

Research on simulation of a bullet skimming the ground by the finite element method

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ABSTRACT

It is greatly complicated to research the process of bullets penetrating into the ground due to the diversity and heterogeneity of ground physical characteristics. The empirical formulas have been developed for scenarios involving deep penetration of bullets into the ground so far; however, equivalent calculations for bullets skimming the ground scenarios remain absent. This paper has established a finite element method (FEM) simulation model for deep penetration and validated it against empirical data. Leveraging this validated model, simulations have been extended to examine the bullets skimming the ground behavior of bullets. The results have delineated the impact angles at which bullets skimming the ground occur for soil with average compaction density. This methodology can be adapted to various soil types to construct a comprehensive set of parameters for bullets skimming the ground angles, thereby optimizing artillery performance.

Keywords: Bullets skimming the ground; Bullets penetrating into the ground; Simulating bullet skimming the ground; Simulating bullets penetrating the ground.

1. INTRODUCTION

Studying the process of bullets penetrating into the ground is a highly complex issue. The complexity arises from the diverse and heterogeneous mechanical properties of the soil, as well as the wide variety of bullets in terms of size, weight, and shape. Although there has been extensive research on the deep penetration of bullets into the ground, there has been no study specifically addressing the phenomenon of bullets skimming the ground [1-5]. Previous research on deep penetration has employed a combination of theoretical and empirical formulas to describe the axial forces acting on the bullet. However, at bullets skimming the ground angles, the reactive force from the compressed soil beneath the bullet is greater than that from the soil above it, causing the bullet to move upwards and resulting in a bullet skimming the ground phenomenon. To date, no theoretical or experimental research has accurately determined the perpendicular reactive forces responsible for this bullet skimming the ground.

In combat situations where the target is within an area with a bullet skimming the ground angle, using a delayed-action fuse mode is recommended to increase the effectiveness of damage. When firing with a delayed-action fuse, the reactive force exerted by the target on the bullet is less compared to firing at a steeper angle. The reliability of the fuse operation under this reduced reactive force has so far been tested empirically without a corresponding calculation formula. Different soil types, with varying compression densities, affect the maximum bullets skimming the ground angle achievable by the bullet. Additionally, to design the optimal delay time from when the bullet impacts the ground until it rebounds to the optimal explosion height, a trajectory chart specific to bullets skimming the ground is required. Therefore, researching the bullets skimming the ground process is crucial for determining.

- For each type of soil, what is the maximum impact angle at which a bullet demonstrates bullet skimming the ground behavior?

- For each type of soil, what is the minimum impact angle at which the fuse operates reliably? (The design objective is to ensure the fuse functions reliably at all impact angles and across all soil types.)

- The trajectory of the bullet following a bullet skimming the ground (to determine the delay time required for the fuse to detonate the bullet at the optimal height).

This paper examines a representative scenario involving bullets impacting soil with average compaction density. The study aims to establish the firing angle at which bullets skimming the ground occur and to generate the trajectory profile following such impacts.

To achieve these objectives, the paper will employ the Finite Element Method (FEM) using Ansys software to model the process. Initially, simulations of deep penetration into the soil will be conducted, with results compared against empirical formulas to validate the simulation model. Once the deep penetration simulation aligns with empirical data, this validated model will then be used to simulate the bullets skimming the ground process.

2. BUILD A MODEL OF BULLETS PENETRATING INTO THE GROUND

2.1. Calculated according to the experimental formula

To calculate the dynamics of the process of the bullet penetrating into the ground, the authors put forward the following hypotheses:

- The collision environment is homogeneous;
- The angle of contact between the bullet and the ground is equal to 90°;
- Horizontal resistance and resistance torque for the center of gravity are zero, and the frontal resistance of the environment applied to the bullet is calculated according to the formula [1]:

$$R = \frac{\pi d^2}{4} \cdot \frac{A}{\lambda} (1 + B \lambda^2)$$

In which:

+ A, B are the coefficients typical of the collision environment. They depend on the mechanical properties, sustainability of the environment, determined experimentally;

+ λ is the coefficient dependent on the shape of the bullet: $\lambda = 1 + 0,3\left(\frac{H}{d} - 0,5\right)$;

+ H is the length of the bullet;

+ d is the bullet diameter.

With the above assumptions, the equation of motion of the bullet in the collision environment is as follows:

$$m \frac{dv}{dt} = - \frac{\pi d^2}{4} \cdot \frac{A}{\lambda} (1 + Bv^2) \quad (1)$$

Where: m is the mass of the bullet, v is the velocity of the bullet.

From the above equation, we calculate the penetration depth corresponding to the velocity values according to the formula:

$$s_t = \frac{2m\lambda}{AB\pi d^2} \cdot \ln \left(\frac{1 + Bv_c^2}{1 + Bv_t^2} \right) \quad (2)$$

2.2. Calculation according to the finite element method

To simulate the determination of velocity and depth of penetration, respectively, use the Ansys explicit self-evident dynamics module for simulation. The order of building the simulation problem is as follows:

Declare materials → Build geometric models → Grid (divide objects into finite standard elements) → Establish the conditions of the → Solve the problem → Process the results.

- Declaration of materials:

+ Bullet: select the common steel material (Structural Steel) included in the material library of Ansys software [6];

+ Ground: select soil with medium density, specific gravity to take the values in the range of average soil density: $\rho = 1100, 1300, 1500$ (kg/m³) [7]. The simulation results are compared with the results from the experimental formula according to the medium-density ground to determine the specific gravity value used for simulation when the bullet is sharpened.

- Build geometric models. The collision model is built as follows:

+ Bullet is a detail with the same mass, shape and center of gravity as a real bullet;

+ Ground: With the desire for the ground to be as long as possible until the bullet stops. However, if the soil block is longer, while the simulation results are desired, the number of elements will be very large, and the computer will not be able to process it. Therefore, the ground is chosen as a rectangular box with the size 1 m x 1 m x 2 m.

- Grid division: To balance the processing speed of the computer and the required accuracy, the bullet and the ground are meshed to ensure convergence results. The simulation results show that the size of 15 mm is suitable for both the ground and the bullet (The bullet surface is meshed with a size of 5 mm to create smoothness for the profile). The bullet uses a tetrahedral linear element, the ground uses a hexahedral linear element (figure 1).

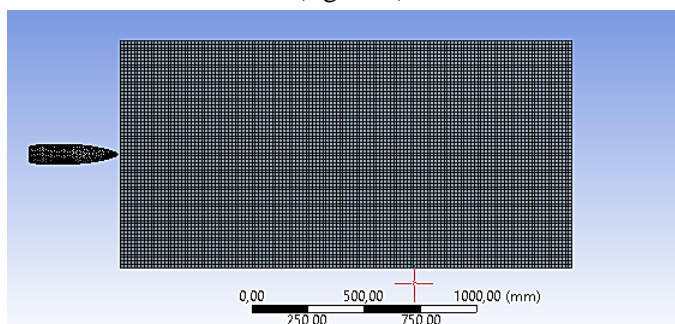


Figure 1. Image of meshing bullets and ground.

- Set the conditions of the problem:

The simulation is built with the assumption that the bullet has the following parameters: Diameter $d = 85$ mm, average impact velocity $v_c = 300$ m/s, bullet weight $m = 10$ kg, bullet length $H = 220$ mm, penetration time $t = 5$ ms.

- Solve the problem, after the computer finishes solving the problem, take the parameters of velocity and depth of collision to evaluate the simulation results. Below are some images of the simulation results with the ground with $\rho = 1300$ (kg/m³) (figure 2):

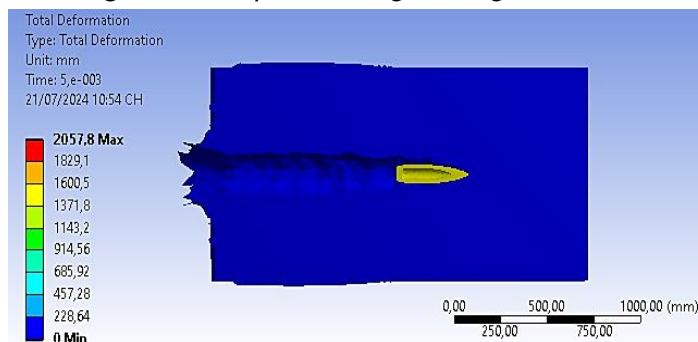


Figure 2. Image of the bullet penetrating the ground at 5 ms.

Perform the simulation with the same model for different specific gravity cases to determine the velocity at $t = 5$ ms. Figure 3 is the simulation result with the specific gravity values $\rho = 1100, 1300, 1500$ (kg/m³).

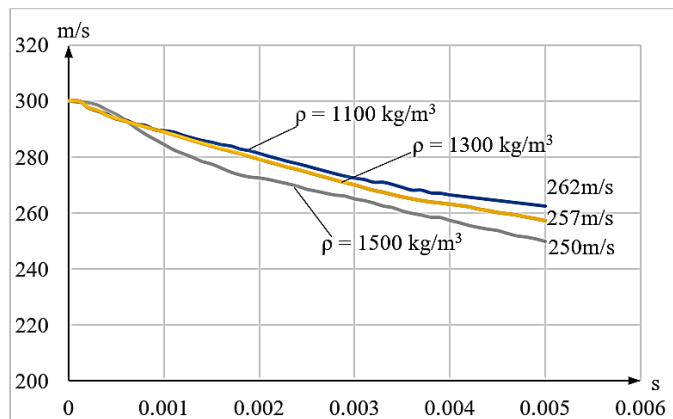


Figure 3. Velocity graph depending on the specific gravity of the soil.

Calculated from the experimental formula (2) with soil with average density [1]: $A = 3.7 \cdot 10^6$ N/m²; $B = 62 \cdot 10^{-6}$ s²/m², we get the result in table 1.

Table 1. Comparison table of results calculated according to the experimental formula and simulation results.

| No. | Specific gravity of soil ρ (kg/m ³) | v_t (m/s) | Penetration Depth (m) (Calculated according to the experimental formula) | Penetration Depth (m) (According to simulation results) | Simulation difference vs Experimental formula |
|-----|--|-------------|--|---|---|
| 1 | 1500 | 250 | 1,674 | 1,355 | -19% |
| 2 | 1300 | 257 | 1,427 | 1,381 | 3,2% |
| 3 | 1100 | 262 | 1,254 | 1,413 | 12,7% |

The simulation results show that the specific gravity of the soil greatly affects the depth of penetration of the bullet. With soil density $\rho = 1300$ kg/m³, the simulation results are consistent with the calculation results according to the experimental formula. On the basis of comparing with the experimental formula when the bullet skims the ground, the above model is used with the ground with a specific gravity $\rho = 1300$ kg/m³ to simulate the case of the bullet skimming the ground.

3. SIMULATION OF BULLETS SKIMMING THE GROUND

3.1. Determination of the angle of contact of the skimming bullet

To simulate a sharp-skimming bullet, use the bullet model and ground parameters defined in section 2 (ground dimensions: width 1 m x height 0.5 m x length 2.5 m).

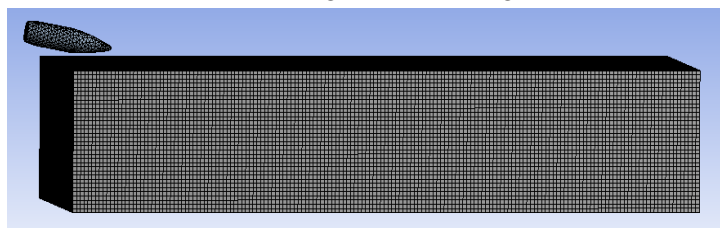


Figure 4. Form of bullets skimming the ground.

The simulation was done with contact angles from $2^\circ \div 25^\circ$. Some pictures when the bullet skims the ground (figure 5):

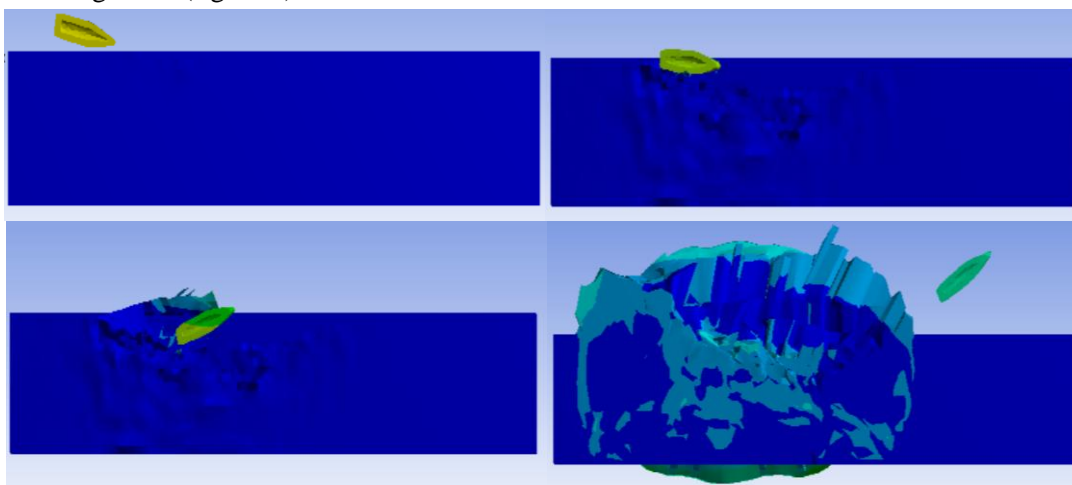


Figure 5. Skimming bullets after contacting the ground.

The graph of the bullet as it penetrates the ground and then creeps or continues to penetrate deep is shown in figure 6. From the graph, we can see the sharpening bullet with contact angles from $2^\circ \div 20^\circ$. When the angle of contact increases to 22.5° , the bullet will penetrate deep into the ground, the trajectory of the bullet is a curve as in the angles of contact from $2^\circ \div 20^\circ$. When increasing the angle of contact to 25° , the bullet penetrates the ground with a straight trajectory. Thus, with a ground with an average density, the bullet will shear with a contact angle less than or equal to 20° .

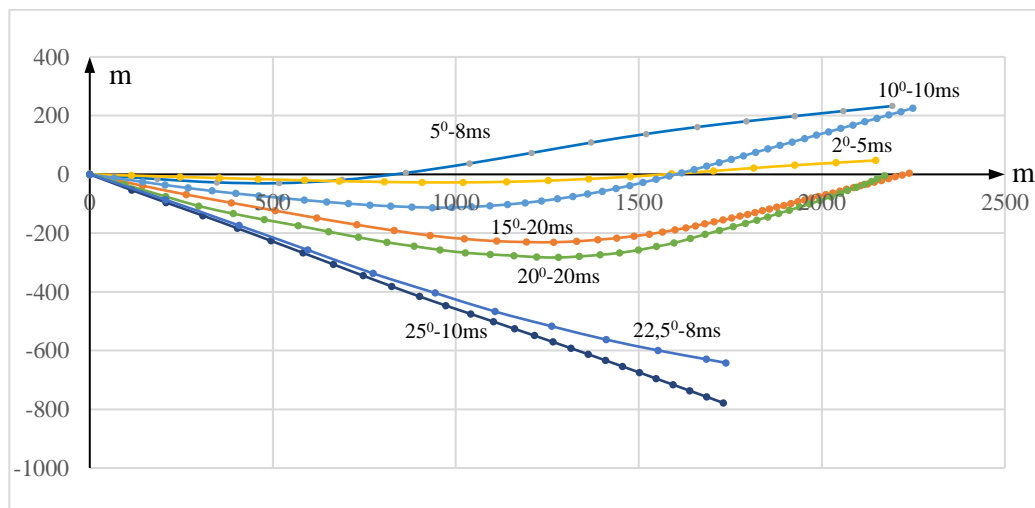


Figure 6. External projection when penetrating the ground at $2^\circ \div 25^\circ$ angles.

3.2. Bullet trajectory when skimming

When firing in skimming mode, the bullet must ensure that it is detonated at the optimum height. If the explosion height is low, the scattered fragment area will be small, if the explosion height is too high, the scattered fragment area will be large, but due to the decrease in the kinetic energy of the bullet fragment, the damage effect of the bullet fragment is not high. For each type of ammunition there will be an optimal explosive height. Based on the optimal explosion height, the operating time of the delayed burning pillar in the detonator is determined.

Continuing the simulations with contact angles from $2^\circ \div 20^\circ$, with a time increase of up to 100 ms, we get a graph of the bullet launch technique as shown in figure 7.

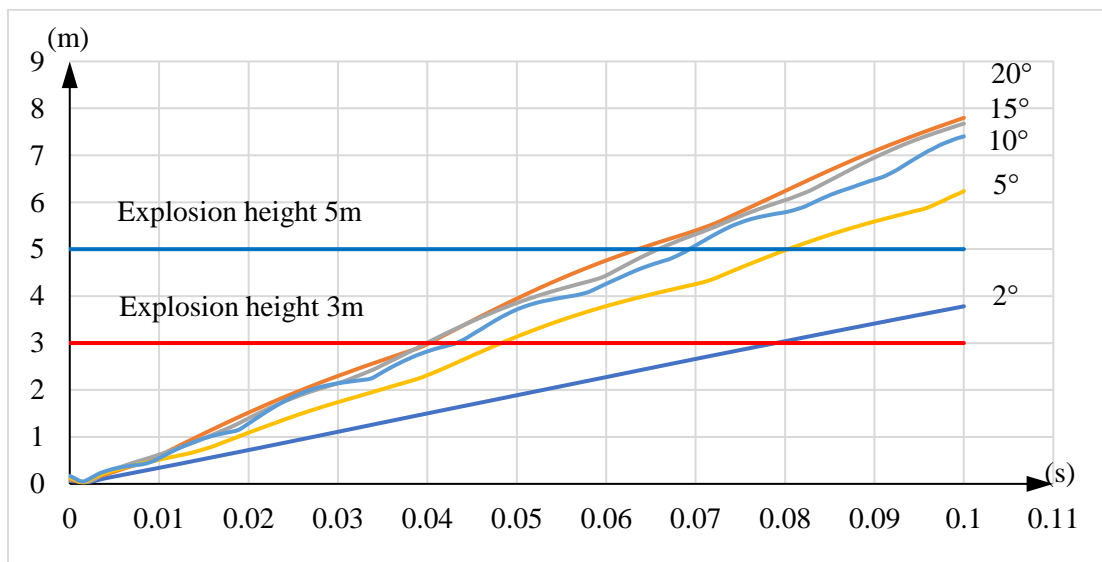


Figure 7. Bullet trajectory when skimming.

From the graph, we can see that, with the optimal explosion height of the bullet is 4 ± 1 m, from the external ejection graph above, the choice of the delayed burning time for the fuse is about $0.04 \div 0.07$ s is relatively appropriate. This is the basis for calculating the design of the fuse.

4. CONCLUSIONS

Based on the comparison of the simulation results when the bullet penetrates the ground and the calculation results according to the experimental formula, the paper has built a model of the bullet penetrating the ground to apply that model to simulate the process of the bullet skimming the ground. The results indicate that with a ground with an average density of bullets, it will sharpen with a contact angle of less than 20° . In order to have a full set of parameters about the angle of contact that the skimming bullet serves artillery operations, it is necessary to continue to simulate with different types of ground. In addition, the paper has developed a graph of the bullet trajectory to determine the delayed time when calculating and designing the fuse. The next research direction is to build the resistance function when the bullet skims the ground by the finite element method.

TÀI LIỆU THAM KHẢO

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TÓM TẮT

Nghiên cứu mô phỏng đạn chạm đất thia lia bằng phương pháp phần tử hữu hạn

Nghiên cứu quá trình đạn xuyên vào đất là vấn đề hết sức phức tạp, do tính đa dạng và không đồng nhất các đặc trưng cơ lý của đất. Đến nay, đã có các công thức thực nghiệm cho trường hợp đạn xuyên sâu vào đất mà chưa có các tính toán cho trường hợp đạn chạm đất thia lia. Dựa trên việc so sánh kết quả mô phỏng bằng phương pháp phần tử hữu hạn khi đạn xuyên sâu vào đất và kết quả tính toán theo công thức thực nghiệm, bài báo đã xây dựng được mô hình mô phỏng đạn xuyên sâu vào đất để ứng dụng mô hình đó mô phỏng quá trình đạn chạm đất thia lia. Kết quả mô phỏng đã chỉ ra được góc chạm mà đạn thia lia cho trường hợp nền đất có mật độ nén trung bình. Phương pháp này có thể được ứng dụng để mô phỏng cho các loại nền đất khác nhau nhằm xây dựng bộ thông số góc chạm mà đạn thia lia phục vụ cho tác chiến của pháo binh.

Từ khoá: Đạn chạm đất thia lia; Đạn xuyên vào đất; Mô phỏng đạn chạm đất thia lia; Mô phỏng đạn xuyên vào đất.