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NUMERICAL ANALYSIS OF METAL PROJECTILE PENETRATION INTO SOIL IN HYDRODYNAMIC MODE

S.V.Fedorov[1], V.A.Veldanov[1] and V.S.Kozlov[2]

*[1]Bauman Moscow State Technical University, 105005 Moscow,
2nd Baumanskaya Str. 5, Russia*
*[2]Research Industrial Enterprise "Contour", 105120 Moscow, Lyalin Str. 5/1,
Russia*

The paper is devoted to study of high-velocity penetration of extended and compact metal projectiles into a soil target. The impact velocity range from 2 up to 7 km/s was considered. The researches were carried out on the basis of numerical modeling within the framework of two-dimensional axis-symmetrical problem of mechanics of continuum. Projectiles of different metals (steel, aluminum and lead) were calculated. At a stationary stage of penetration of extended projectiles the differences from result, predicted by the hydrodynamic theory of penetration on the base of incompressible liquid model were determined. These differences are caused by essential compressibility of soil and generation of an adjoined shock wave in it during penetration. The calculations also showed that the depth of the crater in the soil can be increased more than twice as a result of segmentation of extended projectile. The influence of the number of elements, originated from the extended projectile, and distanced from each other along the flight line on the increase of penetration depth was studied. The penetration of tube-like metal projectiles was also considered. The penetration of such projectiles can be accompanied by formation of a powerful flow of the target material, moving backward inside the projectile hollow.

INTRODUCTION

The studies of hyper-velocity interaction (velocity of some kilometers per second) of metal projectiles with soil targets can be interesting for research of heavenly bodies (planets, asteroids and comets) with the help of spacecrafts. Such projectiles can be used to create a channel (crater) in a soil of some depth and transversal size for the following deepening of a device modulus with the sensors of different purpose through it. The other area of application of the studies is the penetration of metal jets from shaped charge perforators into soils for petroleum production. At the said velocities of interaction the influence of strength properties of materials of the penetrator and soil is not considerable, and the penetration is in the regime, close to hydrodynamic [1]. During penetration the length of the projectile decreases because of flow (flowing-out) of its material.

The studies are based on numerical simulation within the framework of two-dimensional axial symmetrical problem of mechanics of continuum. In order to describe the behavior of material of the penetrator and target one uses the model for a compressible elastic-plastic matter. The pressure in the metal and the soil is determined from barotropic lines. The Tate Hugoniot is used for the metal [1].

The equation for compressibility for the soil is used as for multi-component matter, including the air voids, liquid and solid components

$$\rho_{t0}/\rho_t = \sum_{i=1}^{3} \alpha_i \left(1 + p/K_i\right)^{-1/n_i} , \tag{1}$$

where the values α_i characterize the phase composition of the matter and correspond to volume fraction of the air voids (α_1), as well as liquid (α_2) and solid (α_3) components; ρ_t is the soil material density at pressure p; ρ_{t0} is the density of the soil at normal conditions (zero pressure); K_i and n_i are test parameters [2]. At the known phase composition of the soil its density in normal conditions is determined as $\rho_{t0} = \alpha_2\rho_{20} + \alpha_3\rho_{30}$, where $\rho_{20} \approx 1000$ kg/m^3, $\rho_{30} \approx 2600\ldots2700$ kg/m^3 are the densities of the liquid and solid components. Taking into account the obvious formula $\alpha_1 + \alpha_2 + \alpha_3 = 1$ to set the compressibility law (1) one should only set the values of volume fractions of any two components. The calculations were carried out for a soil like a dense matter ($\alpha_1 = 0.25$; $\alpha_2 = 0$; shift strength is 15 MPa).

PENETRATION OF EXTENDED PROJECTILES

The penetration into the soil of extended cylindrical projectiles within the impact velocity v_0 range from 2 to 7 km/s has been simulated. Steel with yield strength of 400 MPa, aluminum and lead have been considered as projectile materials. The initial length of projectiles l_0 consisted from $2.5\,d_0$ to $10\,d_0$, where d_0 is the projectile diameter. Fig.1,a shows the relative depth of penetration L/l_0 for projectiles with different elongation l_0/d_0 into the dense soil.

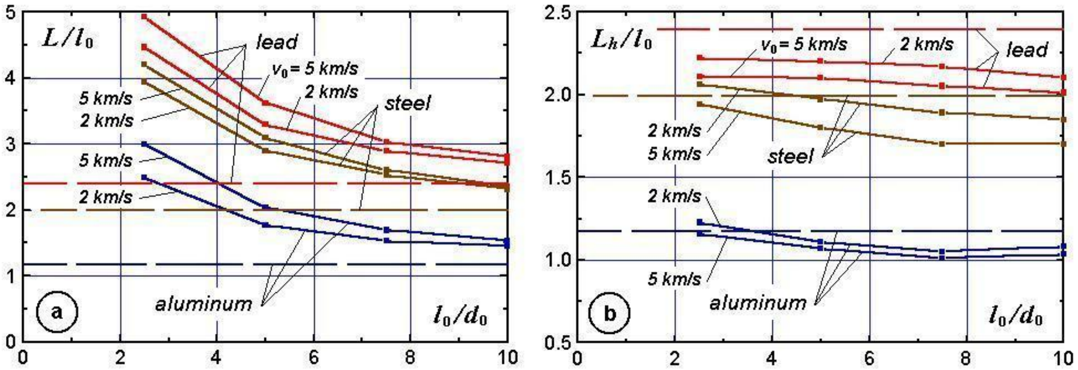

Figure 1. Total penetration depth (a) and penetration depth at hydrodynamic stage (b) for projectiles of different elongation and made of different materials

The results for L/l_0 resulted from numerical calculations exceed the level, predicted by the hydrodynamic theory of penetration, based on the model for incompressible liquid [1]

$$L/l_0 = \sqrt{\rho_{p0}/\rho_{t0}}\,, \tag{2}$$

where ρ_{p0} is the density of the projectile material (Fig.1 shows this level with horizontal dashed lines). As the projectile elongation l_0/d_0 decreases, the deviation of L/l_0 from the value (2) increases.

The analysis of the results of the numerical simulation allows to separate the process of high-velocity penetration into the soil target into two stages (Fig.2). The first stage is hydrodynamic. At this stage the projectile penetrates with “flowing” of its material. The feature of the ending of the hydrodynamic stage is complete “depletion” of the projectile length. However the increase of the crater depth in the soil doesn’t end. The second stage of the penetration begins – inertial stage. At this stage the following expansion of the crater takes place due to inertial motion of the material.

Fig.1,b shows the relative depth of penetration L_h/l_0 at the hydrodynamic stage. It happens to be, vice versa, a bit lower than the value, determined from formula (2). It’s characteristic, the increase of the interaction velocity v_0 one observes the tendency to decrease of L_h/l_0.

Fig.3 shows the increase of the penetration depth at the inertia stage L_{in}/d_0. The increase doesn’t practically depend on the elongation of the projectile and grows as its velocity increases. The increase of the relative penetration depth L/l_0 of projectiles of small elongation is connected with the small dependence of the value L_{in} on the projectile elongation l_0/d_0 (Fig.1,a).

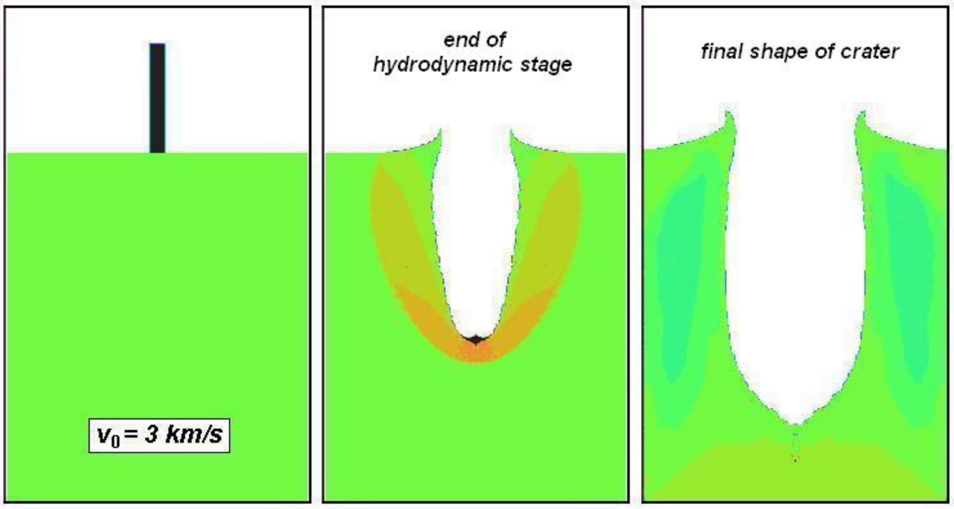

Figure 2. Stages of formation of crater in dense soil

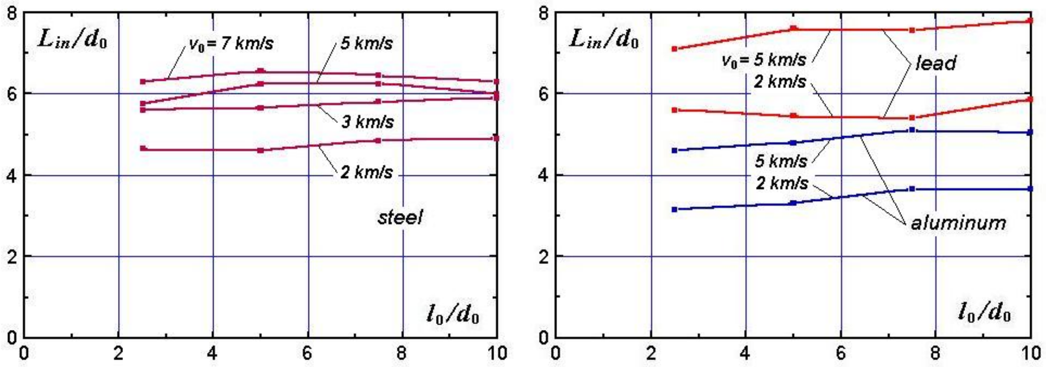

Figure 3. Increase of penetration depth at inertial stage

One considered the physical reasons of deviation of the penetration depth of extended projectiles at the hydrodynamic stage from the value (2), resulted from the hydrodynamic theory with supposition on non-compressibility of materials. The observed differences are conditioned by the considerable compressibility of the soil and formation an adjoined shock wave in it during penetration. Taking into account these facts one can develop a simple mathematical model to determine the penetration depth of extended projectiles at the hydrodynamic stage, similar to one, considered in [3]. The model includes the conservation laws for mass and momentum at the front of the adjoined shock wave in the soil, equation for the dynamic compressibility of the soil (1) and Bernulli equation, which connects the parameters at the contact point with the parameters at the shock wave front for the soil and with the non-disturbed parameters for the projectile. The material of the projectile is considered as non-compressible at that. The model allows obtaining the following formula for the penetration depth at the hydrodynamic stage

$$L_h / l_0 = \sqrt{\rho_{p0} / \rho_{t0}} \Big/ \sqrt{2 - \rho_{t0} / \rho_{ts}} \,, \tag{3}$$

where ρ_{ts} is the density of the material of the soil target at the front of the adjoined shock wave. As the interaction velocity v_0 increases, the intensity of the shock wave generated into the soil grows, that results in the decrease of the ratio ρ_{t0}/ρ_{ts} and, in accordance with (3), decrease of L_h/l_0.

PENETRATION OF SEGMENTED PROJECTILES

The increase of the crater depth in the target can be achieved by separation (segmenting) of an extended projectile into separate elements, moving in series (one after another) at some distance (stand-off) from each other [4,5]. The number of factors, conditioning the increase of the penetration depth, includes the number of elements *n*, resulted from the separation of the extended projectile ($l_e = l_0/n$ is the longitudinal size of the separate element) and distance between neighboring elements h_e (distance from neighboring elements along the motion line). Fig.4 shows the penetration of the extended ($l_0 = 4d_0$) and "separating into four" ($l_e = d_0$) steel projectiles. One can see the increase of the distance h_e between the elements results in the increase of the penetration depth, and the decrease of the average crater diameter. It's clear the increase of the crater depth from the increase of the distance between elements h_e will happen only to some limit; then one will see some "saturation" (the following "distancing" will have no effect on the crater depth). The feature of achievement of "saturation" is a characteristic wavy shape of the side crater surface (obvious sections of the crater, formed by separate elements). The increase of the interaction velocity v_0 should also results in increase in distance between segments, at which the penetration depth is maximum. Correspondingly, the more the velocity v_0 is, the bigger the increase in penetration depth due to segmenting (separation) of the projectile can be achieved.

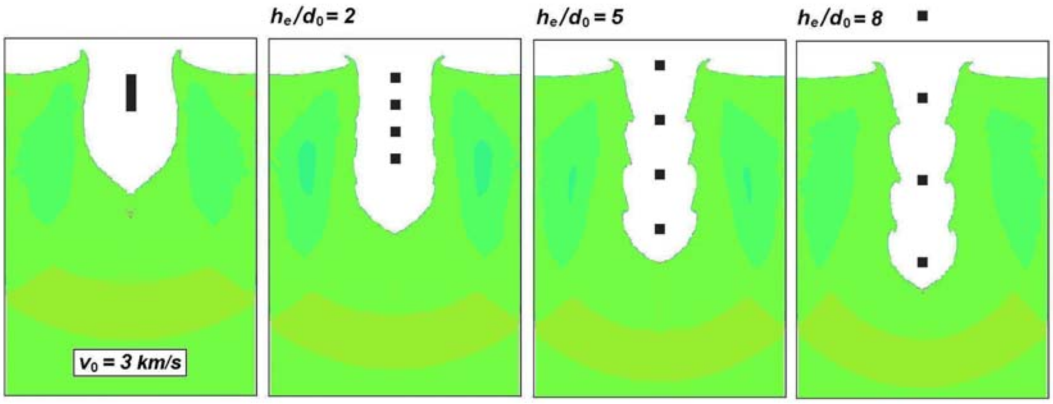

Figure 4. Influence of distance between elements on crater depth

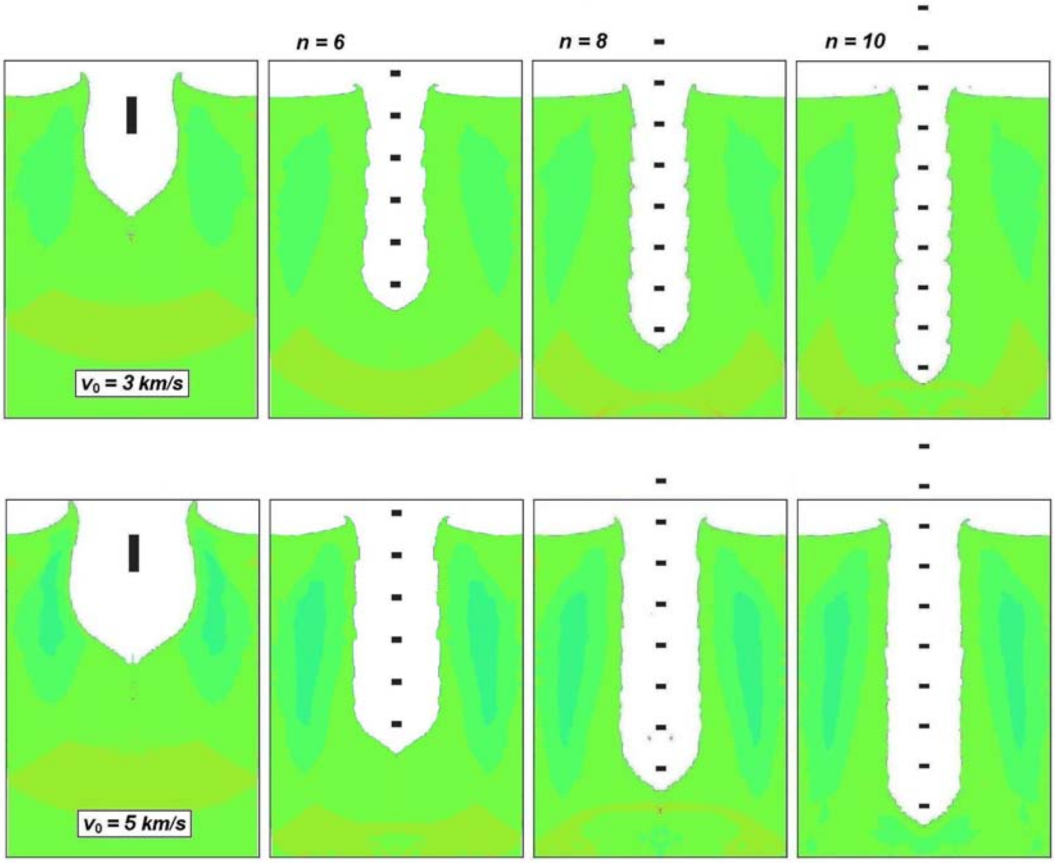

Figure 5. Influence of number of elements on crater depth

The increase of the penetration depth (accompanied by the decrease of transversal size of the crater) also resulted from the increase of number of segments n, originated from the extended projectile (Fig.5). The elongated steel projectile ($l_0 = 4d_0$) at separation into ten elements ($l_e = 0.4d_0$) distance $h_e = 4d_0$ the crater depth increases more than twice. One notes at a fixed number of segments and distance between them the increase of velocity of segments has just no influence on the crater depth, increasing its transversal size only.

When simulating the interaction of segmented projectiles of other metals (aluminum and lead) with the dense soil one obtained approximately the same increase of the penetration depth of the segmented projectile (in comparison with non-segmented, entire projectile), that for the analogues conditions for the steel projectile.

PENETRATION OF TUBE-LIKE PROJECTILES

Investigations of penetration of tube-like projectiles are interesting as they are used as elements of telescopic projectiles. A telescopic striker in the initial (folded) state consists of tube elements, one inserted in another, and is relatively short. Before interaction with target, the elements pulls out and the projectile length considerably increases. Fig.6 shows penetration of a steel tube-like projectile of orifice diameter $d_h = 0.5d_0$ (d_0 is the external projectile diameter) into a soil.

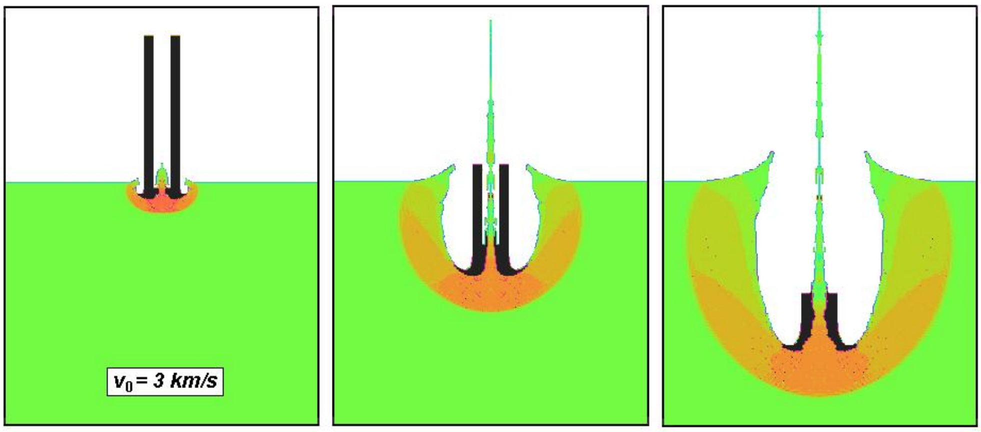

Figure 6. Features of penetration of tube-like projectile into soil

One sees the penetration of the tube-like projectile is accompanies by the formation of a powerful flow of the target material backward inside the projectile hollow.

Fig.7 shows the change in the complete penetration depth L/l_0 into the soil and penetration depth at the hydrodynamic stage L_h/l_0 for the steel tube-like projectile with elongation of $l_0/d_0 = 5$ versus the relative diameter of the internal hollow d_h/d_0 (velocity $v_0 = 3$ km/s).

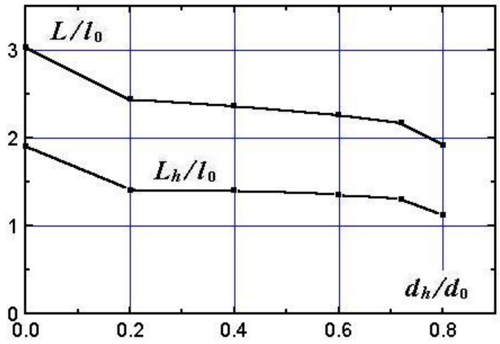

Figure 7. Influence of diameter of orifice in tube-like projectile on penetration depth

The presence of the internal hollow leads to the visible decrease of the penetration depth of the tube-like projectile. Even at relatively small diameter of the hollow $d_h = 0.2d_0$ the decrease of penetration in comparison with a solid cylindrical projectile is about 20%. The analysis of the results of numerical simulation allows supposing, that the decrease is conditioned by the soil pressure, acting in the internal hollow at the contact surface. The action of the internal pressure results in the expansion of the tube-like projectile near its end, contacting with the soil. This part of the projectile obtains visible radial velocity and bends outward. Thus the contact area with the soil and resistance against penetration increase.

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