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# HIGH-SPEED PENETRATION INTO SAND

A.F. SAVVATEEV, A.V. BUDIN, V.A. KOLIKOV, PH.G. RUTBERG

Institute of Problems of Electrophysics of Russian Academy of Sciences (IPE RAS), Dvortsovaya nab. 18, St.-Petersburg, 191186, Russia.

**Abstract**—The series of experiments aimed at the exploring high-speed impact of bullet on non-solid target were carried out at IPE RAS. The electro-discharge launcher (EDL) employed in these experiments can reach the projectile velocities of 4 km/s. The following topics were considered: the phenomena related to the high-speed penetration into non-solid targets, the parameters that influence the penetration depth and the projectile design suitable for the deepest penetration into sand. Experimental equipment allows the measurement of the penetration depth of bullet, its path inside the sand and the shock waves caused by the high-speed bullet impact. Experiments had shown the absence of significant deviation from a straight-line trajectory for the any tested bullet shapes at the impact velocity of 1.5-3.0 km/s. The most interesting result is the existence of a critical velocity for this type of interaction. The full bullet wear due to the friction with sand occurs at this velocity. The critical velocity value depends on bullet material and dimensions. Experiments show that exceeding the critical velocity leads to reduce in penetration depth. The influence of bullet material, shape and velocity on its penetration depth into sand was measured. These data allow a determination of the main characteristics of projectile for deep penetration into sand.


## INTRODUCTION

The experiments were carried out at IPE RAS to study the high-speed interaction of different bullets with granular targets. Similar experiments have been performed by other authors [1,2,3]. They consider meteorite impacts into a ground at higher impact velocities (usually more than 6 km/s). In this paper the results of experiments for high-speed impact of shaped bullets into sand is presented.

The EDL was used as accelerator in experiments performed. The use of the EDL enables a bullet velocity up to 4 km/s [4,5]. Dry sand was used as the target. The density of sand (granular material) is 1.82 g/cm$^3$.

Bullet penetration ability from high-speed impact into sand was studied. The first stage was to study the phenomena related to such impact. We explored the processes of the high-speed interaction of a bullet with sand, defined the principal features of such interaction. It was of interest to study the parameters that influence the penetration depth of bullet into sand. In the experiments the following parameters were varied: bullet material (aluminum, steel and tungsten alloy), bullet shape and aspect ratio ($\lambda$=l/d, where $l$ - bullet length, $d$ - bullet diameter) and impact velocity $V$=1-3 km/s. The results of these experiments showed the existence of a critical velocity that when exceeded led to the reduction in penetration depth. It was caused by the wear of the bullet due to the friction with sand. The value of this critical velocity depends on the choice of bullet material and increases as melting temperature of bullet material increases. The influence of bullet shape on penetration depth is not as strong as in case of a bullet penetration a semi-infinite metal target. Results of these experiments allow us to define

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the optimal bullet parameters (shape, material and velocity) to produce the maximum possible penetration depth in sand.

## TEST INSTALLATION

The EDL of 31-mm caliber [7] was used as accelerator in these experiments. Hydrogen was the working gas. This launcher has worked in IPE RAS for more than ten years and has been a reliable scientific device to launch bodies at high speed. It is possible to accurately predict the bullet velocity for a given mass and energy input [4,5,7]. The characteristics of the launcher permit us to use bullets of different shape and mass at velocity 1.3-4.0 km/s. The typical projectile designs developed in IPE RAS for the use on EDL [8] are presented in Fig.1.

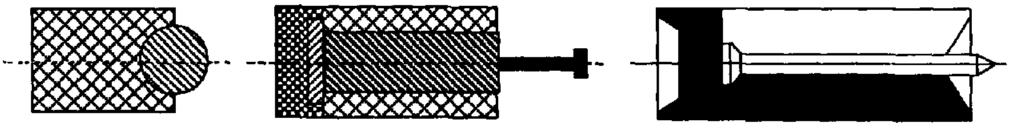

Fig. 1. Projectile designs.

The use of such aerodynamic shapes provided reliable bullet stabilization before the impact with the target unit. The target unit was filled with sand and equipped with piezoelectric pressure transducers. Inside the target box the plastic witness-plates with wire-blocking frames were installed through equal distances. These plates register both the path of the bullet in sand and its deceleration. Pressure transducers were installed on the side and rear walls of the target box to measure the shock waves. During the experiment the projectiles consisting from bullet plus sabot of mass 30-100 g were launched. Bullet mass varied from 7g to 30 g. It permits us to explore the velocity range from 1.3 km/s up to 4 km/s.

## RESULTS OF EXPERIMENT

During the first stage of experiments the phenomena of high-speed interaction of the bullet with sand were studied and the range of interest of experimental parameters was defined. Bullet materials, shape and launch velocity were varied. The experiments were carried out with bullets manufactured from aluminum, steel and tungsten alloy at the velocities of 1- 4 km/s.

Analyses of bullet residuals (Fig. 2, 3 and 4) permit us to make a some conclusions:

- the bullet follows straight line path in the sand;
- long bullets (aspect ratio $\lambda$=12, see Fig. 3) may bend in spite of high strength of bullet material;
- in addition to abrasive deterioration the bullet material may melt;
- bullet abrasive deterioration depends weakly on impact velocity at these impact velocities;
- the bullet begins to melt when its impact velocity exceeds a critical velocity that depends on bullet material.

Fig. 2. Tungsten bullets. a - original bullet shape, b - bullet after the interaction with sand at the $V$=1.3 km/s, c - bullet after the interaction with sand at the $V$=2.4 km/s.

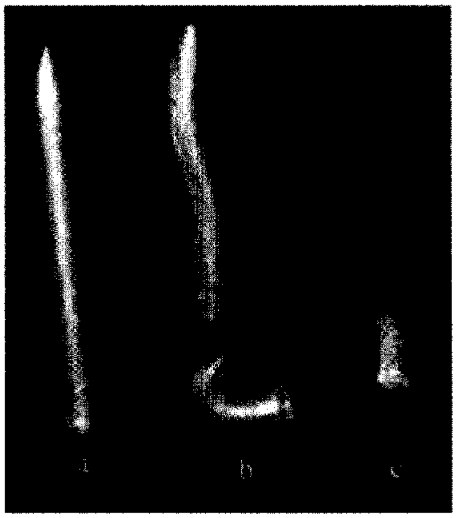

Fig. 3. Steel rod. a - original bullet shape, b - bullet after the interaction with sand at the $V$=1.67 km/s, c - bullet after the interaction with sand at the $V$=2.1 km/s.

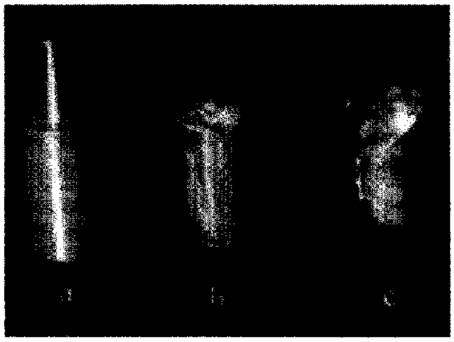

Fig. 4. Tungsten cylinder. a - original bullet shape, b - bullet after the interaction with sand at the $V$=1.3 km/s, c - bullet after the interaction with sand at the $V$=2.25 km/s.

Data obtained from initial tests suggested velocity range of interest to be 1.3-2.5 km/s. In this range the influence of bullet material, shape and velocity on the penetration depth was determined.

The most important feature of this type of interaction is the existence of a critical velocity $V_{cr}$, exceeding of which does not lead to increasing penetration depth (Tab. 1).

Table 1. Summary of bullet characteristics

| *Projectile/ material* | *Mass (g)* | *Length (mm)* | *Diameter (mm)* | *Velocity (km/s)* | *Penetration depth (mm)* |
|---|---|---|---|---|---|
| Steel ball | 8 | 12 | 12 | 0.85 | 180 |
| Steel ball | 8 | 12 | 12 | 1.3 | 220 |
| Steel ball | 8 | 12 | 12 | 1.58 | 240 |
| Steel ball | 8 | 12 | 12 | 1.67 | 230 |
| Steel ball | 8 | 12 | 12 | 2.0 | 150 |
| Steel ball | 8 | 12 | 12 | 2.27 | 130 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 1.55 | 410 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 1.65 | 410 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 2.0 | 410 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 2.3 | 390 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 2.5 | 350 |
| Fig.3. Steel | 7 | 60 | 4.7 | 1.7 | 230 |
| Fig.3. Steel | 7 | 60 | 4.7 | 2.05 | 240 |
| Fig.3. Steel | 7 | 60 | 4.7 | 2.25 | 230 |
| Fig.3. Steel | 7 | 60 | 4.7 | 2.45 | 210 |
| Fig.3. Steel | 7 | 60 | 4.7 | 2.92 | 150 |

It was found that the decrease in penetration depth is caused by the full melting of the bullet when the impact velocity exceeds $V_{cr}$. Moreover, increasing the impact velocity over $V_{cr}$ gives decreasing penetration depth due to the more extensive melting bullet. The quantitative analysis of experimental results has shown that the main parameters defining $V_{cr}$ are: melting temperature and heat of fusion of bullet material (overall energy needed for the full melting per unit mass of bullet material $E_m$). The bullet shape has a weak influence on its melting during the penetration, because the melting appears only on the front part of bullet (Fig. 2c, 3c and 4c). It can be assumed that melting rate of bullet material depends on the bullet kinetic energy. The experimental data show that for the full melting of the bullet its kinetic energy has to exceed twice the energy needed for the full bullet melting ($E_m$).

$$\frac{mV_{cr}^2}{2} = 2E_m = 2m(C_b \Delta T + \lambda_b);$$

$$\text{then, } V_{cr} = 2(C_b \Delta T + \lambda_b)^{1/2} \tag{1}$$

where m is the bullet mass, $V$ is the bullet impact velocity, $C_b$ is the bullet material specific heat capacity, $\Delta T = T_m - T_0$; $T_m$ is the bullet material melting temperature, $T_0$ is the initial bullet temperature and $\lambda_b$ is the bullet material heat of fusion. Hence, at the critical impact velocity the bullet kinetic energy is dissipated by equal quotas between the heating of sand and bullet itself.

It ought to be mentioned that Equation (1) is tested only for the explored range of bullet dimensions. The experiments used bullets manufactured from steel, aluminum and tungsten alloy (WNiFe, density $\rho$ =16.5 g/cm$^3$). Full melting of steel bullets occurs at the velocity 1.8-2.0 km/s depending on bullet shape (aspect ratio). Full melting of tungsten alloy bullets appears at the velocity 2.3-2.5 km/s. The calculated values of critical velocity according to Eqn. (1) are following: $V_{cr}$=1.84 km/s for the steel bullets and $V_{cr}$=2.4 km/s for the tungsten alloy bullets. It can be assumed that the bullet melting rate depends on the bullet size and relationship between the bullet volume and its surface. Analysis of experimental result shows that enlarging in bullet dimensions gives increasing in $V_{cr}$. It was estimated that for the bullets used at the velocity less than $V_{cr}$, the penetration depth is proportional approximately to the $V^{0.4}$.

Next, experiments studied the influence of bullet shape on its penetration depth. The bullet aspect ratio was varied from $\lambda$=1 (ball) up to $\lambda$=12 (Fig. 3a) during the experiments. The experiments show (see Tab.1) that the penetration depth (*P*) is not proportional to bullet length, a result that in differs from case of bullet interaction with a semi-infinite metal target [6]. The results against sand indicate another type of interaction. In the experiments we did not observed the dependence of maximum penetration depth normalized by the bullet length (*P/l*) on the relationship of bullet and target densities (hydrolimit $P/l=(\rho_b/\rho_t)^{1/2}$, here: *P* is the maximum penetration depth, *l* is the bullet length, $\rho_b$ and $\rho_t$ are the bullet and target material densities correspondingly). It is easy to see from table 1 that deepest normalized penetration for a ball $(P/l)_{max}$=24, but for a long rod $(P/l)_{max}$=4. Moreover, the maximum penetration depth for the bullets of different shape but produced from the same material is changing weakly (Tab.2).

Table 2. Maximum penetration depth

| *Projectile/ material* | *Mass (g)* | *Length (mm)* | *Diameter (mm)* | *Velocity (km/s)* | *Penetration depth (mm)* |
|---|---|---|---|---|---|
| Steel ball | 8 | 12 | 12 | 1.58 | 240 |
| Fig.3. Steel | 7 | 60 | 4.7 | 2.05 | 240 |
| Fig.4. Steel | 12.7 | 20 | 10 | 1.7 | 230 |
| Fig.2. WNiFe | 15.6 | 27 | 6 | 2.0 | 410 |
| Fig.4. WNiFe | 27 | 20 | 10 | 2.3 | 500 |

It ought to be mentioned that for the bullets of large aspect ratio ($\lambda$>8), bending and breaking occur (Fig. 4b) in spite of the high strength of the steel from which bullets were manufactured. Examination of bullet residuals shows only abrasive deterioration of the front of bullet and practically no deterioration of the rear and side parts (Fig. 2b, 3b and 4b). This fact testifies agrees with the absence of bullet deviation and rotation while it moves through the sand. The holes in the witness-plates demonstrate a direct trajectory of bullet.

The experiment results show that bullet material features have the strongest influence on penetration depth Tab. 3.

Table 3. Material characteristics influence on penetration depth

| *Projectile/ material* | *Mass (g)* | *Density (g/cm³)* | *Melting temp. (C°)* | *Length (mm)* | *Diameter (mm)* | *Velocity (km/s)* | *Penetration depth (mm)* |
|---|---|---|---|---|---|---|---|
| Fig.4. Al | 4.8 | 2.7 | 660 | 20 | 10 | 1.95 | 50 |
| Fig.4. Steel | 12.7 | 7.8 | 1500 | 20 | 10 | 1.7 | 230 |
| Fig.4. WNiFe | 27 | 17 | 3380 | 20 | 10 | 1.3 | 410 |
| Fig.4. WNiFe | 27 | 17 | 3380 | 20 | 10 | 1.6 | 470 |
| Fig.4. WNiFe | 27 | 17 | 3380 | 20 | 10 | 1.65 | 480 |
| Fig.4. WNiFe | 27 | 17 | 3380 | 20 | 10 | 2.0 | 495 |
| Fig.4. WNiFe | 27 | 17 | 3380 | 20 | 10 | 2.3 | 500 |

It is seen that in the explored range of bullet parameters the penetration depth is proportional to bullet material density and that the melting temperature of bullet material is determining $V_{cr}$. An empirical dependence Equation (2) that allows predicting the bullet penetration depth into dry sand when $V<V_{cr}$, is based on obtained experimental data.

$$P = 0.1\rho_b\left(26.2\sqrt{d} - 1/\lambda + 1.75l\text{-}5.3\right)(V)^{0.4} \quad (2)$$

where $P$ (cm) is the bullet penetration depth, $\rho_b$ (g/cm$^3$) is the density of bullet material, $\bar{V} = V/V_0$ is the velocity normalized by the $V_0$=1 km/s, $d$ (cm) is the bullet diameter, $l$ (cm) is the bullet length. This Equation is valid only for the explored range of experimental parameters and allows calculating of the penetration depth. The comparison of the calculated and experimental penetration depths is presented in Fig.5.

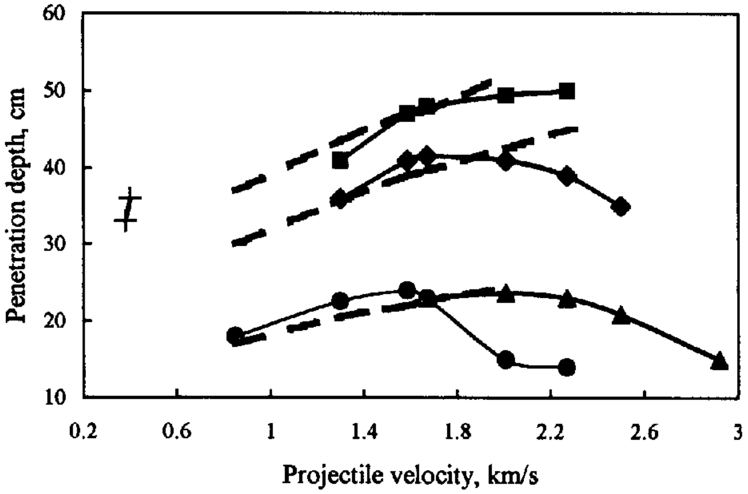


Fig.5. Penetration depth versus impact velocity; ◆ - Fig.2 (W-Ni-Fe), ▲ - Fig.3 (Steel), ■ - Fig.4 (W-Ni-Fe), ●– steel ball (dry sand), × - steel ball (wet sand); dash lines – calculation according to the Eqn. 2.

This dependence is not the final relationship but it shows the degree of each parameter influence on the bullet penetration depth during high-speed impact on sand.

The last revealed feature of the high-speed interaction of bullet with sand was the appearance of quasi-stable channel. The channel diameter was equal to 3-4 times to diameter of bullet. The existence of this channel is confirmed by the penetration of the plastic parts of sabot into sand on the same depth as a bullet itself. In case of separated flight of bullet and sabot this is possible only if plastic parts move in sand inside an already existed channel of sufficient diameter.

The obtained data allow determination of the optimal parameters for achieving the deepest penetration of sand. Thus, it is best to use bullets manufactured from refractory material of high density (W, Mo). The use of these materials allows the increasing in penetration depth due to two reasons. First is large bullet material density $\rho_b$. Secondly is to increase the impact velocity without the exceeding of $V_{cr}$. The most suitable bullet shape is a cylinder or ogive of aspect ratio $\lambda \approx 5$. In the explored range of experimental parameters the maximum penetration depth of a bullet manufactured from tungsten alloy of length 20 mm and diameter 10 mm was 50 cm at the impact velocity 2.3 km/s (Tab.2).

The disturbance propagation in sand was also explored during the performed experiments. The disturbance was provided measured by the piezoelectric pressure transducers, which were installed in the back and side walls of target unit along the bullet trajectory. The side transducers were installed at a distance of 10 cm from the target shot-line axis. The appearance of significant pressure pulses was not observed. The absence of such pulses is attributed to the high absorptive ability of dry sand.

Additional experiments showed that penetration depth depends strongly on the sand conditions (dry or wet). Presence of liquid reduces the friction between the sand particles that causes the significant increase in penetration depth of steel ball (see Fig. 5).

## CONCLUSION

The results of this experimental study show that bullet penetration depth into sand is limited by melting of bullet material. This melting process begins as the bullet velocity exceeds a critical velocity, which depends on bullet material melting temperature and takes place only on the front bullet. The amount of melted material of the bullet depends on the bullet kinetic energy. The full melting of the bullet occurs when its kinetic energy is approximately twice the energy needed for a complete melt. It is best to use refractory materials (such as tungsten alloy) for maximum depth of penetration. In this case the projectile velocity can be increased without its melting to increase the penetration depth. The most suitable shape of projectile is rod of aspect ratio $\lambda$=5-7. A projectile of greater aspect ratio bends and breaks.

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