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ON YAWING MOTION, VELOCITY DECAY, AND PATH DEFLECTION OF PROJECTILES PENETRATING CAVITATING MEDIA

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April 1986

US ARMY BALLISTIC RESEARCH LABORATORY
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Simultaneously flashed orthogonal radiographs were measured to obtain the spatial location and angular orientation of a projectile penetrating gelatin and soil. A methodology that pools the measurements from several firings is developed. As a result of this pooling, the continuous nature of the yawing motion, velocity decay and path deflection can be inferred. Further, the drag, lift and overturning moment can be obtained as functions of instantaneous yaw. Keywords.

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INTRODUCTION

The depth to which a projectile will penetrate a dense medium, such as soil or water, with little or no material strength has been of interest for more than a century. Euler and Poncelet are among the early investigators who searched for correlations of penetration depth with striking velocity. Such correlation fails, however, for projectiles that are unstable during penetration because, as the yaw (angle between the projectile's axis of symmetry and the instantaneous tangent to the trajectory) increases, the resistance force (drag) increases and the depth of penetration becomes a function of random initial conditions as well as projectile design.

Simultaneously flashed orthogonal radiographs provide a highly precise means of obtaining the spatial location and angular orientation of a projectile penetrating x-ray transparent media: gelatin, water, soil, snow, etc. By arranging a sequence of such views (stations), one obtains the time history of the projectile's motion. Unfortunately the number of stations that can be juxtaposed to view the relatively short trajectory of the projectile is too small to infer the continuous nature of the projectile's angular motion, deceleration, and path. Yet, it is this continuous information that is needed to extract the forces and moments exerted by the medium on the projectile as a function of time and distance, in particular, the drag force, the lift force, and the overturning moment. And, it is these fluid dynamic characteristics of the projectile, when related to its physical properties, that are required to build a solid data base for non-deforming projectile penetration of the media of interest.

The technique described in this paper overcomes this raw data deficiency by pooling the measurements of several projectile firings (three to five are sufficient). Both the theoretical and experimental justification for this methodology follow.

EXPERIMENTAL SET-UP

The instrumentation, as shown in Figure 1, consisted of three spark stations before and three after the gelatin block along with eight orthogonal x-ray stations positioned to record the penetration event. The primary purpose of the other instrumentation was to evaluate energy deposition in the block, and those data are not germane to this paper.[1 2] Although x-ray stations could have been employed, the spark station triads were used to measure projectile velocity entering and exiting the gelatin block because of the higher precision they provide: at a velocity of 600 m/s the precision would be 0.06% as compared to the 3% between consecutive x-ray stations. The times of the flash radiographs are known to within 0.7 microsec; and the spatial coordinates of the projectile, to within 0.5mm. The yaw values derived from the orthogonal x-ray images are believed to be known within one-half to one degree precision for yaws between, say, 60 and 180 degrees.

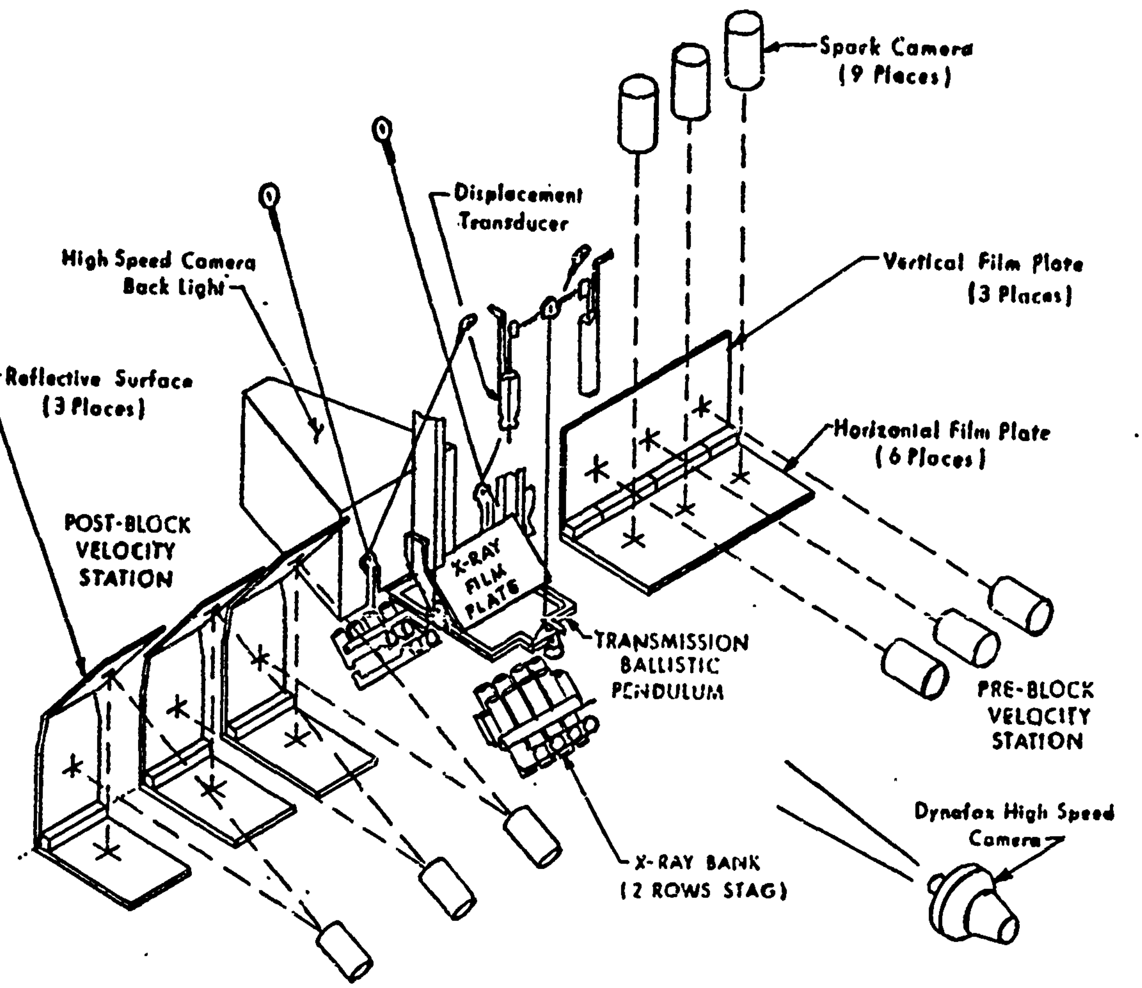

Figure 1. Test Set-Up

YAW GROWTH

Experimentally we find that rounds impacting at the same nominal speed will vary in depth of penetration before beginning to tumble due to differences in striking yaw; however, from the onset of rapid yaw growth to yaws of 135 degrees or so, the growth of yaw with path length (penetration) is the same for each round.

A. THEORETICAL BASIS

The author has previously developed the equation of motion that governs the growth of yaw for gyroscopically unstable, non-deforming projectiles penetrating a dense fluid,[3]

$$\frac{d^2\alpha}{ds^2} = M \cos\alpha \sin\alpha \qquad (1)$$

where α is the ballistic yaw (combined pitch and yaw) and s is the path length. In this form M is expected to be independent of velocity for the trajectory of a given test firing. The right hand side of Equation 1 is the ratio of the overturning moment exerted by the fluid on the projectile to the product of the transverse moment of inertia and the instantaneous velocity squared. By dividing the overturning moment by the square of the velocity, one obtains a term that is independent of the velocity change during penetration as long as the flow is subsonic but fast enough to remain cavitational. Thus, M is expected to be a function of α alone but a much slower varying function of α than the cos α sin α factor in Equation 1.

B. APPLICATION TO EXPERIMENTAL DATA

To fit Equation 1 to the measured yaw versus distance data, M will be treated as a constant and any departure from that assumption can be treated empirically.

1. INITIAL TRAJECTORY - SMALL YAW

Since all the firings of the projectile resulted in small, but different, striking yaws, we can assume small yaw during the inital penetration. Equation 1 becomes:

$$\frac{d^2\alpha}{ds^2} \simeq \dot{M}\alpha \qquad (2)$$

since $\alpha \simeq \sin\alpha$, $\cos\alpha \simeq 1$. Equation 2 can be integrated in closed form to give α equal to the vector sum of $\alpha_{01}\exp[\sqrt{(M)}(s - s_0)]$ and $\alpha_{02}\exp[-\sqrt{(M)}(s - s_0)]$, these two terms being, in general, out of phase. The second term vanishes so rapidly, however, that the solution to Equation 2 can be written:

$$\alpha = \alpha_0 \exp[\sqrt{(M)}(s - s_0)] \qquad (3)$$

where $\alpha_0 = \alpha_{01} = \alpha$ at $s = s_0$. Since our measurements are of projectiles starting at small yaws, a degree or two, we can use Equation 3 to provide one of the two initial conditions required for solution of the general, large yaw Equation 1 without introducing an arbitrary constant. Differentiating Equation 3, we have:

$$\frac{d\alpha}{ds} = \sqrt{(M)}\alpha_o \quad \exp[\sqrt{(M)}(s - s_o)] \quad . \tag{4}$$

Therefore,

$$\frac{d\alpha}{ds}(s = s_o) = \sqrt{(M)}\,\alpha_o \quad . \tag{5}$$

Thus, instead of three unknowns: M, α_o and dα/ds at $s = s_o$, we have two: M and α_o.

2. COMPLETE TRAJECTORY

Using Equations 1 and 5, the radiographic measurements of yaw versus distance can be fitted in the least squares sense to determine M and α_o. However, with only a few stations per firing and with yaws growing from zero to 160 degrees, the inherent system measurement error would result in imprecise estimates of M, sufficiently imprecise that even the multiple firings would provide less than satisfactory "average" estimate of M. However, Equations 1 and 5 suggest a technique for pooling the data for the multiple firings such that, when fitted by the least squares method, one value of M and N a_o's are determined instead of N M's and Nα_o's, N being the number of firings.

Experimentally we find that rounds impacting at the same nominal speed will vary in depth of penetration before beginning to tumble due to differences in striking yaw; however, from the onset of rapid yaw growth to yaws of 135 degrees or so, the growth of yaw with path length (penetration) is the same for each round. Physically, this means that the overturning moment, which determines the growth of yaw, is insensitive to the small changes in velocity and spin among the rounds, but is a function only of the instantaneous yaw. Mathematically, this means we can pool the yaw versus penetration curves of the rounds by superposition, shifting the abscissa as needed. Figure 2 shows the resulting curve of such a pooling for one projectile.

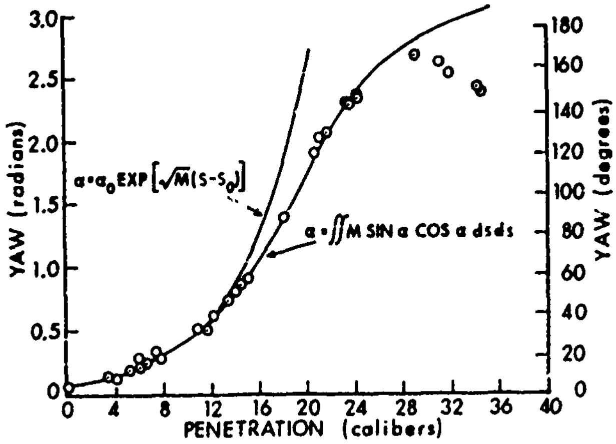

FIGURE 2. Yaw versus Path Length of a Bullet in Gelatin.

The data in Figure 2 is taken from earlier firings, the test set-up of which differed from that of Figure 1, namely, four stations viewing a 15 cm long block of gelatin rather than eight stations and a 30 cm block. Eight rounds of one projectile design were fired at a nominal velocity of 870 m/s. Each round provided three or four good yaw measurements for a total of 29 pooled data points. As seen in Figure 2, a constant value for M for the solution of Equations 1 and 5 is valid for a suprisingly large depth of penetration and growth of yaw - to 135 degrees. Beyond that value (the base forward zone) the projectile yaw increases at an even slower rate to a value greater than 160 degrees but then begins a retreat toward a stable position of 90 degrees. It was impossible to obtain even this qualitative type of information by examining each firing separately. Also plotted in Figure 2 is the "small" yaw approximation given in Equation 3. It is seen that the approximation is reasonable to 30 degrees of yaw, considering the precision of measurements involved.

The results in Figure 2 are not an isolated situation. Fifteen other sets of pooled data (twelve in the 15cm gelatin block and three in the 30cm block) were analyzed according to the above method. There were fourteen configurations in all, two of which were observed at two distinct nominal striking velocities; and each produced results similar to that in Figure 2 with a precise estimate of its own M. Further, the author has successfully applied the method to a set of three projectile firings through soil with observed yaws reaching 35 degrees.

VELOCITY DECAY

Our aim now is to find a means of pooling the rounds with regard to velocity loss. We obtain velocity versus penetration points for each round by taking divided differences of the penetration-time data.

A. THEORETICAL BASIS

The decay of projectile velocity is traditionally expressed by:

$$\frac{dV}{ds} = - D \cdot V \quad . \tag{6}$$

where V is the instantaneous velocity and D is equal to the ratio of the drag force to the product of the projectile mass and V^2. Like M, D is expected to be insensitive to the change in V during the penetration event because the flow is cavitational and subsonic. D is, of course, highly sensitive to the ballistic yaw, α. Thus, upon integration Equation 6 becomes:

$$\frac{V}{V(o)} = \exp \left[-\int_{s_o}^{s} D(\alpha)\, ds \right] . \tag{7}$$

The right hand side of Equation 7 is independent of V; and, therefore, only α dictates its behavior.

B. APPLICATION TO EXPERIMENTAL DATA

From the results in the YAW GROWTH section, we see that the same shifts in s that permitted pooling α versus s data will serve here to pool the data for plotting $\frac{V}{V(o)}$ versus s. For convenience, V(o) is chosen for each firing at that position where the onset of rapid yaw growth is established in the pooled α versus s data.

The results of one such pooling, firings into the 30 cm block of gelatin at a nominal striking velocity of 590 m/s, are given in Figure 3.

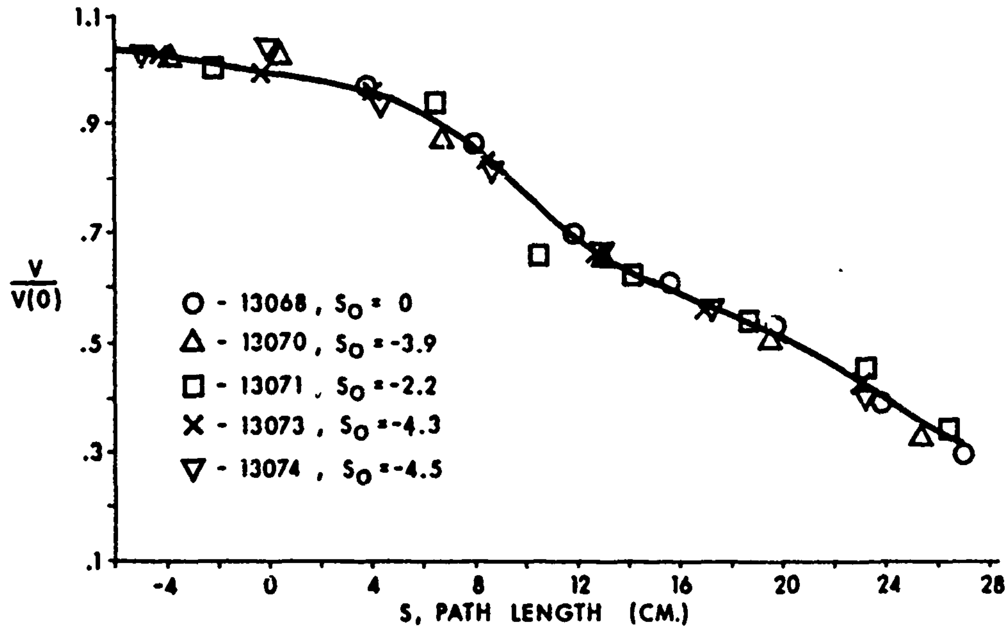

FIGURE 3. Normalized Velocity versus Path Length.

1. DRAG COEFFICIENT IN GELATIN

The curve in Figure 3 can be numerically differentiated to provide C_D versus s since:

$$\frac{\rho A}{2m} C_D = D = - \frac{dV/ds}{V} \tag{8}$$

where ρ is the density of the gelatin, A is the cross-sectional area of the projectile and m is the mass of the projectile. Although we have C_D versus s, we know that C_D is exhibiting its dependence on α. Hence, using the pooled α versus s curve, similar to that in Figure 2, we can construct C_D versus α. This is done in Figure 4 for the velocity decay data shown in Figure 3. The maximum value of C_D agrees with that of cavitational cross flow for cylinders.

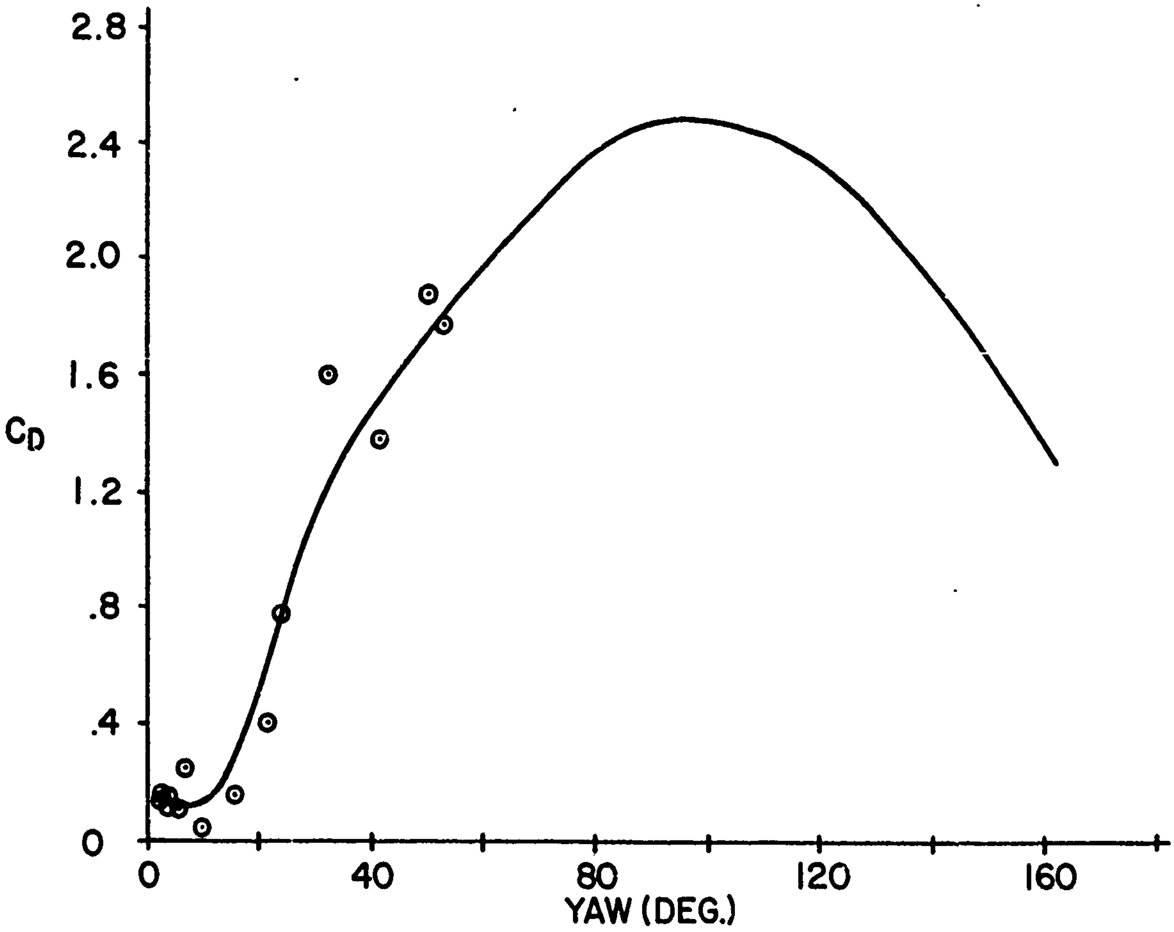

FIGURE 4. Drag Coefficient versus Yaw.

2. OBSERVATIONS IN SNOW

Two of the projectiles tested in gelatin were also measured for velocity loss through various thicknesses of packed snow. Pooling the $\frac{V}{V(o)}$ versus s data resulted in a velocity decay curve similar to that in gelatin. Using the values of M determined for gelatin, the values for M in snow were estimated since M is directly proportional to the fluid density. The results suggest a yaw growth in snow that agreed with the gelatin prediction.

PATH DEFLECTION

To complete the understanding of unstable motion of projectiles in cavitational flow, one needs to measure the deviation of the penetration path from a straight line, often called swerve.

A. THEORETICAL BASIS

Again, we are interested only in the motion in the plane of the ballistic yaw, not in the history of the orientation of that plane, which is controlled by the projectile spin. For the short duration of the penetration process gravity can be ignored, and the equation for swerving motion is:

$$\frac{d^2r}{ds^2} = L \sin \alpha \cos^2 \alpha \tag{9}$$

where r is the radial displacement from the initial straight line path (cylindrical coordinates r, θ, s). L is equal to the ratio of the lift force to the product of the projectile mass and V^2 and, like M, is expected to be independent of V during the penetration. The integration of Equation 9 results in:

$$r = \int_{s_o}^{s} \int_{s_o}^{s} L \sin \alpha \cos^2 \alpha \, ds ds. \tag{10}$$

There are no explicit constants of integration since they serve only to define the initial straight line path and r is defined as the displacement from that path. L, like M, is expected to be constant for a good portion of the yaw growth; and, since α has an approximately exponential growth with s until, perhaps, 30 degrees, r will grow exponentially with s until about 20 degrees. This results from comparison of α with the integrands of yaw growth (sin α cos α) and swerve (sinα $\cos^2$ α).

Consequently, it is expected that a marked increase in r will take place when a rapid increase in yaw growth begins, and r will be dependent only upon α. Hence, the pooling technique can be applied to path measurements. The measurements from several rounds can be superposed upon each other provided that first the spatial axes are rotated to align the individual initial straight line paths and then the rounds are shifted individually along the now common initial straight line path until the growths in r coincide.

B. APPLICATION TO EXPERIMENTAL DATA

Although flash radiography does provide measurements of the three spatial coordinates of the center of mass of the projectile, such data have not been analyzed at this time. However, the trajectory traces left behind by two unstable projectiles penetrating clay were analyzed by this pooling technique for each of the two striking velocities. The results for one pooling are given in Figure 5.

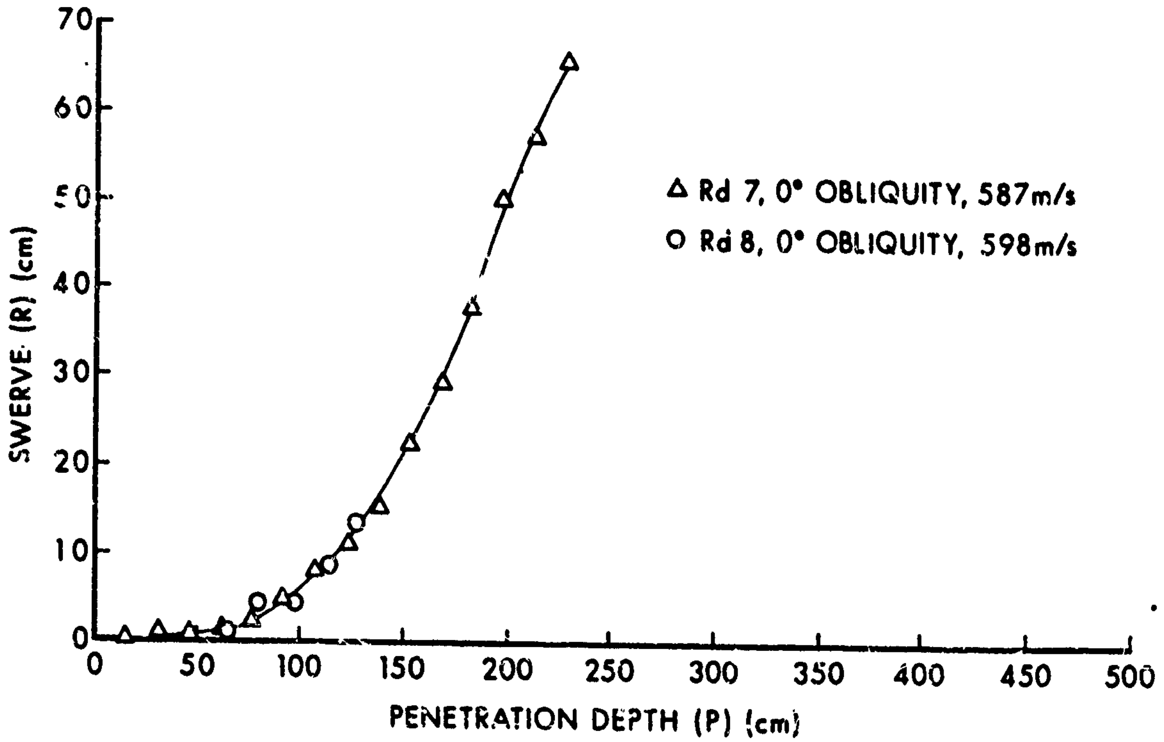

FIGURE 5. Swerve versus Penetration

CONCLUSION

The equations of motion governing the growth of ballistic yaw, the velocity decay, and the deviation of the trajectory from a straight line have been identified.

A methodology consisting of pooling flash radiographic (or other) measurements from several firings of projectiles penetrating gelatin, soil, snow, etc., has been developed with the result that precise experimental solutions to the above equations can be obtained.

The resulting drag force, lift force, and overturning moment data form the best empirical data base for unstable projectile/motion in dense media.

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