INVESTIGATIONS IN TERRADYNAMICS

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ABSTRACT

A review of theoretical and experimental results on impact, refraction, ricochet, penetration and steady motion of rigid shapes or groups of projectiles into the terrestrial media with sub-and-supersonic velocities is represented.

KEYWORDS

Plasticity, refraction, penetration, splitting, cavitation, cavern.

INTRODUCTION

Terradynamics as a branch of science likely began with the work of Sir Isaak Newton about the cannon-ball penetration depth into the ground. Since that time a considerable volume of work has been done on various aspects of impact and penetration into metals and grounds in many laboratories of the world. First, the empirical relations to predict forces (Poncelet, 1838; Young, 1969), the cylindrical and spherical cavity expansion approximations of target response (Hill, 1980; Longcope and Forrestal, 1983) are considered. The review of physical mechanisms and engineering models in terradynamics can be found by a reader in articles by Backman and Goldsmith (1978), Anderson and Bodner (1988), the books by Sagomonian (1974) and edited by Zukas (1990). The detailed numerical modeling becomes now the main method.

This paper reviews only results on impact-penetration-refraction phenomena in the earth media obtained in the Institute for Problems in Mechanics RAS for more then twenty years. The efforts were expended to prove mathematically the known empirical polynomial representation for forces, to calculate exactly splashes at the wedge impact onto water, to clear up the empirical ricochet-refraction laws and the cavity formation by one and group of projectiles, to solve some modeling problems for different rigid bodies steady motion (or to examine its stability) into elastic and plastic media by asymptotical and approximate methods. Then the parametric analysis and optimization become possible. This topic is relevant for studies on unit and separated meteorite impact, the design of different kinetic systems at piece terradynamic technology.

THEORETICAL INVESTIGATIONS

Thin rigid wedge steady motion into elastic-brittle media. Dynamic splitting. In addition to the first known results for splitting of brittle-elastic medium, the thin wedge steady motion into homogeneous medium at intersonic speed as well as along interface at subsonic one are studied by Simonov (1984, 1985). Effects of weak singularity, cavity formation and the Brilluen-Villa condition at the point of separation as in a liquid are revealed in the first case. The analytical relations for the contact force and moment, the length of head crack are deduced in the case of wedge motion along the interface. The results based on the theory of elasticity are valid for rocks and soils possessing different dissipative mechanisms as assessments from above or from below of real integral characteristics.

Oblique entry of wedge in water. The arbitrary angle wedge impact onto incompressible liquid, known as the Wagner selfsimilar problem, has been solved with high degree accuracy by Chekin (1989). The thin wedge oblique entry is examined too but neglecting by splashes (Chekin, 1994). The rapid growth of errors in values of forces and moments versus the wedge angle increase are revealed at comparison with exact solution ($\approx$ 50% for 20^0-wedge). The pictures of pressure distribution along wedge side and splashes are shown on Fig. 1. The study of impact in hydrodynamics enables us to estimate the terrestrial events from other point than in the theory of elasticity.

Quasi-static cone motion into plastic medium. Analytical solution for the infinite rigid cone slow motion into a rigid-plastic medium was obtained by Balashov and Zvolinsky (1996). The limit shear stress is modeled by the Mohr-Coulomb failure criterion. The new experimental penetration method for the measurement of an unknown plastic medium strength is suggested.

Steady high-speed motions into elastoplastic medium. The assessments for maximum normal stress, resistance and plastic zone size are obtained by L.M. Flitman (1990, 1991) at flow of blunted (intersonic velocity) or thin sharped (subsonic speed) bodies of revolution by srength medium. Asymptotic approaches are based on the plastic boundary layer theory by Flitman (1982) or on the "thin body" assumption. The key to the theory

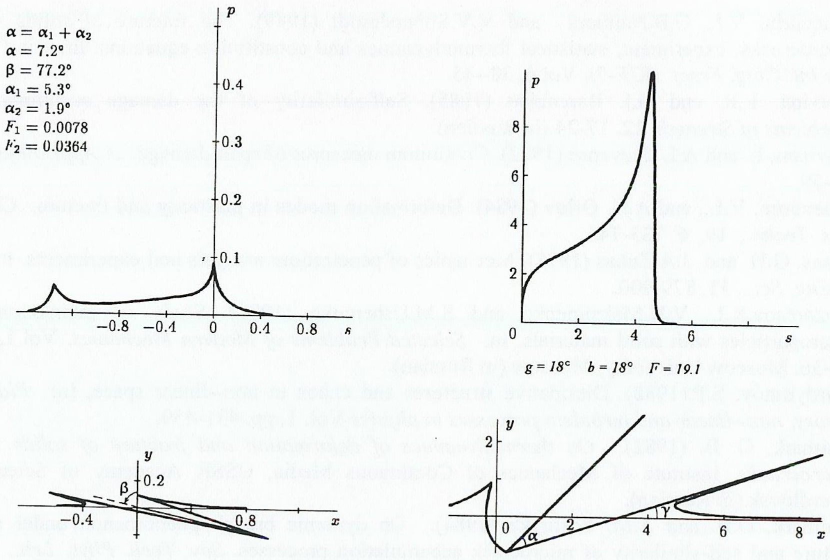

Fig. 1. Pressure p versus distance along the wedge face s and shape of distorted boundary of the liquid semi-space at the oblique wedge entry without and with splash separation

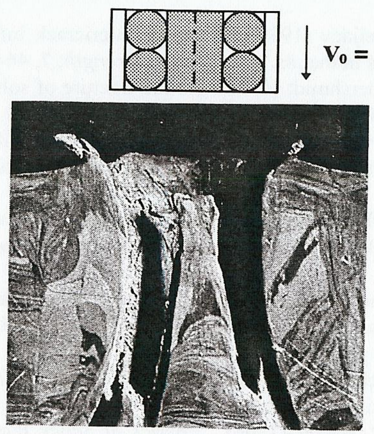

Fig. 2. Cavern after multiimpact

is to use Lavrentjev's idea that the strength led to the small corrections to the hydrodynamic results at high velocities. The structure of expressions for integral characteristics (forces, depths of penetration) is revealed to be the same as in the polynomial empirical representations. Therefore, they are proved mathematically and, moreover, the obtained coefficients in them obviously depend on the constitutive parameters.

At the relatively low velocities, when the inertia forces and cavitation are of minor importance, the minimum resistance body contour is most likely close to the ogival shape examined by Yankelevsky (1980). But when they become essential, the most part of kinetic energy of a body uses up for the cavern formation. Then the minimum resistance is approximately equivalent to the minimum cavern radius at the constant body cross-section as well as in liquid and the hydrodynamic theorem by Gonor and Zabutnaya (1985): minimum resistance shape is a configuration entered inside the cavern behind disk, becomes true. Thus, a blunted body has minimum resistance at the developed cavitation. The approximation formula for depth of penetration by blunted (continuous or like tube) bodies are deduced taking into account the cavitation (Bivin and Simonov, 1993; Simonov, 1994). The calculations predict a possibility to reach the large depths by the massive minimum resistance penetrators into the not very strong grounds as shown below.

Yield stress τ_d (kg/sm^2)	30			100			500			
Velocity v_0 (km/s)	0,5	1	2	1	2	3	1	2	3	4
Depth H	18	75	280	20	115	200	7	14	30	85

where H is related to the equivalent cylinder length.

Estimates of maximum pressure, temperature and resistive coefficient at the supersonic motion of a blunted body. Some geological media are distinguished by the low weak wave propagation velocities. Hence, the supersonic motion of a penetrator without damage is possible. To determine the maximum values of some physical parameters on its contact surface, the algebraic equations are deduced from the conversation and Hugoniot laws for head shock wave, Mie-Grünaisen or Tait constitutive equations and Bernoulli integral behind the shock (Simonov, 1995). The calculations have been made for two types of sands, clay and water at velocities from 0,5 to 4 km/s. The essential temperature decrements ($\approx 100^0 - 1000^0$) take place only for the sands and v_0 =2-3 km/s. The pressure P_* in the

stagnation point dominates over its maximum on the shock wave front for the Mach number $M < 2$ and has the same order for $M \geq 2$. The values P_* are relatively close to each other for different medium at the same velocity.

Approximate methods of calculations. They are based on the isolate elements method. The surface of a figure is mentally divided into the parts, on each of them the stress vector is considered as known if kinematics is known. In contrast to the empirical approaches, here the relations between the dynamic and kinematic parameters are supposed to be the same as in the modeling problems for steady motion of cones or cylinder or sphere. The experimental and theoretical fact that not very large differences in the contact normal stresses in various cases enable us to be sure in true order of obtaining results. The penetration experiments with clay, plasticine and sand prove the quick stabilization of contact shear stress τ at velocities more than several m/s (Bivin *et al.*, 1980; 1982). Therefore, the condition $\tau = const$ is used in contrary to the usual Mohr-Coulomb law. The curve trajectory of a penetrator is often watched in experiments. So, the stability of rectangular motion of a body into a strength media is in question. Based on the isolate elements method and a empirical criterion of the separation of the flow on the lateral surface, the mathematical model is suggested for description of the rigid body in-plain motion (Simonov, 1997). The analysis of stability by the known Liapunov method gives criteria of stability regarding the mass center position of an elongated penetrator in case of full wetting of the lateral surface and the small free zones appearance as well.

LABORATORY-SCALE EXPERIMENTS

The different calibers light-gas guns are used in experiments. They provide velocity up to 1 km/s for mass up to one kg and much more for the smaller mass. Materials of targets are clay, plasticine, sand, ice and water. The aluminum, tungsten alloy, copper and steel spheres, cylinders, cones and conecylinders are used as projectiles. The depth of penetration, cavern formation, change of trajectory, forces are the main questions under investigations.

Refraction-ricochet-penetration empirical laws. The pioneering empirical laws for refraction-ricochet phenomena are discovered at the oblique enter of different stable shapes in some terrestrial media similar to the well known Snella law in optics (Bivin, 1982; Bivin, *et al.*, 1982)

$$\sin\alpha/\sin\beta = n(v_0\ \tau_d) \tag{1}$$

where α *and* β are angles of entry and refraction, n is a function of velocity v_0 and τ_d for the strength media (clay, plasticine and sand) and is a constant for water. With point of view (1) ricochet begins under condition $\beta = 90^0$ like in optics and is the limit case of refraction and there is a smooth transformation from penetration to ricochet (Bivin, *et al.*; 1994) The calculations of the oblique impact are in reasonably good agreement with the test results (Kolesnikov, 1981). Bivin (1993) revealed very interesting differences in refraction-ricochet between the cases of unit and separated (compact group) projectiles oblique impacts. First of all the intermediate case of a partial ricochet is watched and measured. Some part of projectiles arranged in single file disposition penetrates into plastic medium and the other ricochets into air. There are two limit angles of full ricochet and full penetration. The difference between them is approximately equal 9^0 in case of three spheres. These results are relevant for understanding of response on a destroyed asteroid impact.

Method of contact shear stress and virtual mass determination. This method is worked out by Bivin *et al.* (1980, 1982). The empirical assessments of virtual mass m' have been made at the inertia motion of metal sphere and disk into water and cones into plasticine at the reentry speeds $v_0 \sim 10^2 - 10^3 m/s$. In the first case the method bases on decoding of film pictures and the Newton motion law where the force is represented as the sum of hydrodynamic and inertia resistance. In range $v_0 = 200 - 600$ m/s

$$m' = (1.7 \pm 0.6)m'', \qquad m'' = 1.35\rho a^3$$

$$m' = (2.1 \pm 0.6)m'', \qquad m'' = 2/3\rho\pi a^3$$

were m'' is the impact virtual mass, a and ρ are radius and density of body. For the light cone-shaped projectiles (Al) the non-proportionality of the penetration depth in plasticine target by mass of the body is explained by influence of virtual mass being measured as $m' = (0.64,\ 0.15,\ 03,\ 0.51)\rho\pi a^3$ versus the half cone angle $\gamma = 15^0,\ 30^0,\ 45^0,\ 90^0$. The apparent nonsense in value m' at $\gamma = 15^0$ is explained by simple reason: 30^0-cone has maximum instability and the value m' corresponds to the variable cross-section area. The fact the limit shear stress τ_d is constant on the contact surface is convincingly established by direct measurements and very important. It enables us to use surely the plastic friction condition $\tau = \tau_d = const$ in contrast to the common belief in the Mohr - Coulomb law. The point is that some restrictions on the use of the last law take place. The measured penetration depths of different shapes into the earth media are in good agreement with the theory.

Very long projectiles. Experiments with steel needles by Bobrovnitzky and Simonov (1996) are a subject of great interest with theoretical point as asymptotic $E \to \infty$, where E is elongation (one parameter degenerates), and for practice as a case, when the mass load over cross section and, consequently, penetration depth have maximum until friction does not become the main. But the small angles of entry and attack essentially influence on the contact stresses distribution in contrast to the shot penetrators. An engineering model is suggested and the strange test results are explained.

Instable and stable shapes. The study of influence of geometry on instability of motions at oblique enter and internal penetration is performed. In particular, the homogeneous 30^0-cone is established to have the shape of minimum stability. The design of optimal stable shapes and caverns is developed with regard to the rectangular motions right after impact or inside target at the developed cavitation.

Classification of craters formed by impact of group of projectiles or flow of particles. Responses of plastic media on impact are studied by Bivin (1993, 1996) in dependence on velocity (up to 1 km/s), shapes, deformability and projectiles arrangement in a group. The following general statements have been concluded from the experiments: the strong dependencies of distribution of bodies into target, crater configuration and depths on the mentioned arrangement and very wide possibility for control of the crater architecture. In particular, in case of single file disposition of N projectiles with distance l between, it is established that the cavern transverse size does not depend on N. The depth of penetration depends on v_0, N, l but it less than the unit equivalent body. The latter is a consequence of the general empirical law which can be concluded from many Bivin's experiments: the separated body penetration depth is always less (or seldom equal) than that of equivalent unit body. The cavern shapes and sizes are analyzed for different layered disposition of N metal spheres. It is well known that cavern shape as response on unit rigid body impact does not depend on its configuration, if cross section is the same, and the entry angle α. For unit deformable penetrator it depends on elongation E, v_0, α, ρ_r (relative density). Let us see the differences in case of group of projectiles. The cavern shape depends on E, v_0, α, ρ_r, N (if $N \leq 10^2$) and shapes of the pieces. Thus, at the one, two and more lays in the group this shape is a cone, $\approx$ cylinder and expanded with the depth, respectively. At the growth of number N it stops to depend on N and becomes similar to that of produced by the equivalent unit deformable projectile or flow of particles. In result, control over the cavern formation is possible and different shapes: semi-spherical, with different ratio D/H, expanding or narrowing, different sign curvature, ringing and others can be exerted. One of the cavern cross section after multiimpact is illustrated on Fig. 2. *Applications.* The above-listed fundamental researches are oriented on the design of different kinetic systems for astrophysical researches, asteroid annihilation and other piece technology (Byers *et al.*, 1978). In addition, a kinetic system is suggested for control influence on an active volcano for prevention of catastrophic events by penetration of weak places on the volcano walls in order to direct the gas-gusher and lava flow outside in the safe place (Bivin *et al.*, 1992). This method is *non-alternative.* The method of rapid and economic formation of prospect-holes and wells in the ground is developed by Simonov and Khavroshkin (1993).

CONCLUSIONS

In spite of the great achievements in terradynamics reached by many groups of scientists there are many "blank spaces" in this domain. First of all, the same fundamental problems as in hydrodynamics takes place: stability of motion and the separation of flow. Then, the influence of thermodynamics at the high-velocity processes, wear-and-tear and the accident (weak) or given various types of asymmetry, determination of the limit impact parameters for the posterior motion of a penetrator without causing its failure or, in general, any loss of its integrity, the curve trajectory control, penetration into the brittle-elastoplastic or/and layered, pre-stressed media, the constitutive equations for grounds with complex rheology as applied to the penetration process.

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