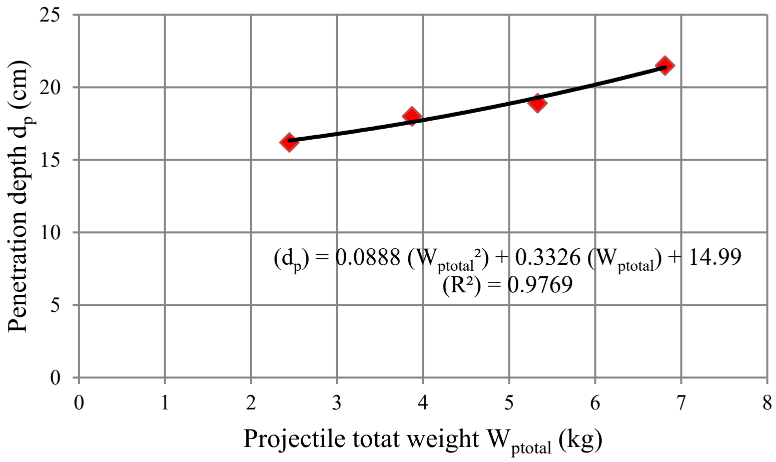

Figure 6: The effect of projectile total weight (W_{ptotal}) in very dense soil target (RD = 95%) on penetration depth (d_p).

To further quantify this relationship, a second-degree polynomial regression was performed based on the experimental results, as illustrated in Figure 6. The resulting correlation equation is:

$$d_p = 0.0888\,(w_{ptotal}{}^2) + 0.3326\,(w_{ptotal}) + 14.99 \qquad (R^2 = 0.9769) \qquad \text{Equation (1)}$$

This empirical equation captures the non-linear trend observed in the data, where the penetration depth increases progressively with projectile weight. The presence of both quadratic and linear terms confirms that the effect of weight is not purely proportional; rather, its impact becomes more pronounced at higher values. The high coefficient of determination ($R^2 = 0.9769$) indicates that the model accurately fits the experimental data and reinforces the conclusion that projectile weight plays a key role in overcoming the resistance of dense sand and increasing penetration depth.

3.2. Influence of Projectile Apex angle on Penetration Depth

The second set of tests evaluated the effect of apex angle on penetration depth while keeping the projectile weight constant. The investigated apex angles were 10°, 30°, 60°, and 90°. For the 30° apex angle, the experiment was repeated three times to ensure consistency and repeatability. Data presented in figure 6 demonstrated that sharper apex angles (10° and 30°) resulted in greater penetration depths compared to blunter angles (60° and 90°). This outcome is attributed to smaller area which interact with the projectiles of smaller apex angles generating higher stresses, allowing the projectile to remarkably penetrate the dense sand. In contrast, blunter apex angles distribute the impact force over a larger surface area, increasing the resistance from the sand and decreasing the depth of penetration. The findings are consistent with the work of Dinotte et al. [2], who reported that projectiles with sharper nose geometries achieved deeper penetration in granular media due to the concentrated stress at the point of contact. Additionally, Giacomo et al. [7] observed similar results in soil penetration experiments, highlighting the critical role of apex angle in determining penetration performance.

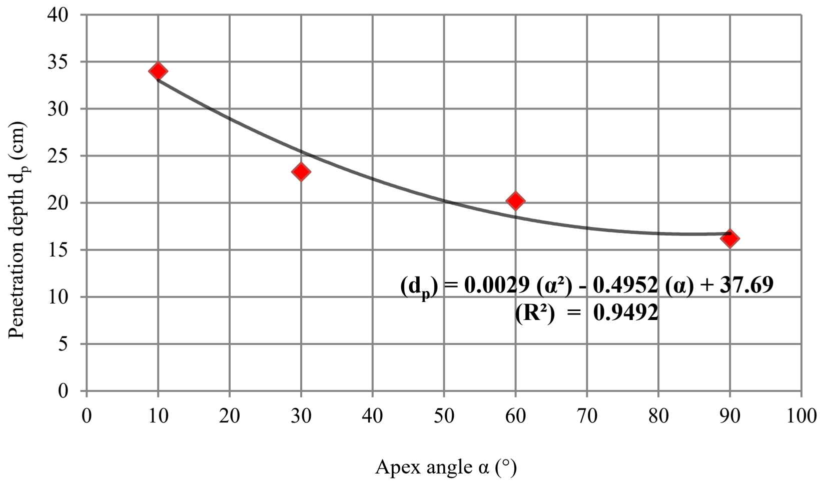

Figure 7: The effect of different projectile apex angle on penetration depth (d_p).

To mathematically describe the observed trend, a second-degree polynomial regression was applied to the experimental results, yielding the following empirical equation:

$$d_p = 0.0029\,(\alpha^2) - 0.4952\,(\alpha) + 37.69 \qquad (R^2 = 0.9492) \qquad \text{Equation (2)}$$

This equation effectively captures the non-linear inverse relationship between apex angle (α) and penetration depth (d_p). The negative linear and quadratic coefficients indicate that as the apex angle increases, the penetration depth decreases at an accelerating rate. The high coefficient of determination ($R^2 = 0.9492$) confirms the model's ability to accurately represent the experimental data. This regression further reinforces the conclusion that sharper projectile noses enhance penetration capability by concentrating impact stresses, whereas blunter noses lead to a broader contact area and greater resistance from the soil.

4. Conclusion

This study systematically investigated the effects of projectile weight and apex angle on penetration depth in very dense sand with a relative density of 95%, ensuring controlled experimental conditions. The main findings from the current research can be found as follows:

- Increasing projectile weight results in greater penetration depth due to higher kinetic energy at impact.
- Sharper apex angles (10° and 30°) lead to deeper penetration, as they concentrate impact force on a smaller area, allowing the projectile to overcome sand resistance more efficiently.
- Blunter apex angles (60° and 90°) distribute force over a larger area, increasing penetration resistance and reducing penetration depth.
- The results demonstrate that both projectile weight and apex angle play a crucial role in penetration resistance, but their effects are moderated by the density of the granular medium.

These findings provide practical insights into the design of protective systems and future research in penetration mechanics.

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