

Determination of the kinetic parameters of the projectile when penetrating the wooden target by finite element methods

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ABSTRACT

The inertial force that occurs when a projectile impacts or penetrates depends on various factors, such as the diversity and heterogeneity of the physical and mechanical characteristics of the obstacle, as well as the structural features of the projectile. These factors are not calculated accurately but need to be combined with actual testing to determine. Many studies have been conducted on the process of projectiles penetrating into soil, rock, concrete, as well as research on projectiles penetrating steel plates. However, up to now, studies on bullets penetrating wooden targets are still limited. This is because, in reality, wooden targets are not common battlefield targets. In fuze tests, wooden targets are widely used to ensure safety and standardisation during testing, but the acceleration values obtained to activate the fuze have not been quantified. Based on this reality, this article investigates the applicability of formulas for the process of projectiles penetrating steel targets in order to apply them when calculating the penetration of projectiles into wooden targets. The simulation results identified the critical coefficient when projectiles penetrate into oak wood targets, with projectile sizes ranging from 57 to 100 mm, velocities ranging from 500 ÷ 1000 m/s, and wood thicknesses ranging from 10 to 50 mm, with values ranging around 1320 ÷ 1825. The test firing results for a specific case (76mm projectile, 30mm thick target) do not deviate much from the simulation.

Keywords: Projectile penetration into wooden target; Projectile penetration into steel plate; Fuze test; Penetration depth.

1. INTRODUCTION

When a projectile collides with an obstacle, the fuze components may experience a reaction force, inertia, or stress wave, which serves as a signal to activate the fuze. Among these signals, the inertial force is commonly used in fuzes for shells or missiles [1, 2]. The inertial force arises when the projectile slows down during the penetration process into the obstacle. The resistance of the obstacle depends on many factors, and these factors cannot be calculated precisely but must be combined with actual experiments to determine. Obstacles, when the projectile penetrates, include soil, rock, concrete (such as bunkers, trenches, or pillboxes), or steel plates (for armoured targets). Many studies have been conducted on the process of projectiles penetrating into soil, rock, and concrete [3-5], as well as studies on projectiles penetrating steel plates [6]. However, up to now, studies on bullets penetrating wooden targets are still limited. L. Koene and F.R. Brockhuis used theoretical and experimental models to study 9mm bullets penetrating wooden targets [7]. Elina Barone, Baiba Gaujena and Janis Videmanis studied the process of 9mm bullets penetrating wooden layers [8], etc. In general, studies mainly focus on the penetration depth of small bullets penetrating wooden targets, with little mention of dynamic parameters when penetrating targets, especially for large bullets used for fuze testing. In fuze testing, wooden targets are widely used to ensure safety and standardisation during the process, but the acceleration values obtained to activate the fuze have not been quantified. Based on this fact, this article investigates the applicability of formulas for projectile penetration through steel plates to be applied when calculating projectiles penetrating wooden targets.

2. COMPUTATIONAL MODELS

2.1. The projectile penetration model through steel targets by Zakodoma

When studying projectiles penetrating steel plates, Zakodoma [6] proposed a model and method for calculating the resistance when a projectile penetrates a steel plate as follows (figure 1):

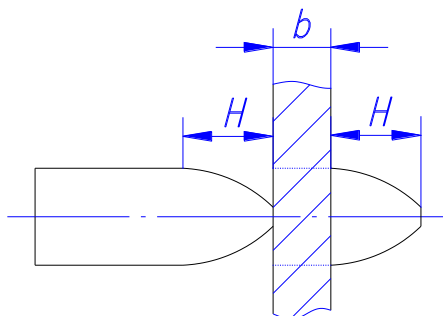


Figure 1. The model for determining the inertial force acting on the fuze components when a projectile penetrates a steel plate.

Where:

- b is thickness of steel plate;
- H is the length of the conical section of the projectile, assuming that the projectile does not deform when penetrating the steel target (the length of the conical section remains unchanged).

The kinetic energy of the projectile when it impacts the steel plate:

$$E_c = \frac{Mv_c^2}{2}$$

The kinetic energy of the projectile and the target portion that is destroyed when the projectile penetrates:

$$E = \frac{(M + M_{dv})v^2}{2}$$

M is the mass of the projectile, M_{dv} is the mass of the broken steel moving with the projectile, v_c is the velocity when the projectile hits the target, v is the velocity after the projectile penetrates the target.

The kinetic energy lost to penetrate the target E_b is calculated according to the formula:

$$E_b = \frac{Mv_b^2}{2} = \frac{Mv_c^2}{2} - \frac{(M + M_{dv})v^2}{2}$$

where v_b is called the limited velocity (required) for the projectile to penetrate the target.

The distance travelled by the projectile through the steel plate is $(b + H)$, so the time taken to penetrate the steel plate is:

$$t_{ib} = \frac{b + H}{v_{ib}} = \frac{2(b + H)}{v_c + v}$$

From there, we can calculate the average acceleration of the projectile:

$$\left(\frac{dV}{dt}\right)_{ib} = \frac{v_c - v}{t_{ib}} = \frac{v_c^2 - v^2}{2(b + H)}$$

To determine the average acceleration and velocity as the projectile penetrates the target, the author tested to determine the limit velocity value v_b :

$$v_b = k_{th} \frac{d^{0,75} b^{0,7}}{M^{0,5} \cos \alpha} \quad (m / s)$$

$$\Rightarrow k_{th} = \frac{M^{0,5} \cos \alpha}{d^{0,75} b^{0,7}} \sqrt{v_c^2 - \left(1 + \frac{M_{dv}}{M}\right) v^2} \quad (1)$$

Where: d - Size of the projectile, in dm;
 b - Thickness of steel plate, in dm;
 M - Mass of projectile, in kg;
 α - Angle between the normal and projectile axis;
 k_{th} - Coefficient, equal to 1800 with homogeneous steel; equal to 2000 ÷ 2200 with heterogeneous steel, equal to 2400 when shooting at an angle with heterogeneous steel.

For each type of material, the limiting velocity is different. Based on the model and formula for calculating the penetration through the steel plate, the article uses the finite element method to simulate the wood material to determine the coefficient k_{th} to calculate the kinematic parameters in the process of the projectile penetrating the wooden target.

2.2. Finite element model of a projectile penetrating a wooden target

To simulate the determination of the critical coefficient k_{th}, use the explicit Ansys dynamics module to simulate. Below are some assumptions and limitations:

- Impact velocity of projectiles is between 500 – 1000 m/s;
- The direction of the projectile velocity vector coincides with the projectile axis, the projectile axis is perpendicular to the target plane;
- Projectile size: using 03 types of 57 mm, 76 mm, 100 mm projectiles, the projectile tip is in the oval shape;
- Wooden target: 10 – 50 mm thick;
- Neglecting the rotational movement, processive tonic movement of projectiles;

The sequence of simulated problem development (figure 2):

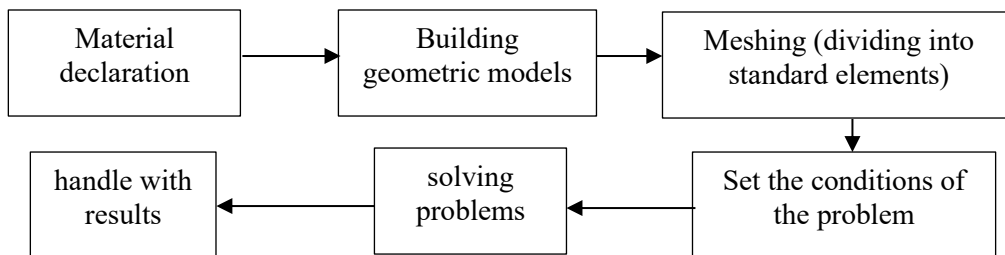


Figure 2. Sequence of building simulation problems.

- Material declaration:
 - + Projectile: select common steel material (Structural Steel) available in the material library of Ansys software, with the following parameters [9]:

Table 1. Projectile material parameters.

TT	Property	Value	Unit
1	Density	7,896	Kg/m ³
2	Specific	452	Kg ⁻¹ C ⁻¹
3	Initial yield stress	3,5e+8	Pa
4	Hardening constant	3,5e+8	Pa
5	Shear Modulus	8,18e+10	Pa

Research

+ Wooden target: Choose oak wood in the material library of Ansys, with the following parameters [10]:

Table 2. Parameters of Oak material.

TT	Property	Value	Unit
1	Density	935,7	Kg/m ³
2	Poisson's Ratio	0,3742	
3	Young's Modulus	2,278e+10	Pa
4	Bulk Modulus	3,018e+10	Pa
5	Shear Modulus	8,2885e+9	Pa
6	Specific Heat	1685	Kg ⁻¹ C ⁻¹

- Building geometric models:

The penetration model is built as follows (figure 3):

+ The projectile is a cylindrical part with an oval tip;

+ Square wooden target with size: 0.5m x 0.5m, thickness varies.

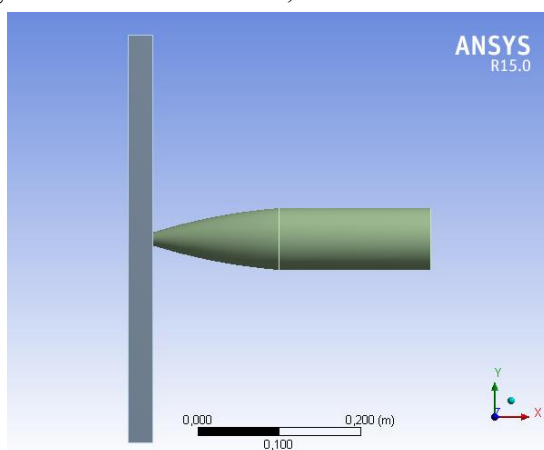


Figure 3. Geometric model of projectile impact on wooden target.

- *Meshing*: The model uses a Lagrange grid, the target and the projectile are meshed with gradually finer sizes from 8 mm, 6 mm, 4 mm, 2 mm until the simulation results reach convergence. Table 3 shows the simulation results corresponding to the fineness of the mesh divided for a 76 mm projectile, a 30 mm thick target.

Table 3. Simulation results corresponding to the fineness of the meshing.

Projectile 76 mm, b = 30 mm, v _c = 600 m/s				
Mesh size (mm)	8	6	4	2
Velocity after target v (m/s)	501	549	569	572
Deviation from the previous mesh size		9.6%	3.6%	0.5%

When the size was reduced from 4 mm to 2 mm, the simulation results were almost constant (0.5% change). Therefore, in order to balance the machine running time and the required accuracy, the projectile and wooden target are meshed to a size of 4 mm.

- *Problem-solving*: Proceed to solve the problem to determine the velocity after the projectile penetrates the target to determine the critical coefficient k_{th}.

3. SIMULATION CALCULATION RESULTS

Figure 4 is a sequence of images as projectiles penetrate the wooden target. The image of

projectiles penetrating through a wooden target resembles the model of projectiles penetrating through a steel target that the authors have shown in figure 1.

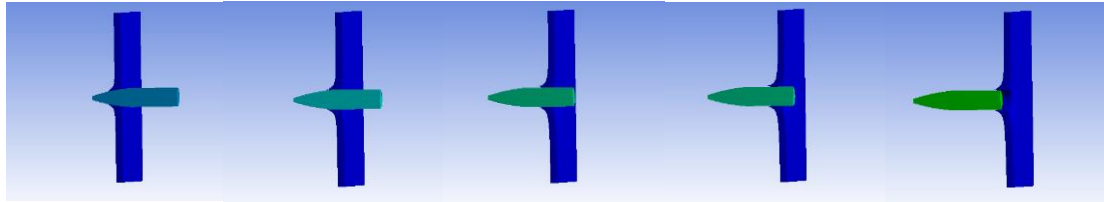


Figure 4. Image sequence when the projectile penetrates the wooden target.

When the projectile hits the target, the portion of the target that was in contact with the projectile is smashed. The simulation results show that when the taper of the projectile penetrates the target, the projectile moves at a constant velocity (figure 5).

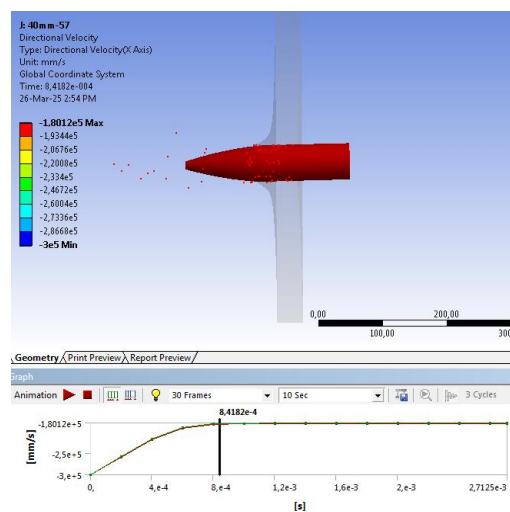


Figure 5. Image of the surface of the target that was shattered by the projectile.

The simulated image shows that the dynamic nature of the process of the projectile hitting the steel target and the wood target is the same. Therefore, if the simulation results are combined with the experimental formula (1), the critical coefficient k_{th} will be determined.

- Simulation results to determine the coefficient k_{th} for 100 mm projectiles:

Mass $M = 10.9$ kg, diameter $d = 100$ mm, impact velocity $v_c = 500 \div 900$ m/s, target thickness $b = 10 \div 50$ mm. The simulation results for the projectile velocity value after hitting the target. From these parameters, the critical coefficient k_{th} can be determined. The calculated results are shown in the figure below (figure 6).

The simulation results for the 100 mm projectile show that the critical coefficient k_{th} ranges from 1434 to 1825.

- + With the same impact velocity, the k_{th} value decreases as the target thickness increases;
- + With the same target thickness, the k_{th} value decreases as the impact velocity decreases;
- + The thickness of the target increases, and the k_{th} coefficient tends to converge.

- Simulation results to determine the coefficient k_{th} for 76 mm projectiles:

Mass $M = 9.52$ kg, diameter $d = 76$ mm, impact velocity $v_c = 500 \div 800$ m/s, target thickness $b = 10 \div 50$ mm. The simulation results for the projectile velocity value after hitting the target. From these parameters, the critical coefficient k_{th} can be determined. The calculated results are shown in the figure below (figure 7).

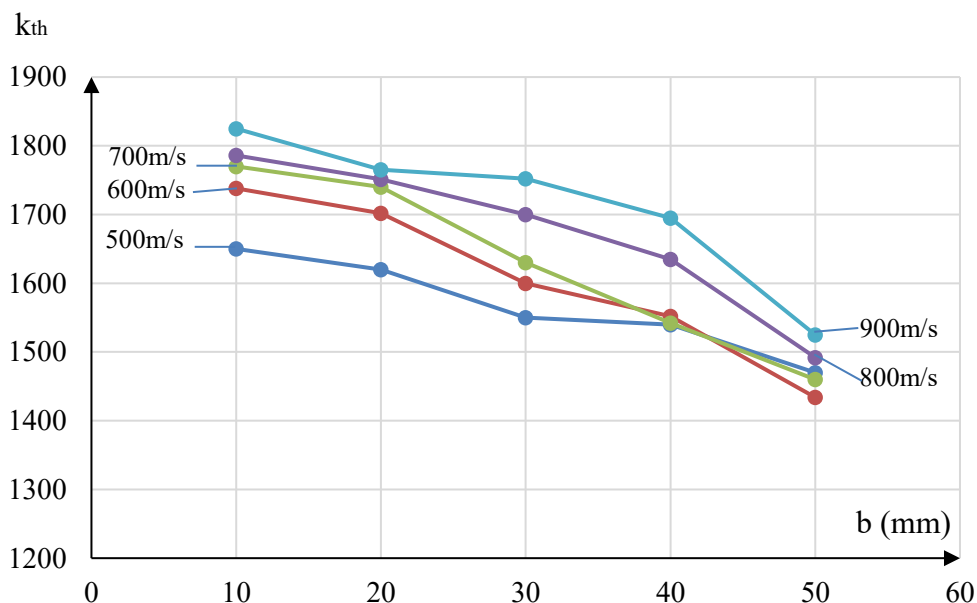


Figure 6. Coefficient k_{th} for 100 mm projectiles.

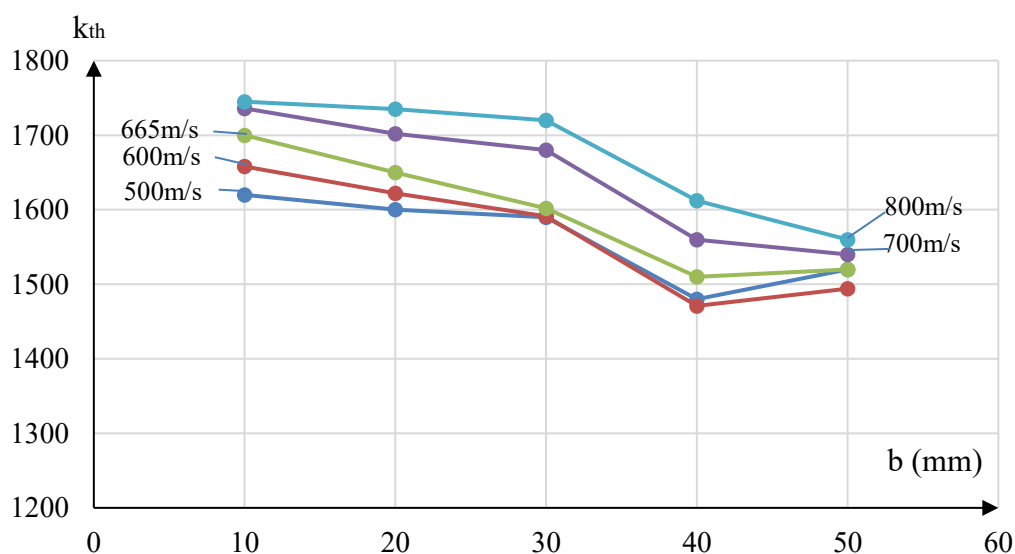


Figure 7. Coefficient k_{th} for 76 mm projectiles.

76 mm projectile simulation results for the critical coefficient $k_{th}=1494 \div 1745$. The k_{th} value varies with the thickness of the target, and the impact velocity is similar to the simulation results for 100 mm projectiles.

- Simulation results to determine the coefficient k_{th} for 57 mm projectiles:

Mass $M = 4.016$ kg, diameter $d = 57$ mm, impact velocity $v_c = 500 \div 1000$ m/s, target thickness $b = 10 \div 50$ mm. The simulation results for the projectile velocity value after hitting the target. From these parameters, the critical coefficient k_{th} can be determined. The calculated results are shown in the figure below (figure 8).

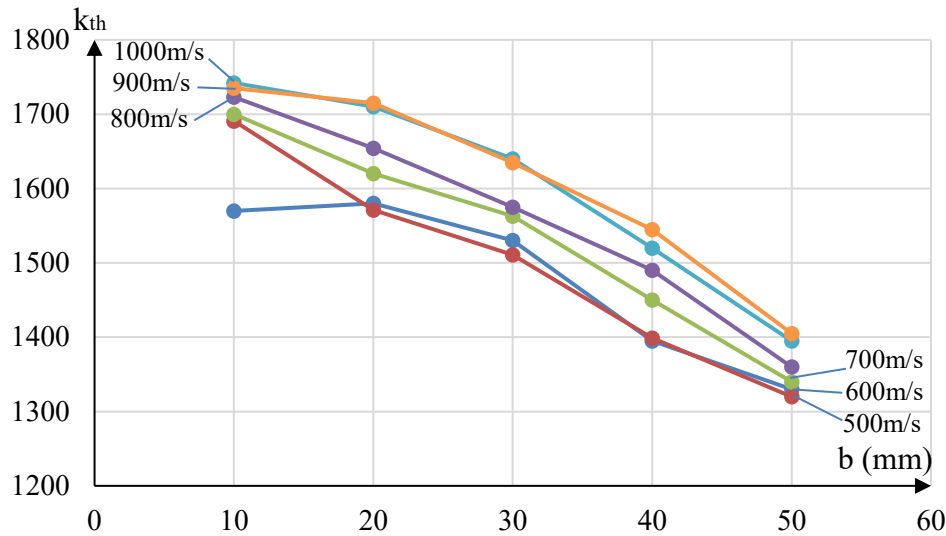


Figure 8. Coefficient k_{th} for 57mm projectiles.

Results of 57 mm projectile simulation for the critical coefficient $k_{th} = 1320 \div 1742$. The k_{th} value varies with the thickness of the target and the impact velocity is similar to the simulation results for 100 & 76 mm projectiles.

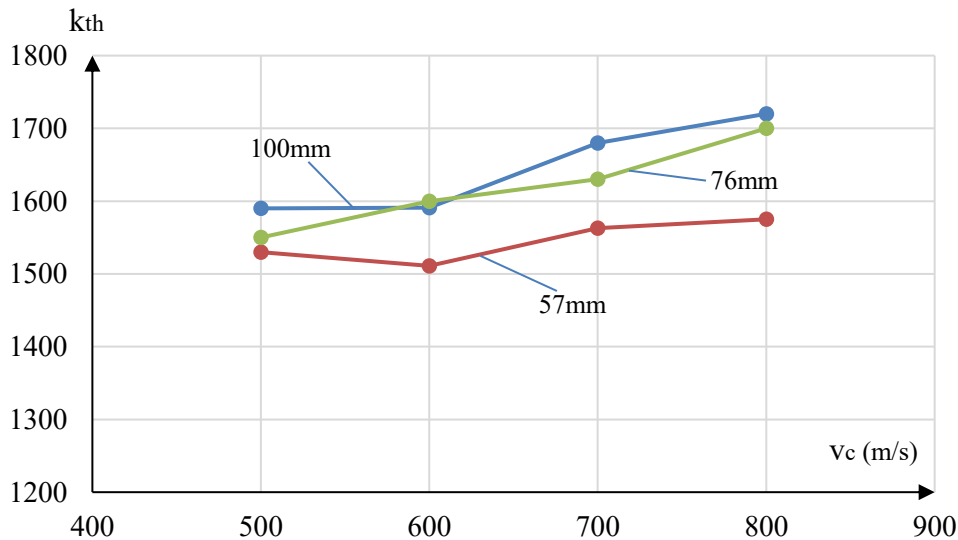


Figure 9. Coefficient k_{th} with a thickness of 30mm of a wooden target.

When comparing the coefficient k_{th} by projectile size, the simulation results show that the coefficient k_{th} increases as the projectile size increases (figure 9). This conclusion is also true for various thicknesses of the wooden target.

4. EXPERIMENT

The experiment was conducted with 76 mm projectile fired on 76-42 cannon, a wooden target (plywood) thickness 30 mm. The target was placed 100m from the canon muzzle. A high-speed camera was used to measure the velocity before the projectile hit the target and after the projectile penetrated the target (The camera was placed horizontally at the wooden target position) (figure 10).



Figure 10. Experiment images.

The test was conducted with 10 test shots, the measured results are shown in the following table (table 4).

Table 4. Results of projectile velocity measurements after the target and corresponding k_{th} values.

TT	v_c (m/s)	v (m/s)	k_{th}	TT	v_c (m/s)	v (m/s)	k_{th}
1	662	635	1519	6	662	635	1519
2	660	634	1484	7	665	638	1522
3	661	634	1518	8	663	635	1553
4	668	640	1557	9	670	644	1493
5	667	640	1524	10	669	644	1458
Average		$v_{ctb} = 664.7$ m/s; $v_{tb} = 637.9$ m/s; $k_{thtb} = 1514.7$					
Simulation Results		$v_c = 665$ m/s; $v = 635$ m/s; $k_{th} = 1602$					
Deviation		$\Delta v = -0.5\%$; $\Delta k_{th} = 5.8\%$					

The experimental results show that the velocity deviation between simulation and actual shooting (0.5%) and the critical coefficient deviation (5.8%) are small. This proves that the simulation method and the use of an empirical formula to calculate the case of a projectile hitting a wooden target are reliable enough to use.

5. CONCLUSIONS

From the simulation image, the formula used to calculate the case of projectiles penetrating the steel target by Zakopdoma [6] can be used to calculate the case of projectiles hitting the wooden target due to similar dynamic model characteristics.

The simulation results show that the coefficient k_{th} for the projectile sizes 57, 76, 100 mm, with the velocity range from 500 ÷ 1000 m/s is in the range of 1320 ÷ 1825. Compared to shooting at a steel target, when shooting at a wooden target, the coefficient k_{th} has a large dispersion value. Nevertheless, when calculating the reliability of opening insurance for the inertial block used in

the experiment, a coefficient with a threshold value can be used to ensure the reliability of the fuze's operation.

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TÓM TẮT

Xác định thông số động học của đạn khi xuyên qua bia gỗ bằng phương pháp phần tử hữu hạn

Lực quán tính xuất hiện khi đầu đạn va xuyên vào mục tiêu phụ thuộc vào nhiều yếu tố do tính đa dạng và không đồng nhất các đặc trưng cơ lý của chướng ngại cũng như các đặc trưng cấu tạo của đạn. Các yếu tố này không tính toán chính xác được mà cần kết hợp với thử nghiệm thực tế để xác định. Đã có nhiều công trình nghiên cứu về quá trình đạn va xuyên vào nền đất, đá, bê tông cũng như các nghiên cứu về đạn va xuyên vào bán thép. Tuy nhiên đến nay các nghiên cứu về đạn va xuyên vào bia gỗ vẫn còn hạn chế chưa có các công trình nghiên cứu đạn va xuyên vào bia gỗ. Bởi vì trên thực tế bia gỗ không phải là mục tiêu trên chiến trường. Trong thử nghiệm ngòi nổ, để đảm bảo an toàn và chuẩn hóa trong quá trình thử nghiệm, bia gỗ là mục tiêu được sử dụng rộng rãi, nhưng giá trị gia tốc nhận được dùng để kích hoạt ngòi nổ chưa định lượng được. Từ thực tế đó, bài báo đã nghiên cứu khả năng ứng dụng công thức tính cho quá trình đạn va xuyên vào bia thép để áp dụng khi tính toán cho đạn va xuyên vào bia gỗ. Kết quả mô phỏng khi đạn va xuyên vào bia gỗ sồi với cỡ đạn từ 57 ÷ 100 mm, dải vận tốc 500 ÷ 1000 m/s, chiều dày bia gỗ 10 ÷ 50 mm, có hệ số tới hạn nằm trong khoảng 1320 ÷ 1825. Kết quả thử nghiệm bắn cho một trường hợp cụ thể (đạn 76 mm, bia dày 30 mm) cho sai lệch không nhiều so với mô phỏng.

Từ khoá: Đạn xuyên bia gỗ; Đạn xuyên bia thép; Thử nghiệm ngòi; Chiều sâu xuyên.