19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

TUNGSTEN INTO STEEL PENETRATION INCLUDING VELOCITY, L/D, AND IMPACT INCLINATION EFFECTS

James D. Walker, Charles E. Anderson, Jr. and Drew L. Goodlin

Southwest Research Institute, Engineering Dynamics Department, P.O. Drawer 28510,
San Antonio, Texas 7822-0510 USA

Recent work in the yaw behavior of penetration (Hohler and Behner, 1999) has allowed the creation of rather general curves for the penetration of tungsten alloy projectiles into armor steel targets. Simple analytical expressions are combined to produce families of penetration curves that include the effects of impact velocity, projectile length-to-diameter (L/D) ratio (Anderson, et al., 1995), crater diameter, and impact inclination (yaw).

INTRODUCTION

Recent work on yawed penetration of tungsten alloy projectiles into armor steel has provided a last piece of information needed for the nearly complete characterization of the penetration of tungsten rods into steel at various impact velocities, projectile aspect ratio (projectile length-to-diameter ratio, *L/D*), and impact inclination (total yaw). This allows an exploration of the penetration regimes, which provides greater insight into the role various parameters play in the penetration process. This paper describes the results of an analytical study of penetration and presents graphs showing the influence of the various variables. The results are applicable to semi-infinite targets at zero degrees obliquity, over the ordnance velocity regime ($0.75 \leq V \leq 1.9$ km/s). With this knowledge, armor designers and engineers have an understanding of the level of performance an armor design might be expected to achieve.

THE MODEL

Data for the penetration of tungsten alloy projectiles into armor steel were used for the analysis. Such data include the influence of length-to-diameter ratio, and impact inclination on penetration. These data were fit with equations and combined with a few assumptions on penetration behavior to make penetration predictions for a wide range of impact velocity, *L/D*, and impact inclination.

Home
Table of Contents

Velocity and L/D Effect

Penetration efficiency is affected by impact velocity V and the *L/D* ratio of the projectile. In the ordnance velocity regime (0.75 ≤ V ≤ 1.9 km/s), penetration is remarkably linear with impact velocity, e.g., see Ref. [1].

The geometric aspect ratio of the projectile also has a relatively strong effect on penetration efficiency. The smaller the *L/D* ratio, the larger the penetration *P*, as normalized by original projectile length *L*. Thus, smaller *L/D* projectiles have a higher penetration efficiency as measured by *P/L*, although in terms of absolute length, the larger *L*, the deeper the penetration. The fit to data for V and *L/D* used in this analysis is from Anderson, et al. [2]. The equation for penetration as a function of *L/D* and impact velocity, for tungsten alloy projectiles impacting rolled homogeneous armor (RHA) at velocities between approximately 0.750 km/s and 1.9 km/s is[1]:

$$\frac{P}{L} = -0.212 + 1.044\,V - 0.194\,\ell n\left(\frac{L}{D}\right) \tag{1}$$

where V is in km/s. Fits to experimental data are used since analytic models showing an L/D effect do not predict as pronounced effect as seen experimentally. Figure 1 shows curves from Eq. (1) compared to experimental data and numerical simulations. The dashed lines are regression fits at each impact velocity, and the dotted lines are from Eq. (1).

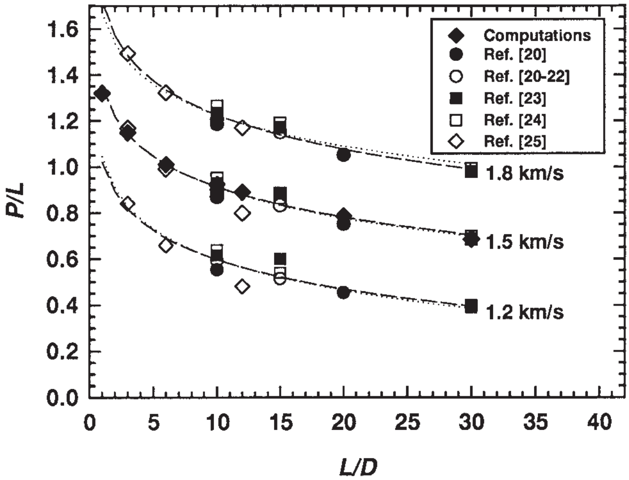

Figure 1. Penetration versus L/D for tungsten projectiles into RHA at three impact velocities (from Ref. [2]; references in figure refer to citations in Ref. [2]).

---

[1] *P/L* vs. *V* is highly linear between 1.2–1.8 km/s, and reasonably linear from 0.75–1.9 km/s. We have elected to extended slightly the linear region of applicability in the spirit of the approximations and the overall degree of accuracy of the equations.

Home
Table of Contents

Yaw

Yaw degrades penetration because the yawed projectile interacts with the penetration channel (the crater wall) rather than just penetrating at the bottom of the crater. The yaw angle at which the projectile tail just begins to contact the side of the penetration channel, i.e., the theoretical onset of degradation, is referred to as the critical yaw angle γ_{crit}, and it is calculated by examining the penetration geometry where the tail of the projectile just touches the crater wall:

$$\gamma_{crit} = \sin^{-1}\left\{\frac{R_c/L - \frac{R_p}{L}\sqrt{1+\left(R_p/L\right)^2-\left(R_c/L\right)^2}}{1+\left(R_p/L\right)^2}\right\} \qquad (2)$$

The critical yaw angle depends on the crater radius R_C and the projectile length and radius, R_C and L, respectively. Often the literature defines the critical yaw angle as

$$\gamma_{crit} = \sin^{-1}\left(\frac{R_c - R_p}{L}\right) \quad \text{for } L/D \geq 3 \qquad (3)$$

This is an approximation that (as indicated) holds for larger *L/D* rods. In the following, the fully nonlinear definition will be used since projectiles of low *L/D* are also considered in the analysis. The critical yaw is used as a scaling angle for fitting yawed data for differing *L/D* projectiles.

Crater Diameter

To calculate the critical yaw, it is necessary to determine the diameter of the crater. To date there is not a good analytic model of crater diameter, so once again fits to experimental data are used. In particular, three fits in the literature to crater diameter of tungsten alloy projectiles into steel targets are:

$$\frac{R_c}{R_p} = 1 + 0.70V, \qquad \frac{R_c}{R_p} = 1 + 0.2869V + 0.145V^2, \qquad \frac{R_c}{R_p} = 1.524 + 0.3388V + 0.1286V^2 \qquad (4)$$

where V is the impact velocity in km/s. The first two equations are from Walker and Anderson [3], and are shown in Fig. 2. The third equation is due to Bjerke, *et al.* [4], and is shown in Fig. 3. All three provide good fits to the respective crater radius data for tungsten alloy penetrations into steel. For a velocity of 1.6 km/s, for example, the respective values of the ratio of the crater radius to projectile radius are R_C/R_p = 2.12, 1.83, and 2.02. Although these values are slightly different, they are within approximately 7% of the mean; which is typical of the accuracy of the other approximations. An average value of 2.0 for this ratio was used in the curves to be presented later.

Home
Table of Contents

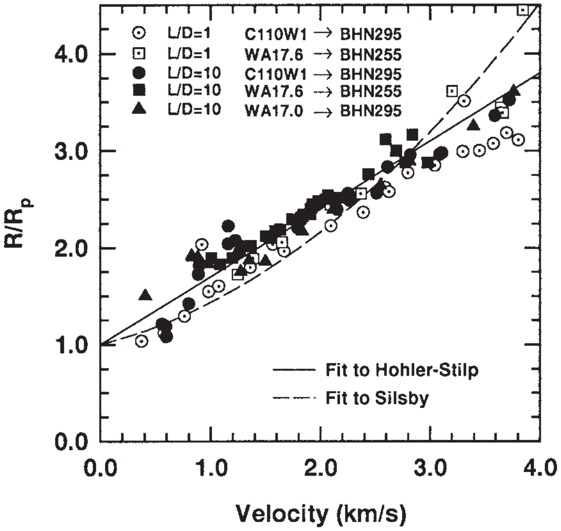

Figure 2. Ratio of crater radius to projectile radius for various impact conditions, from Ref. [3].

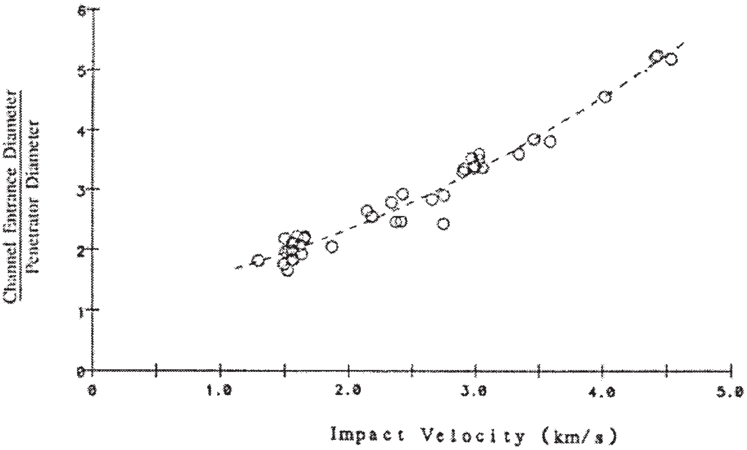

Figure 3. Ratio of crater radius to projectile radius for tungsten into steel, from Ref. [4].

Yaw Data

With an expression for the crater radius and critical angle, it is now possible to examine yaw data for a specific *L/D*, and then extend the results to other *L/D*'s. In particular, a fit to data has been given by Hohler and Behner [5], for *L/D* = 20 tungsten alloy projectiles fired into steel targets at 1.65 km/s. The fit to their data is:

$$P = (P_0 - P^*)\frac{1}{1+0.0104(\gamma/\gamma_{crit})^2} + P^* \qquad (5)$$

where the equation has been modified to scale with the critical angle. (Their original equation had $1+0.0045\gamma^2$ in the denominator with γ in degrees, but has been modified here to allow for different *L/D's* and different impact velocities by assuming that γ_{crit} is an appropriate scaling parameter.) In Eq. (5), P_0 is the depth of penetration for normal incidence (zero yaw) and P^* is the number that allows the equation to produce the *L/D*= 1 penetration when the yaw is fully 90°. (P^* should rather be the value that produces the penetration for the rod impacting sideways. However, the *L/D*= 1 penetration value provides a good approximation, and there are usually *L/D*= 1 data available to determine P^*, whereas side-on impact data for projectiles are pretty much the result of luck – usually, bad luck.) Figure 4 shows the fit compared to the Hohler and Behner data, where penetration is normalized by zero-yaw penetration.

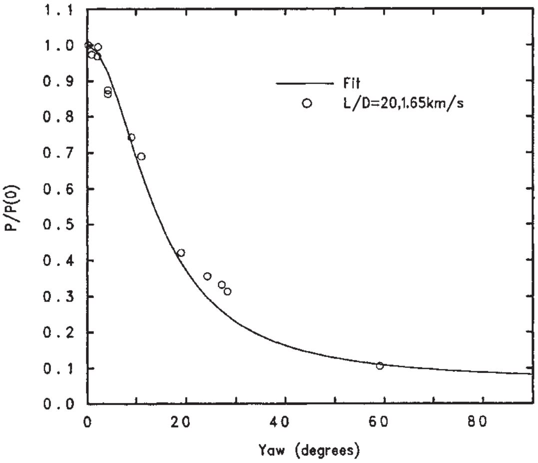

Figure 4. Penetration data and equation fit for tungsten into steel at 1.65 km/s. The assumed ratio of crater radius to projectile radius is 2.0.

Since these data are for a specific case, it is desirable to verify the applicability of Eq. (5) against a second set of data under different impact conditions. Figure 5 shows data from Yaziv, et al. [6], for a *L/D* 10 tungsten alloy projectile impacting a steel target at 1.4 km/s. Here, the assumed ratio of the crater radius to projectile radius is 1.8. Agreement is good. Finally, Fig. 6 shows both sets of data plotted on the same graph, where the horizontal axis is the yaw angle scaled by the critical yaw angle.

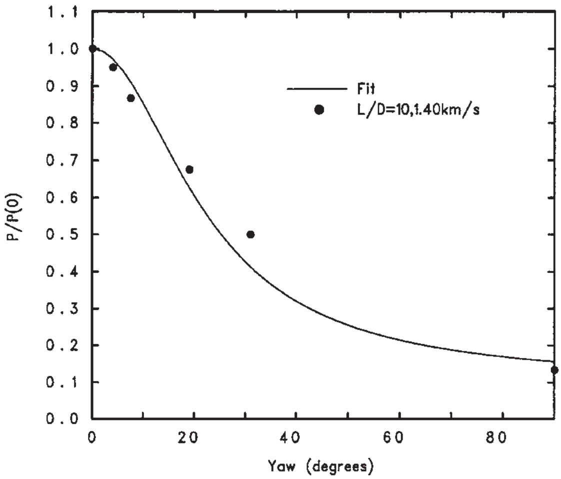

Figure 5. Data and fit for *L/D*=10 tungsten rods into steel targets at 1.4 km/s.

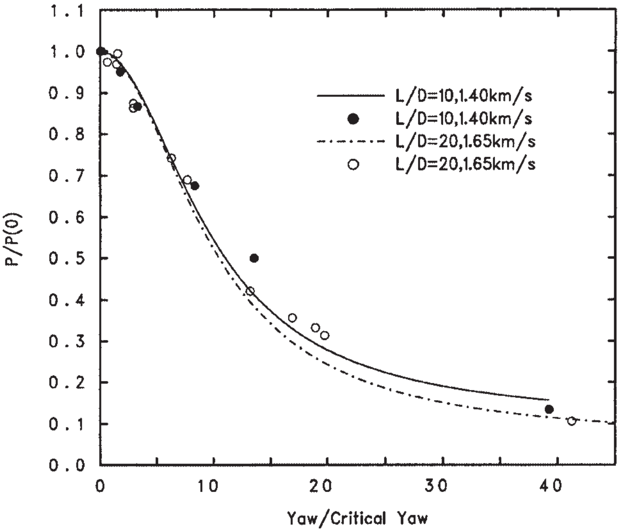

Figure 6. Normalized penetration (by zero yaw penetration) versus yaw scaled by critical yaw for the data for *L/D*=10 and *L/D*=20 tungsten alloy projectiles impact steel targets.

PUTTING EVERYTHING TOGETHER

Now that all the pieces are in place it is possible to calculate the depth of penetration into RHA steel as a function of *V*, *L/D*, and yaw. The depth of penetration normalized by projectile diameter versus *L/D* for impact of tungsten alloy projectiles into armor steel (with an assumed $R_c/R_p = 2.0$) is shown in Fig. 7 for various impact yaw angles, at an impact velocity of 1.6 km/s. The concave down nature of the zero yaw curve is due to the *L/D* effect. The effect of yaw on the depth of penetration is large: for an *L/D* = 10 rod, each additional 10° of yaw results in nearly a 20% decrease in penetration; while for an *L/D*= 30 rod, each additional 10° of yaw reduces penetration by another factor of 2. Figure 8 shows the same results in a different way, this time plotting the normalized depth of penetration versus impact yaw for a variety of *L/D*'s.

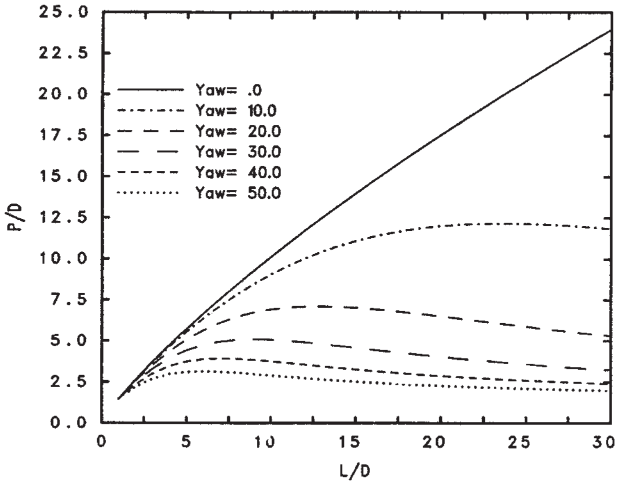

Figure 7. Penetration normalized by projectile diameters versus *L/D* for a number of impact yaw angles (in degrees): *V*= 1.6 km/s.

CONCLUSION

A series of analytical expressions have been combined that predict the penetration of tungsten alloy projectiles into armor steel as a function if impact velocity, projectile aspect ratio (*L/D*), and impact inclination (yaw). These expressions have been used to predict depth of penetration, normalized by projectile diameter, as a function of *L/D* for various impact yaw angles. Alternatively, *P/D* has been plotted as a function of impact yaw versus various *L/D*'s.

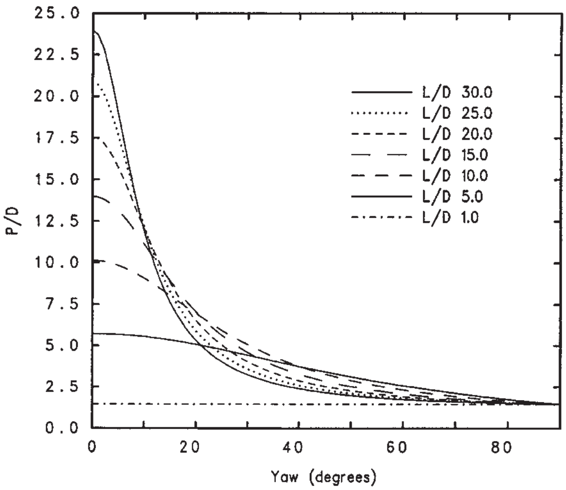

Figure 8. Penetration normalized by projectile diameters as a function of yaw for various *L/D*'s: *V* = 1.6 km/s.

REFERENCES

1. C. E. Anderson, Jr. and B. L. Morris, "The Ballistic Performance of Confined Al_2O_3 Ceramic Tiles," *Int. J. Impact Engng*, **12** (2), pp. 167–187, 1992
2. C. E. Anderson, Jr., J. D. Walker, S. J. Bless, and Y. Partom, "On the L/D Effect for Long-Rod Penetrators," *Int. J. Impact Engng*, **18**(3), pp. 247–264, 1996
3. J. D. Walker and C. E. Anderson, Jr., "A Time-Dependent Model for Long-Rod Penetration," *Int. J. Impact Engng*, **16**(1), pp. 19–48, 1995
4. T. W. Bjerke, G. F. Silsby, D. R. Scheffler and R. M. Mudd, "Yawed Long-Rod Armor Penetration," *Int. J. Impact Engag*, **12**(2), pp. 281–292, 1992
5. V. Hohler and Th. Behner, "Influence of the Yaw Angle on the Performance Reduction of Long Rod Projectiles," *Proc. 18th Int. Symp. on Ballistics*, San Antonio, Texas, pp. 931–938, 1999
6. D. Yaziv, J. D. Walker and J. P. Riegel, III, "Analytical Model of Yawed Penetration in the 0 to 90 Degrees Range," *Proc. 13th Int. Symp. on Ballistics*, Stockholm, Sweden, Vol. III, pp. 17–23, 1992