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A NUMERICAL COMPARISON OF THE BALLISTIC PERFORMANCE OF UNITARY ROD AND SEGMENTED-RODS AGAINST STATIONARY AND MOVING OBLIQUE PLATES

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Abstract—The purpose of this paper is to investigate the ballistic performance of segmented-rods against stationary or moving oblique plates. To do this, a series of three-dimensional numerical simulations for the impact characteristics of segmented-rods (5 of L/D=1) into stationary or moving oblique thin-plate targets is conduced. To provide a base line data, an L/D=5 unitary rod projectile which has the same mass and kinetic energy is also considered. The ballistic characteristics of the projectiles are evaluated by examining the crater profile in a thick witness target that is placed behind the oblique plate. The impact velocities considered are 1400, 1800 and 2200 *m/s*. The results for the test range show that the unitary rod projectile shows better performance in the moving oblique target than the stationary one and the segmented-rods always show slightly better performance in the stationary target. From the impact velocity of 2200 *m/s*, the outstanding penetration performance of the segmented-rods can be observed. This trend is due to the interaction between the reactive plate and projectile. The extent of the interaction relies on the relative velocities of the plate and projectiles, the plate angle and extended total length of the segmented-rods

Keywords: segmented-rods, unitary rod, oblique plate, reactive plate

INTRODUCTION

Recently, a number of investigators have shown an outstanding penetration performance of segmented-rods for normal impact into a thick target. Although oblique plate impact is one of the important projectile/armor design concerns, most of the work examined in the open literature concerned with segmented-rods was interested in segments impacting semi-infinite targets at normal incidence [1-4]. The potential improvement in penetration performance per unit collapsed length of single segment is enormous, if it could be realized. Collapsed length is the total length without spacing as shown in Fig. 1. The penetration of segmented rods generally exhibited large scatter, but L/D=1 segments demonstrated a performance increase of approximately 65% versus L/D =30 [5] long rod projectiles (P/L of 2.4 vs. 1.45) at the velocity of 2.6 km/s. L and D are the length and the diameter of the projectile, respectively. P is the penetration depth. To examine the segmented rod performance, De Rosset and Sherrick [6] reported on CTH numerical simulations for a fixed segment spacing at 1.7 and 2.6 *km/s* against rolled homogeneous armor (RHA). One of the important results is that they observed penetration degradation, attributed to the successive segments impacting the rear of previous segments. This effect was more pronounced at low velocities. Hauver and Melani [7] also found that successive segments contribute progressively less to the total penetration because of their interaction with residue. Hence, the actual penetration performance of n-segmented rods is less than that obtained by the multiplication scheme (n times of the single penetration) [8].

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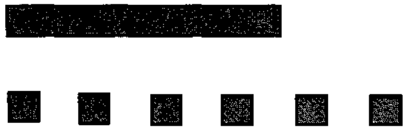


Fig. 1. Long rod and equivalent segmented-rods.

The penetration of long rod projectiles into oblique plate target was investigated numerically [9, 10] and analytically [11] by several researchers. The interaction of the projectile with the oblique plate and the induced projectile rotation was the main concern of the study. Recently, the penetration performance of the segmented-rods against stationary or moving oblique plate targets is becoming the subject of detail investigation. For instance, the terminal ballistic performance of long rod and segmented-rods against spaced as well as reactive targets is investigated experimentally [12, 13]. One of the results is that the segmented-rods cannot outperform homogeneous rods of equal length. This is due to the fact that the segmented-rods are very sensitive against lateral loading. Hence, in this numerical study the outstanding performance of segmented-rods shown in thick normal targets is tested against oblique reactive plate targets. The characteristics of the interaction between the projectiles and oblique reactive targets are identified by calculating the crater profile formed in a thick witness target that is placed behind the oblique plate with some distance. For comparison purposes, an equivalent long rod is also considered. As shown in Fig. 2, the impact of L/D=5 unitary rod and 5 of L/D=1 segmented-rods into an oblique plate is considered in this study. The oblique angle between the impact vector and plate normal is 60 degrees.

NUMERICAL SIMULATIONS

Numerical simulations of the impact of a unitary rod and segmented-rods into the stationary or moving oblique plate and detached witness block were conducted using the AUTODYN hydrocode. The objective of the simulation is to compare the ballistic performance of segmented-rods with that of unitary rod projectiles with respect to the interaction between the projectile and oblique plate. This is because the outstanding performance of segmented-rods is mainly tested for the normal impact into a thick target.

The plate and witness targets considered were RHA steel. The thickness of the oblique plate and witness target was 0.8 times the projectile diameter and 1.5 times the rod length, respectively. The actual projectile radius was 10-mm. The tungsten-alloy, unitary rod projectile was modeled with an aspect ratio (L/D) of 5; the length was 100-mm. The diameter of the segment is also 20-mm. The witness block was placed 140-mm behind the front center of the oblique plate. The velocity range of interest is 1.4-2.2 km/s.

Although a three-dimensional calculation was conducted, there is a symmetry surface (x-z plane, Fig. 2). 5 cells across the radius and 20 cells along the length of the long rod projectile are used. The plate thickness is specified using 10 cells. The total number of meshes is 31×16×41 for the computational domain of 200-mm×100-mm×150-mm witness block. Square zoning especially in the target interaction region (with ten zones across the diameter of the projectile) was used. This mesh continues for three radii away from the rod. The parameters considered in the simulation are shown in Table.1. The velocity of the plate target is selected to be 200 *m/s* toward the projectile. At 60 degrees oblique angle, the impact normal component is 173 *m/s* and impact direction component is 100 *m/s*.

Equations of state, constitutive and failure models must be specified in the simulations. In this study, the Mie-Gruniesen equation of state (EOS) was used for each material. Constitutive behavior assumed for the materials was elastic-viscoplastic, with the Johnson-Cook viscoplastic model to determine the flow stress,

Table 1. Summary of nominal projectile characteristics

Projectiles	*L/D*	*N*	*Spacing* ($\times D$)	*Impact velocity(km/s)*	*Plate thickness(mm)*	*Witness thickness(mm)*
Unitary Rod	5	1	N/A	1.4, 1.8, 2.2	16.0	150
Segmented-Rods	1	5	1	1.4, 1.8, 2.2	16.0	150

$$\sigma = \left[A + B\varepsilon_p^{\ n}\right]\left[1 + C\ln\dot{\varepsilon}\right]\left\{1 - \left[\frac{T - T_o}{T_{melt} - T_o}\right]^m\right\} \tag{1}$$

Where ε, $\dot{\varepsilon}$ and T are the equivalent plastic strain, strain rate and temperature, respectively. T_{melt} and T_o are the melting and reference temperatures, respectively. A, B, C, m and n are material constants. Values of the material properties for the projectile and target are shown in the Ref. 14.

The Lagrangian scheme is more efficient for the problem considered here, since the grid is only embedded into the projectile and the spaced targets, while the Eulerian scheme must include the entire domain. To solve the penetration of thick target, however, a Lagrangian material should erode and the element essentially disappears although the mass is retained at the nodes.

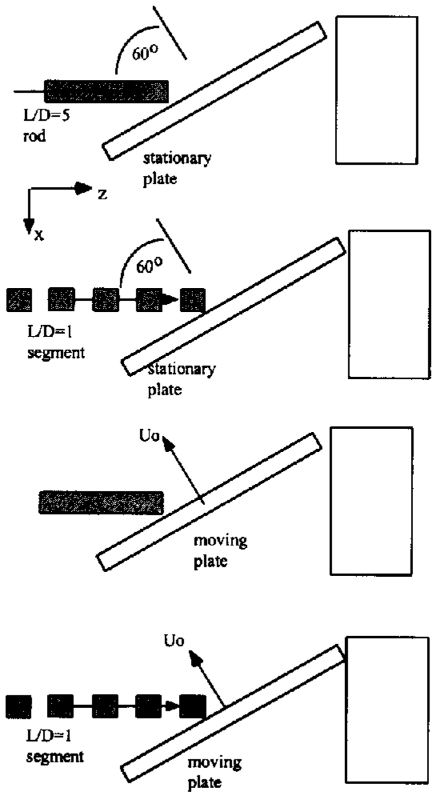


Fig. 2. The impact of segmented-rods and unitary rod into oblique plate and witness target.

RESULTS

Baseline Two-Dimensional Results

It is instructive to examine the penetration of a unitary rod projectile and segmented-rods into a semi-infinite target in this section. The aim is to provide a base line data compared with the impact against oblique plate targets, and the accuracy of the current simulation has been partially assessed. The impact of a single L/D=5 rod and 5 successive L/D=1 segmented-rods into a thick target is considered. The diameter of the projectiles is held constant. The thickness of the target along the penetration direction is 3 times of the rod length and the width is 15 times of the rod radius. The impact velocities considered are 1.8 and 2.2 km/s. For consistency with three-dimensional calculations, the Lagrangian scheme was used, and the simulation results are summarized in Table 2. Clearly, the ballistic performance (P/L) increases with impact velocity for each projectile. P/L=1.49 for the impact of an L/D=5 rod at 2.2 km/s is slightly higher than an L/D =20 long rod. This is due to the fact that the penetration performance (P/L) is greater for small L/D projectiles than for large L/D projectiles, referred to as the *L/D effect* [15]. Note that in this study the penetration depth is calculated at the interface between the tungsten and target, if tungsten residue remains in the crater bottom. Charters measured P/L=1.379 for the impact of an L/D=5 rod at 2.2 *km/s* [16]. One of the interesting results is that the performance of segmented-rods is degraded, compared with that of a single segment (1.65 *vs.* 2.15 at 2.2 km/s). This trend is also well examined in earlier work [8]. One of the available experimental data for the impact of an L/D=1 segment at 2.291 km/s is P/L=1.931 [8]. Generally, the computation results are slightly higher than the experimental data. The increase of P/L for segmented-rods compared with an equivalent unitary rod is estimated to be about 10 % at the impact velocity of 2.2 *km/s* (1.65 vs. 1.49). It is demonstrated that the segmented-rods considered here do not show an outstanding ballistic performance. Some of the reasons are already discussed in the introduction section.

Table 2. Simulation results for normal impact into thick targets.

Projectiles	*L/D=5*		*5 of L/D=1*		*L/D=1 single*	
Velocity (*km/s*)	1.8	2.2	1.8	2.2	1.8	2.2
P/L	1.25	1.49	1.36	1.65	1.85	2.15

Oblique Plate Results

Three-dimensional calculations were investigated in this section. Four cases are considered in this study; (a) the impact of a unitary rod into a stationary oblique plate, (b) the impact of a unitary rod into a moving oblique plate, (c) the impact of segmented-rods into a stationary oblique plate, and (d) the impact of segmented-rods into a moving oblique plate. The oblique plate is specified to move towards plate normal at the velocity of 200 *m/s*. After emerging from the oblique plate, the residual projectile impacts the witness block placed behind the plate.

Figure 3 shows three-dimensional computations for a unitary rod impact into oblique plate targets at the velocity of 1.8 *km/s*. As noted previously, a Lagrangian computation is efficient because the grid is not required for the space between the plate and witness block. It is shown in the figure that the impact of a unitary rod into an oblique plate target will cause the rod to rotate towards the plate normal, and that the rotation is caused by the interaction with the back surface of the plate. Hence, the impact of the residual projectile into the witness target is yawed.

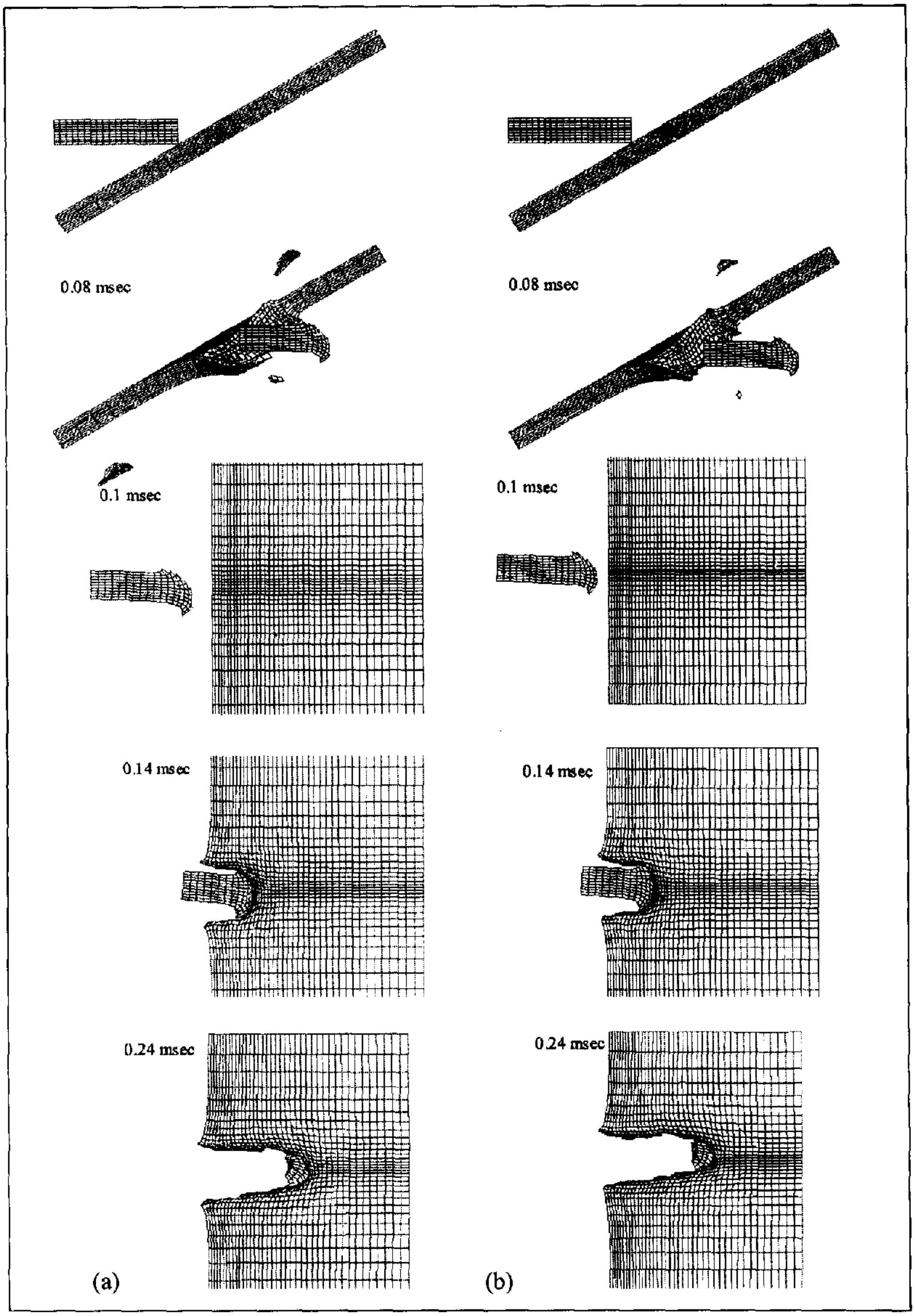


Fig. 3. The impact of L/D=5 rod into (a) stationary and (b) moving plate, 1.8 *km/s*.

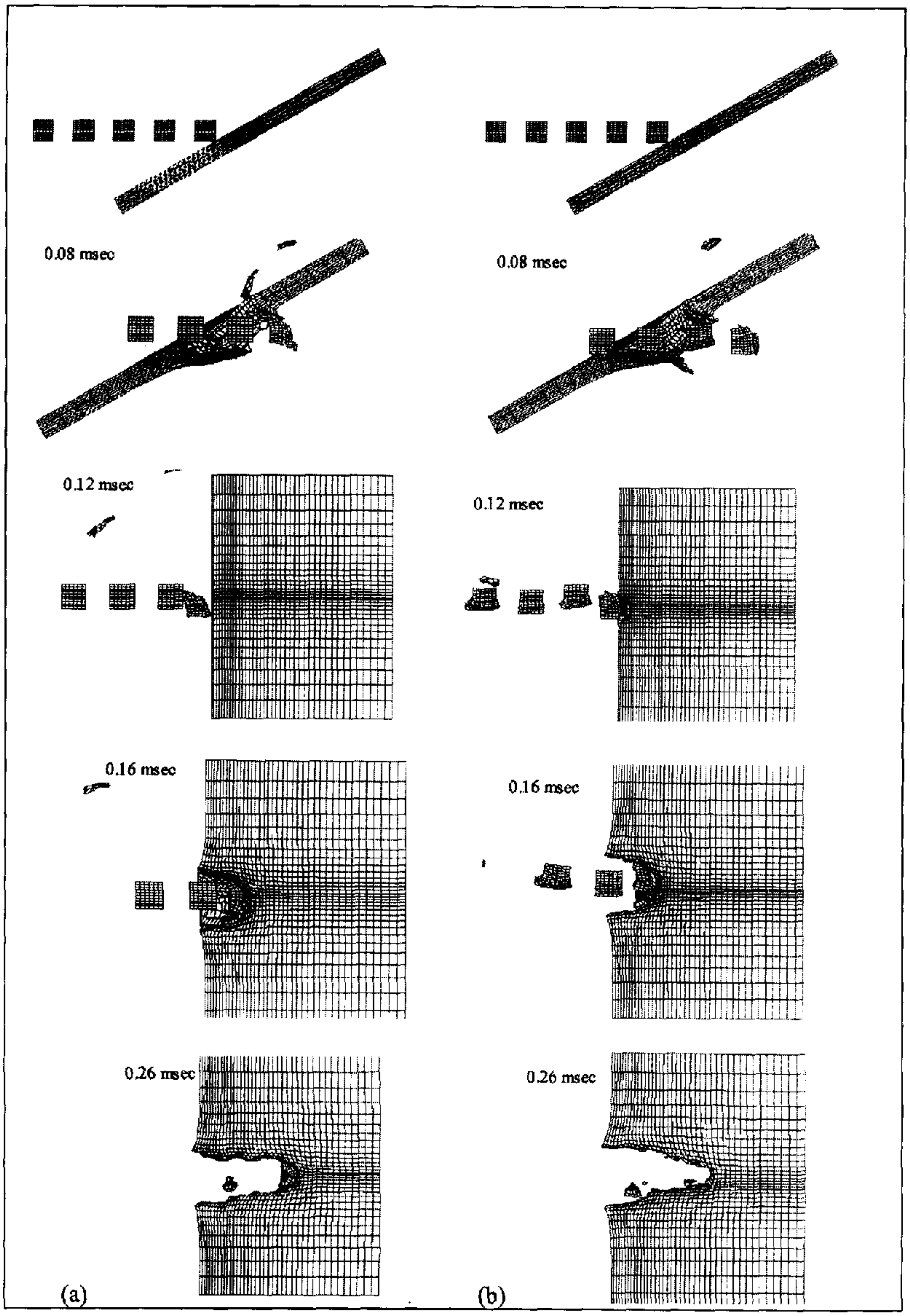
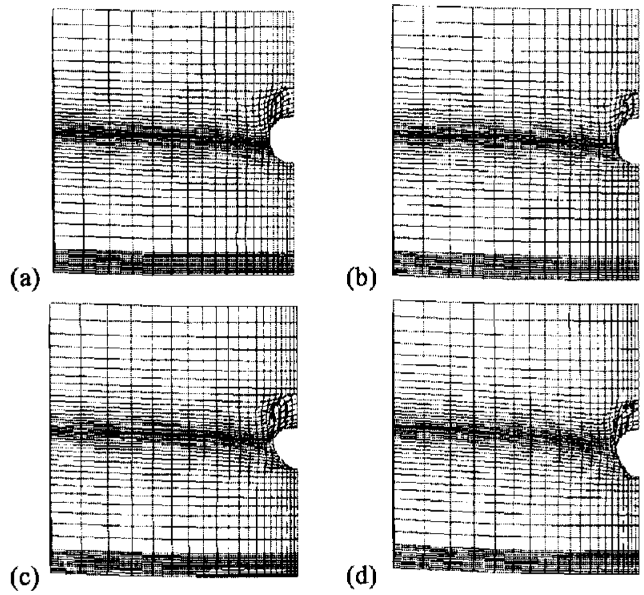


Fig. 4. The impact of segmented-rods into (a) stationary and (b) moving plate. 1.8 *km/s*.

One of the important results for rod projectiles is that the deformation of the rod tip and resulting rotation is less significant in the stationary one. This is because the material of the plate back surface moves away from the projectile. The comparison of the penetration depth calculated in witness target will be shown later in this section.

Figure 4 shows three-dimensional computations for segmented-rods impacting the oblique plate targets at the velocity of 1.8 *km/s*. Again, the Lagrangian computation seems to be much efficient, especially for long segmented-rods. A significant interaction between successive segments and plate target is observed only in the moving target. Due to the extended length of the segmented-rods in this case, however, most of the significant interaction occurs at the front surface of the moving plate. The segmented-rods can be damaged significantly since the projectile is sensitive to the lateral loading. For the stationary plate, the interaction is limited to the first two segments. On the other hand, for the moving plate the interaction occurs in almost every segment. It is most evident that this interaction becomes serious with increased plate velocity and total length of the segmented-rods. We have already observed that the segmented-rods produce a reduced crater diameter in a semi-infinite target compared with a long rod [8]. Since the reduced hole diameter induces more interactions with successive segments, it is necessary to examine the hole diameter. The hole shape seen from the impact direction is shown in Fig. 5. Although the segmented-rods produce a slightly smaller crater diameter, no significant variations are observed in the figures. This is because the crater shape shown in the figures are generated by 5 successive segments interacting with the plate.

A comparison of the penetration depth calculated in the witness target as a function of impact velocity for each projectile is summarized in Fig.6 and Table 3. As is evident from the figure, the penetration depth increases with impact velocity. The first thing to note is that the unitary rod shows better ballistic performance against a moving plate than a stationary one. As shown in Fig.3, this is due to the reduced interaction between the moving plate target and rod, such that the rotation of the rod is decreased. However, the segmented-rods show slightly better, but not significant, ballistic performance against the stationary plate than against the moving one.



(a) (b) (c) (d)

Fig. 5. The crater shapes seen from the impact direction for (a) a unitary rod into a stationary plate, (b) segmented-rods into a stationary plate, (c) a unitary rod into a moving plate, (b) segmented-rods into a moving plate, 1.8 *km/s*.

Table 3. Calculated penetration depth (*mm*) in the witness target.

Impact velocity (km/s)	*1.4*	*1.8*	*2.2*
Rod-stationary plate	47.5	75.8	95.6
Segmented-stationary plate	45.7	8.31	12.03
Rod-moving plate	55.2	8.29	10.10
Segmented-moving plate	43.3	7.95	11.48

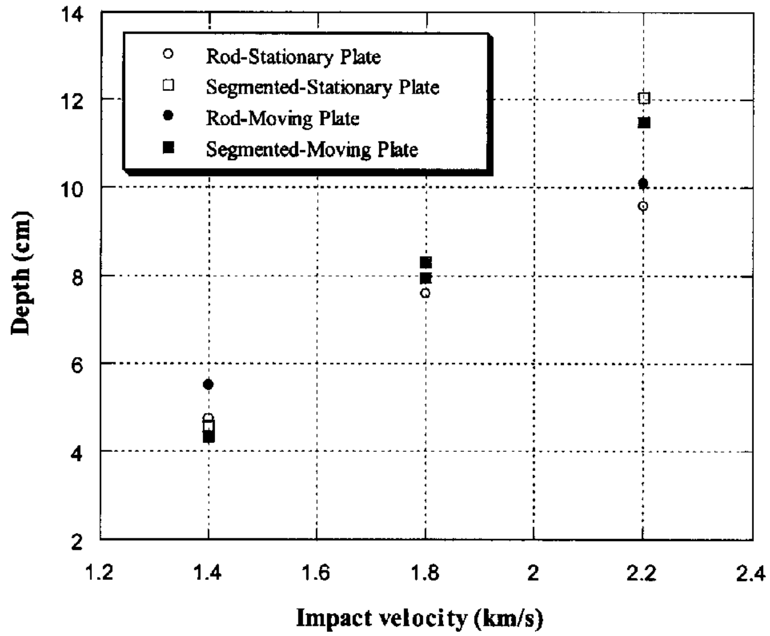


Fig. 6. Penetration depth calculated in the witness target with impact velocity. The oblique plate is moving at the velocity of 200 *m/s*.

The most important result is that the performance of the segmented-rods becomes better at high velocities. Although better performance of the segmented-rods is observed even against the moving plate, it is not so significant as that shown in the normal target. It can be concluded that better performance of the segmented-rods can be achieved at high impact velocity and reduced total length of the projectile.

DISCUSSIONS AND CONCLUSIONS

A numerical comparison of the ballistic performance of a unitary rod (L/D=5) and segmented-rods (5 of L/D=1) against stationary and moving oblique plate targets has been carried out. In this study, the ballistic performances are examined by calculating the depth in the thick witness target placed behind the oblique target with some distance. Although the values of the three-dimensional results are not verified with experimental data, the main purpose of the current numerical study is the comparison of the ballistic performances between a unitary rod and segmented-rods. The characteristics of the interaction between the projectile and target tested in this study are examined. From the study following conclusions can be drawn.

this study are examined. From the study following conclusions can be drawn.

1. In the test range, the unitary rod projectile shows better performance against a moving oblique target than a stationary one, and the segmented-rods show slightly better performance against the stationary target.
2. From the impact velocity of 2.2 *km/s*, an improvement in penetration performance of 2% for the segmented-rods was observed.
3. The important parameters which should be tested in the future study are the impact velocity, oblique plate velocity, the *L/D* of the projectile, the total length of the segmented-rods, and the plate thickness. The interaction between the projectile and oblique plate is mainly governed by these parameters.

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