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A COMPUTATIONAL STUDY OF THE INFLUENCE OF PROJECTILE STRENGTH ON THE PERFORMANCE OF LONG-ROD PENETRATORS

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Summary—Two-dimensional numerical simulations were used to explore the penetration capability of long-rods as a function of their strength. Tungsten alloy rods of varying strengths were 'shot' at semi-infinite armor steel targets in the velocity range of 1.4–2.2 km/s. It is found that penetration depths versus penetrator strength curves have a maximum which depends on the impact velocity. This effect which, to our best knowledge, has not been reported previously can be explained, at least qualitatively, by considering the deceleration of the rear part of the rod, as its strength increases. This deceleration can lead to a substantial decrease in the velocity of the rear part of the penetrator with the result that its penetration capability is reduced beyond that of a nondecelerating penetrator. The deceleration is a direct consequence of the elastic waves travelling along the back part of the rod with an amplitude which is equal to the strength of the penetrator material. Copyright © 1996 Elsevier Science Ltd.

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1. INTRODUCTION

Numerical simulations became an extremely valuable tool in the field of terminal ballistics, to investigate the complex interaction of projectiles with a given target. Recently, we have used two-dimensional simulations to follow the penetration process of long-rod penetrators into semi-infinite metallic targets [1, 2] and in layered targets containing ceramic tiles [3]. In particular, we have demonstrated that the length-to-diameter ratio (L/D) of the rod plays a major role in its penetration capability (P/L) even for very large values of $L/D = 40$. This result is in contrast with existing one-dimensional analytical models (like those of Tate [4] and Alekseevskii [5]), but is in excellent agreement with the experimental results of Hohler and Stilp [6].

The aim of the work to be presented here was to explore the influence of the penetrator's strength (Y_p) on its penetration capability. The drive to perform these simulations came when we realized in Ref. [1] that different projectiles result in different sensitivities to their aspect ratio (see Fig. 3 of Ref. [1]). Thus, at high values of L/D a low strength projectile can be more efficient than a high strength one. This phenomenon can lead to an optimum strength for the penetrator and, as we shall demonstrate later, this is exactly what we found in our simulations.

Previous studies have shown (both experimentally [6], and numerically [7]), that the strength of the penetrator has a minor effect on its performance and that the stronger the projectile the higher the penetration capability for a given configuration. On the other hand, our simulations show that when a large range of values is given to the penetrator strength, a maximum is observed in the curve for the penetration depth vs penetrator strength. These maxima depend strongly on the impact velocity, in the range which has been tested and are weakly dependent of L/D ratio of the rod. These findings can be explained, at least quantitatively, by considering the deceleration process of long-rods as they penetrate semi-infinite steel targets.

It is worth noting that since our study is based only on numerical simulations we could feel free to extend the range of projectile strengths ranging from 0 to 3.5 GPa. This is a much larger range than the one encountered with normal tungsten alloy rods (1.0–1.5 GPa). Thus, one should treat the present study and its conclusion, with appropriate judgement—as a sensitivity study for an effect which may or may not be encountered in real-life ballistics studies.

2. COMPUTER SIMULATIONS

The Eulerian processor of the two-dimensional code PISCES 2DELK V/30 was used in this study, in a similar way to that described in Refs [1–3]. The numerical target is composed of a cylindrical core

180 mm long and 150 mm in diameter which is supported by a square Lagrangian grid 250 mm long and 150 mm wide. The FLOW boundary condition between the core and the Lagrangian grid, on their radial direction, gives the semi-infinite property to the target. The two grids are matched by a strong adhesion condition (NOH), at the back of the Eulerian core, rendering its infinite dimension along penetration axis. Material properties for the steel target, in all the simulations presented here, were taken from Johnson and Cook [8] (as rolled homogeneous armor steel). For the tungsten alloy penetrators (density of 17.1 g/cc) we used a simple elasto-plastic yield criterion (von Mises) in which the yield strength was varied, in different simulations, within the range 0–3.5 GPa. Considering the fact that the normal range of variability of this parameter is much smaller (1–1.5 GPa), we should consider the extreme values of Y_p as theoretical only. Nevertheless, one can learn a lot from these simulations even if the practical range of variables is narrower.

We chose the Johnson–Cook model for the steel target because it is known to result in a good agreement between simulations and experiments in the ordnance velocity (1000–1800 m/s). We would like to point out that the results of our simulations are not dependent on the particular yield model of the target. We performed several simulations with a simple von Mises type yield for the steel target and obtained similar results.

In order to have a better resolution we increased the number of cells, as compared with Refs [1–2], and used 11 cells on the radius of the penetrator (compared with seven in earlier works). This resulted in an increase of computation time by a large factor, but we felt that it was necessary in order to be sure that the results are meaningful. In all our simulations the diameter of the rod is 6 mm and the length is varied to obtain $L/D = 10$ and 20. Figure 1 shows a typical output of a two-dimensional simulation in which the penetration process is presented through the time change in the velocities of the head and tail of projectile (1a), while the residual length and depth of penetration, as a function of time, are plotted in (1b). These are very convenient for presentation purposes and one can clearly follow any change in penetration, due to these parameters, easily.

3. RESULTS AND DISCUSSION

In the first set of simulations we have aimed at reproducing the results of Wilkins and Reaugh [7] for an $L/D = 10$ tungsten alloy rod impacting an RHA target at 2.1 km/s. The velocity we used was 2.2 km/s and the material parameters for our steel target are somewhat different than those of [7], but apart from these small differences the two sets are similar. Considering the fact that our targets are somewhat stronger than those of Ref. [7], we may expect very close results for the two sets of computations. Wilkins and Reaugh [7] varied Y_p in the range of $Y_p = 0.5$–2.0 GPa and obtained a straight line for the penetration vs. Y_p curve. The slope of their line is positive with a value of about $\partial(P/L)/\partial Y_p \approx 0.05$ (GPa)$^{-1}$. This is a relatively low value which indicates that penetration depth is almost insensitive to penetrator strength. In contrast Wilkins and Reaugh find that P/L is much more sensitive to target strength, as is well known from experimental studies, like those in Ref. [6] for example.

Our computational results are shown in Fig. 2, together with the line from Ref. [7], and as is clearly seen we also obtained a slowly increasing P/L curve up to about $Y_p = 2.5$ GPa. The slope of this line, in the $Y_p = 0.5$–2.0 GPa range, is 0.1 GPa which is twice as high as that of Ref. [7]. The difference can be explained by the differences in material properties and impact velocities of the two sets of computations. However, the most important difference is that our simulations show that at higher projectile strength the penetration decreases, resulting in a rather shallow maximum point in the curve. We think that this maximum has not been observed in Ref. [7] because of the limited range of values for Y_p which was covered in that work. The close agreement between our simulations and those of Ref. [7], in the 0.5–2.0 GPa range for Y_p, strengthens our confidence in the validity of these simulations and, specifically, in the existence of the maximum point in the curve.

In order to better demonstrate the existence of this maximum point we show in Fig. 3 the simulation results for the case of $L/D = 20$ rod impacting at 1.4 km/s. The lower velocity of the rod (as compared with 2.2 km/s) makes this maximum much more apparent. The maximum at $Y_p \approx 0.8$ GPa is clearly evident here and (even more surprisingly) the negative slope of the curve is very large. One can argue that the effect of the deceleration of the rear port is much stronger, in this case, than the gain in penetration due to penetrator's strength. As is clearly seen here, the penetration of a $Y_p = 2.0$ GPa tungsten alloy rod is smaller by about 30% than that of a $Y_p = 1.0$ GPa rod.

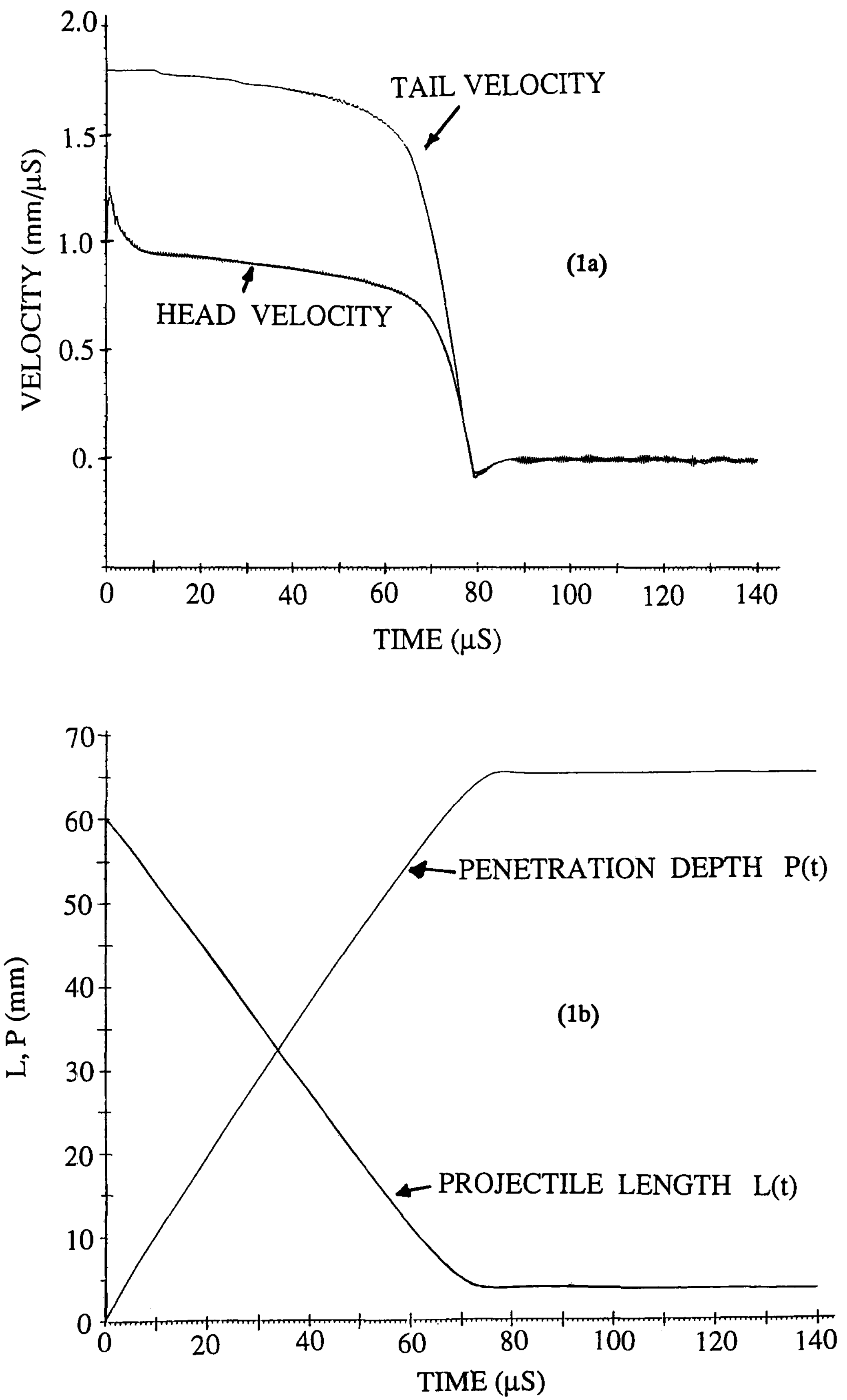

Fig. 1. The output from a typical 2-D simulation. (a) Head and tail velocities vs time. (b) Penetrator length and penetration depth vs time.

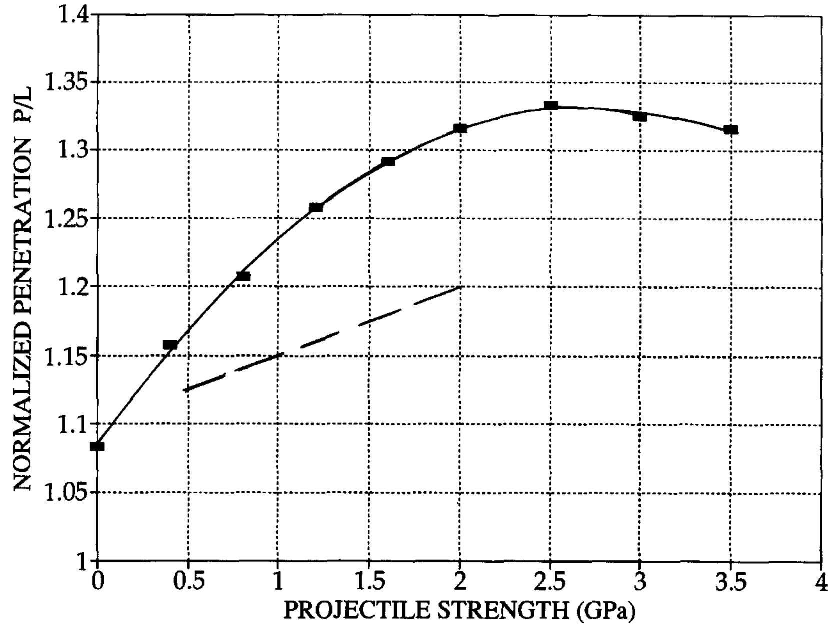

Fig. 2. Simulation results for P/L vs Y_p for the case of $L/D = 10$, $V_0 = 2.2$ km/s. (The results of Ref. [7] are shown with a dotted line.)

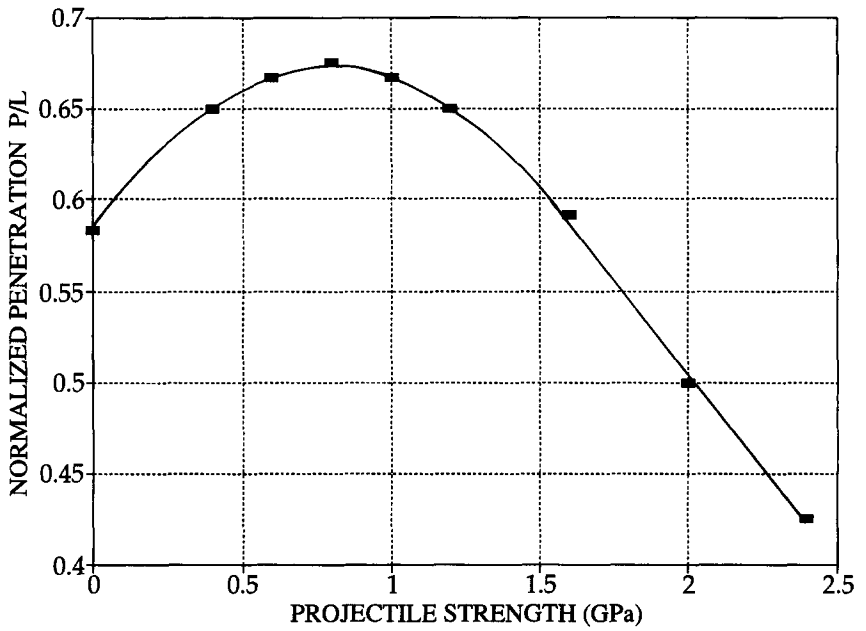

Fig. 3. Simulation results for P/L vs Y_p for the case of $L/D = 20$, $V_0 = 1.4$ km/s, with the clear maximum near 0.8 GPa.

One should not confuse these maxima with the well known rigid body penetration of Tate's model [4]. There it is shown that when the projectile strength is much higher than target strength, a maximum point can be obtained in the penetration vs impact velocity curve. The optimum in Tate's curves always appears to occur at velocities above the rigid body-eroding body transition velocity, sometimes considerably so. In all our simulations the penetrators are eroding so that these maxima are not the result of the rigid-body phenomenon. In order to further demonstrate this issue we performed a special simulation in which we increased the strength of the penetrator to a 100 GPa so that it is a very rigid one. This penetrator resulted in a value of 1.1 for P/L at an impact velocity of 1.4 km/s. Thus, one can assume that by further increasing Y_p (over the 3.0 GPa value in Fig. 3) another extremum will occur since at a certain value of Y_p the values of P/L should jump to much higher values than those of Fig. 3. This subject will be discussed in a subsequent paper since it is out of the scope of the present one.

Figures 4–6 present the rest of our simulations in groups which give some idea as to the sensitivity of the effect to impact velocity and the aspect ratio of the penetrator. It is clearly seen that the effect is enhanced with slower rods, while the length of the rod has a relatively minor effect. Figures 4 and 5 give the results at impact velocities of 1.4 and 1.8 km/s, respectively. The effect is most pronounced for the 1.4 km/s case with relatively small changes in P/L for impact velocity of 2.2 km/s. Thus, when looking for experimental verification of the effect, one should work with low velocity impacts (in the 1.4–1.8 km/s range). The curves of P/L vs Y_p are similar for the two values of $L/D = 10, 20$ as far as the

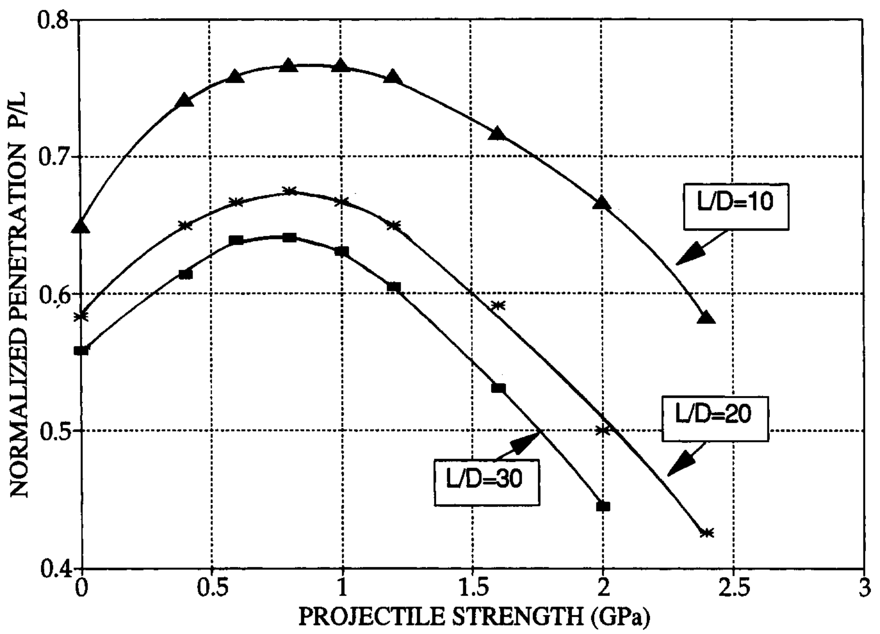

Fig. 4. Result for $V = 1.4$ km/s ($L/D = 10, 20, 30$.)

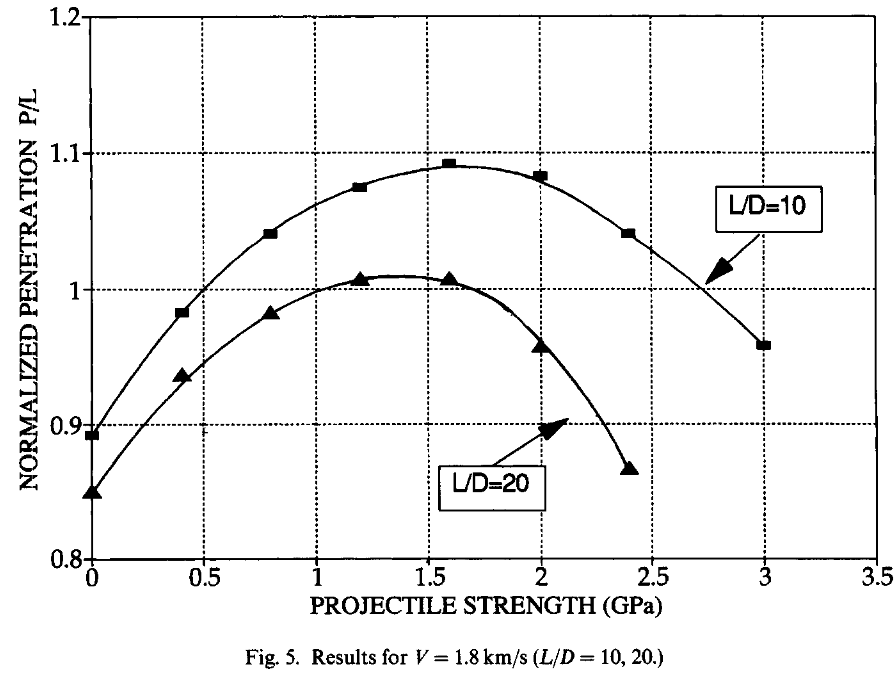

Fig. 5. Results for $V = 1.8$ km/s ($L/D = 10, 20$.)

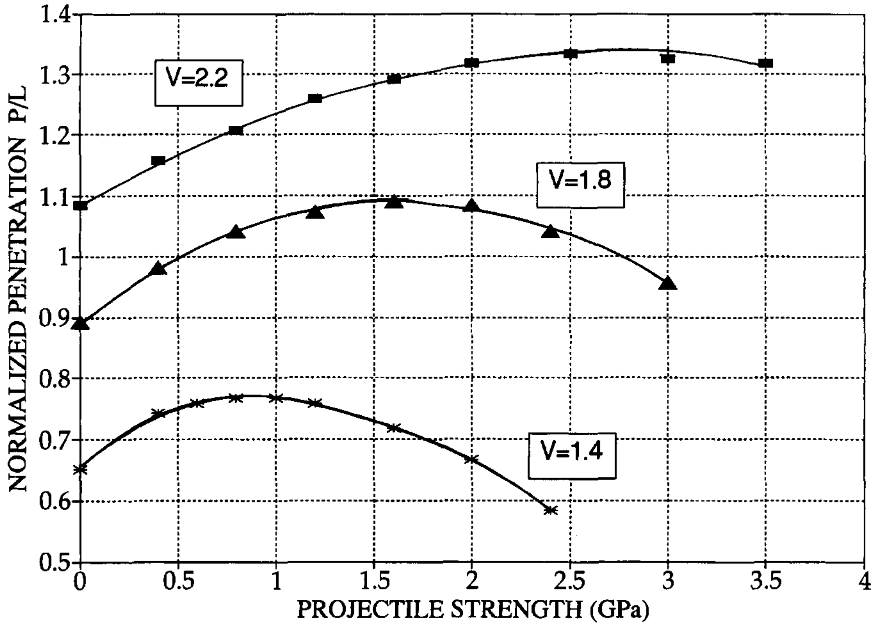

Fig. 6. Results for $L/D = 10$ ($V = 1.4, 1.8, 2.2$ km/s); note the shift in the maximum point to higher Y_p with impact velocity.

location of the maxima is concerned. However, the slopes of the curves are quite different pointing to a much larger sensitivity for penetrators with high L/D values. As far as the location of the maximum points is concerned, there is a small decrease in the value of Y_p, as L/D increases from 10 to 30. On the other hand, for each L/D, the maxima shift substantially with the impact velocity. One can see that with the $L/D = 10$ rod the maximum is at $Y_p \approx 1.0$ GPa for an impact velocity of 1.4 km/s while for 2.2 km/s it has moved to $Y_p \approx 2.5$ GPa. Figure 6 summarizes this trend by showing the sensitivity of the location of the maxima to impact velocity. Due to the rather weak dependence of the maxima on L/D we may assume that a similar trend will result for rods at $L/D = 20$ or higher. The reason for the insensitivity of the maxima to the value of L/D is probably the result of the fact that these maxima convey the compromise between deceleration time and the duration of penetration. Both these times are directly proportional to penetrator's length so we might expect the location of the maxima to be relatively insensitive to the penetrator.

It is also worth noting that the values of P/L decrease substantially as the length to diameter ratio (L/D) of the rod increases. This L/D effect was first demonstrated by us in Ref. [1] where we chose an impact velocity of 1.4 km/s and a tungsten alloy rod with a strength of 1.2 GPa. The present work shows (Figs 4 to 6) that influence of L/D on P/L is substantial for the whole range of Y_p and impact velocities of interest.

4. CONCLUDING REMARKS

Two-dimensional simulations were used to explore the influence of penetrator's strength on its penetration capability. We found that for tungsten alloy rods, impacting armor steel targets at velocities of 1.4–2.2 km/s, a clear maximum is obtained in the penetration depth vs rod strength curve. These maxima are sensitive to the impact velocity (shifting towards high values of Y_p with higher velocities) but relatively insensitive to the length to diameter ratio of the rod. The basic mechanism behind this effect has to do with the deceleration of long-rods, which is dependent on rod strength. Since the penetration capability is a strong function of the impact velocity, the decelerated rear portion of the rod contributes much less to the penetration depth. The higher the strength of the rod, the stronger will its deceleration be. One should take these considerations into account when designing long-rod penetrators. However, one should bear in mind that these predictions are based on simulations which describe the penetration process as a hydrodynamic one. As it turns out, both tungsten alloy and depleted uranium long-rods show features such as adiabatic shear, which are absent in the hydrodynamic description. Thus, it may be that the existence of the maxima points which we found here is obscured by other effects which take place with real penetrators. Thus, an experimental study is necessary to check the predictions presented here.

We would like to point out that a thorough search for experimental evidence for the effect did not result in any conclusive evidence. We checked the database [9], which includes much of the published data on long rods, and could not find a large enough range of projectile strengths to cover the range we have examined numerically here (0–2.5 GPa). It turns out that most of the tungsten alloy rods which are being used in these studies have strengths in the 0.8–1.2 GPa range which covers the peak of our computational graphs. Thus, in order to test our results in a more rigorous way, we need a set of experiments with long rods having strengths in the 1.0–2.0 GPa range with impact velocities around 1.4 km/s. As is clearly seen from our results with higher impact velocities, the maxima in the P/L vs Y_p graphs tend to be shallower, obscuring the effect.

It would also be very interesting to study the case of steel penetrators for which a large range of strengths is possible. In the near future we intend to further investigate this phenomenon with steel projectiles, both numerically and experimentally.

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