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S. J. Bless, D. T. Berry, B. Pedersen, and W. Lawhorn

Institute for Advanced Technology, The University of Texas at Austin
3925 W. Braker Ln., Ste. 400, Austin, TX 78759

Abstract. Tungsten projectiles were shot into sand at velocities between 600 and 2200 m/s. Penetration was maximum at about 775 m/s. Below that velocity, projectiles were apparently stabilized by a fin set. Above that velocity, projectiles were broken by transverse loads. High-speed penetration resulted in comminution of sand particles, reducing their size by about 1000 times.

Keywords: sand, granular materials.
PACS: 83.10.Pp, 83.80.Fg.

INTRODUCTION

High-speed projectiles do not penetrate well into sand. For reasons that are not yet well understood, trajectories often become unstable. Allen et al. [1] fired conical nose steel rods into sand at 600–900 m/s. The data indicated drag coefficients in sand of 1 to 2.

Savvateev [2] used an electric gun to launch short tungsten rods from 750–2900 m/s. Due to erosion, penetration was maximized at about 2.2 km/s. Flis [3] modeled penetration of conical projectiles in sand using an aerodynamic equation. He found that a cone angle of greater than 28 degrees was necessary for stability. Lopatin [4] conducted reverse impact experiments on rods of various nose shapes. He concluded that an ogive was the best nose shape for minimizing drag.

EXPERIMENTAL PROCEDURE

Projectiles were 5 mm diameter, 50 mm long, 14 g 93%W-Ni-Co, the properties of which are given in [5]. Sketches of the designs are shown in Fig. 1. They were flight stabilized with either a fin set or flare, made from aluminum, press-fit onto the rear. As shown, there were three nose designs: ogive, hemispherical, and conical.

The targets were sand-filled wood boxes, approximately 20 × 20 × 244 cm. There were paper time-of-arrival (ToA) screens (paper coated with a conducting mesh) every 15 cm. The sand was Ottawa coarse silica sand (92% of particles between 0.4 and 0.6 mm). The projectiles were fired in separating sabots with a .50-caliber powder gun.

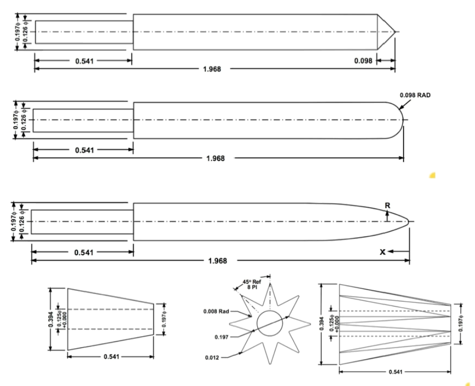

Figure 1. Projectiles, fins, flares. Dimensions in inches.

EXPERIMENTAL RESULTS

The penetration results are given in Table 1 for the three nose shapes and the two stabilizer designs. Penetration is normalized by penetrator length. In two cases, the penetrator exited the rear of the sand tank. The exit velocity was used to estimate total penetration with data from other shots in which velocity decay was measured; uncertainties for those shots are included in the table. In several shots in which penetration was relatively low, the penetrator swerved and hit the side of the box. Penetration as a function of velocity is plotted in Fig. 2.

As velocity increased, the projectile began to break up. Fig. 3 illustrates recovered projectile fragments. The number of fragments is plotted as a function of velocity in Fig. 4.

Angle of attack (AoA) data are also included in Table 1. Penetration as a function of AoA and velocity is plotted in Fig. 5.

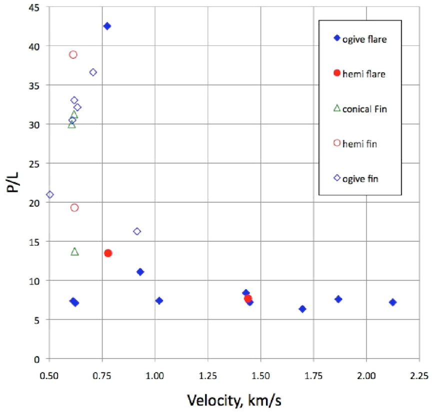

Figure 2. Penetration normalized by projectile length vs. velocity reached a maximum at 774 m/s.

Figure 3. Projectiles broke into more pieces at higher velocities.

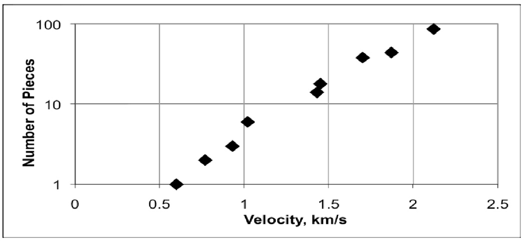

Figure 4. Number of fragments of projectile vs. impact velocity.

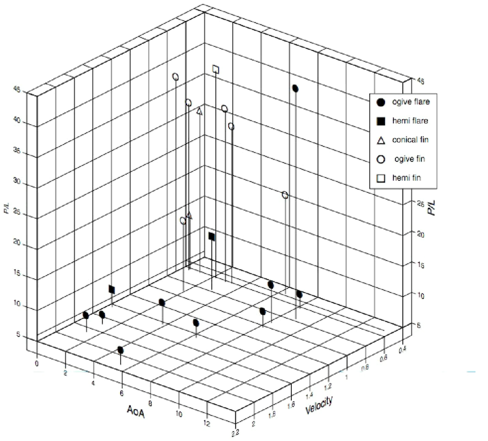

Figure 5. Angle of attack did not by itself correlate with penetration.

The data are sparse for some conditions, but they are consistent with these observations:

(1) There is not a systematic effect of the stabilizer design.

(2) High penetration is only observed for velocities $\leq$ 774 m/s. Even at velocities < 774 m/s, the data bifurcate: a high branch with P/L about 30, a low branch about half that for fin stabilizers, and less for flare stabilizers.

(3) The bifurcation is not a function of impact AoA for flares. There are not enough data to establish this for fin stabilizers.

(4) At velocities above 774 m/s, penetration plateaus. For flare stabilizers, the asymptotic penetration is P/L about 7. There are no high-velocity data for fin stabilizers.

(5) The decrease in penetration at about 774 m/s correlates with the onset of fragmentation. Above that critical velocity, fragmentation increases monotonically with impact velocity.

Velocity inside the target box was measured from the ToA screens. Results are given in Fig. 6. The behavior was approximately consistent with simple drag, in that a great deal of penetration occurred even after the velocity decayed to a small fraction of its initial value. But the data cannot be fit by a constant drag equation—to use simple drag equations requires a drag coefficient that increases as the projectile slows down. The value of drag coefficient computed for conical projectiles was 1.8 to 2.4. This is a little higher than the value reported in [1]. The discrepancy is probably due to the neglect of the area of the stabilizer in our calculations. This interpretation is supported by Fig. 7, in which there is clear evidence of interaction between the fins and the sand.

Table 1. Penetration data (velocity is in km/s; AoA in degrees)

Shot	Nose	Velocity	AoA	P/L	Rear
SCR 1122	Cone	0.617	1.1	31.2	Fin
SCR 1129	Cone	0.606	NM	30.0	Fin
1138	Hemi	1.439	0.3	7.7	Flare
1153	Hemi	0.778	3.0	13.5	Flare
SCR 1123	Hemi	0.613	2.2	38.9	Fin
SCR 1130	Hemi	0.619	NM	19.3	Fin
1135	Ogive	1.697	1.3	6.4	Flare
1136	Ogive	1.448	6.3	7.2	Flare
1137	Ogive	1.43	3.8	8.4	Flare
1145	Ogive	1.867	1.3	7.6	Flare
1146	Ogive	2.124	5.4	7.2	Flare
1147	Ogive	1.02	8.2	7.4	Flare
1148	Ogive	0.93	8.2	11.1	Flare
1149	Ogive	0.774	8.9	42.5$\pm$ 4.5	Flare
1162	Ogive	0.744	8.6	5.1	Flare
1163	Ogive	0.739	4.6	11.5	Flare
SCR 1124	Ogive	0.609	3.3	30.5	Fin
SCR 1218	Ogive	0.707	0.0	36.6 $\pm$ 4.0	Fin
SCR 1220	Ogive	0.623	8.2	7.1	Flare
SCR 1221	Ogive	0.613	NM	7.4	Flare
SCR 1244	Hemi	0.620	0.4	13.7	Flare
SCR 1245	Ogive	0.503	6.4	21.0	Fin
SCR 1258	Ogive	0.633	0.4	32.1	Fin
SCR 1259	Hemi	0.656	3.2	35.1	Fin
SCR 1260	Ogive	0.618	2.9	33.0	Fin
SCR 1262	Ogive	0.915	1.9	16.3	Fin

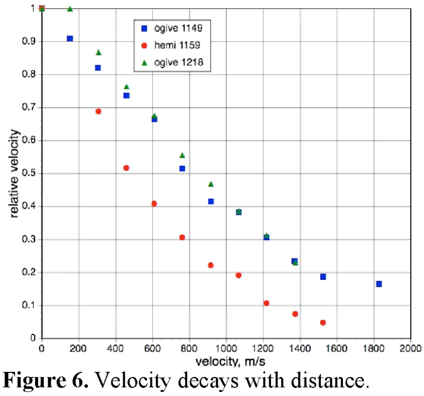

Figure 6. Velocity decays with distance.

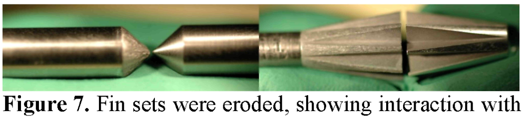

Figure 7. Fin sets were eroded, showing interaction with sand.

Sand in the path of the projectile was pulverized, as shown in Fig. 8. The reduction in grain size was approximately three orders of magnitude. The crushed sand was easily identified by its white color when the target box was carefully excavated, as noted in [1]. The veins of crushed sand came to a sudden stop near the end of the penetration channel, at a point where the velocity was about 80 m/s.

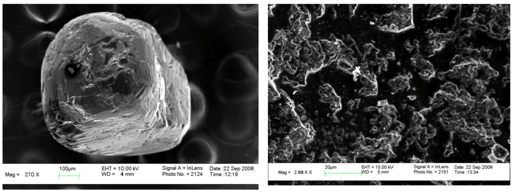

Figure 8. Starting sand particle and fractured sand grains.

DISCUSSION

We believe that maximum penetration represents a transition from rotation to localized fracture of the penetrator. The transverse moment probably increases with velocity. When the rod does not break, the effect of transverse forces is to cause the rod to yaw, which is resisted both by its high moment of inertia and the stabilizing effects of fin lift. However, at a critical velocity, the local stresses are sufficient to fracture the projectile.

SUMMARY

Penetration of rods in sand can be stabilized by flares or finsets. Extremely high values of scaled penetration can result. However, data bifurcate, which does not correlate with AoA. Above about 774 m/s, projectiles begin to break up, and penetration decreases dramatically.

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