Water entry simulation analysis of a truncated projectile

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Abstract. In order to explore the influence of the bevel angle of the projectile on the vertical velocity attenuation characteristics and cavitation of the projectile after it enters the water vertically, this paper uses numerical simulation to analyze the bevel angles of 45°, 30°, 25° and 20°. At the same time, the high-speed camera is used to study the vertical penetration of the projectile with a 45° bevel angle to verify the simulation model. The research results show that the vertical velocity decays exponentially, and the trajectory of the truncated projectile is bent after entering the water so that an asymmetric open cavitation occurs. The bevel angle will affect the degree of trajectory curvature, velocity attenuation and the shape of the cavity. The larger the bevel angle, the greater the degree of trajectory curvature; the smaller the bevel angle, the slenderer the cavity and the smaller the asymmetry.

1. Introduction
When underwater weapons enter the shallow water, it is necessary to consider whether the projectile can complete the posture conversion at a specific water depth to avoid bottoming. To solve this problem, it is effective to change the ballistic of the projectile. Some scholars did research, Wang [1] studied the ballistic characteristics of the elliptical frustum projectile. The trajectory bends after the projectile enters water, and the impact speed and angle of the water-entry will affect the degree of trajectory deflection. Yang [2] studied the influence of the impact speed and angle on the ballistic trajectory and attitude angle of the projectile with a small bevel angle. The results show that the bevel angle causes the projectile to be subjected to a lateral deflection moment, which causes the projectile’s trajectory to bend. Tang [3] studied the low-speed impact velocity at different bevel angles.

The maturity and application of the finite element method provide a convenient and efficient way to study the problem of water-entry. LS-DYNA is an explicit dynamic analysis finite element program that can accurately handle highly nonlinear problems such as fluid-structure coupling analysis. Fang [4], Wang [5] and Wu [6] successively studied the trajectory and cavitation development characteristics of flat-head cylindrical projectiles at high impact speeds based on finite element technology.

This article will analyze the bevel angles at 45°, 30°, 25° and 20° based on the Arbitrary-Lagrange-Euler (ALE) algorithm. The velocity attenuation and trajectory characteristics of the projectile and the growth of the cavity will be studied. The experimental results of the projectile with a bevel angle of 45° will be compared with simulation results. The conclusion will provide a reference for the trajectory bending design of the underwater projectile in shallow water.

2. Numerical simulation
Water-entry is a fluid-structure coupling problem. The fluid-structure coupling algorithm used in this article is the ALE algorithm in the LS-DYNA program. Elements are allowed to move and distort which minimizes advection. This minimizes energy dissipation and speeds up run time.

3D SOLID164 elements are used for the element types of air area, water area and projectile. The air and water areas use ALE algorithm, and the projectile is modeled by Lagrange grid. The keyword of *SECTION_SOLID's element formulation equals 1 and 11, respectively. Select the keyword of *MAT_NULL for the material model of the air and water, and *MAT_RIGID for the material of the projectile. The material properties are shown in Table1. The keyword of *ALE_MULTI-MATERIAL GROUP is used to control the multi-material elements. The fluid structure coupling can be defined by the keyword of *CONSTRAINED_LAGRANGE_IN_SOLID. The boundary of the water and air domain is non-reflective to simulate an infinite water area. Since the deformation of the projectile is negligible, the projectile is simplified to a rigid body made of aluminum with a density of 3.0g/cm3. The resistance of the water is much greater than gravity, the effect of gravity will be ignored in the simulation.

### Table 1. Air and water simulation parameters.

| Parameter | ρ/(kg·m⁻³) | C/(m·s⁻¹) | S1 | S2 | S3 | γ₀ |
|-----------|------------|-----------|----|----|----|----|
| Air       | 1.25       | 344       | 0  | 0  | 0  | 1.40 |
| Water     | 998        | 1500      | 1.92 | -0.096 | 0 | 0.35 |

All parameters are in cm-g-μs unit system. In order to reduce the calculation time, a single-layer simulation model is established. The diameter and length of the projectile model is set as 8cm and 30cm, respectively. The head bevel angle is 45°, 30°, 25°, 20°. The initial velocity of the projectile is set at 95m/s, and the direction is perpendicular to the water surface downward. The length of the water is 200cm and the height is 100cm.

### 3. Model validation

#### 3.1. Experiment design

Figure 1 shows the experiment set-up. The tank is an octagonal prism steel structure with a height and inscribed circle diameter of 4.1mx4.2m, and a protective layer is set at the bottom of the tank. On one side of the tank, 6 observation windows made of PC material with a length and width of 1.06mx0.56m are set up to observe the cavity and the movement process of the projectile. The lamps placed on the inner wall of the tank as the light source. The experiment uses a high-speed camera to record the posture deflection of the projectile and the cavity. The shooting frequency is set to 2147 frames per second, and the exposure time is set to 300 microseconds. PCC high-speed camera control software is used for data acquisition and image analysis. The launching mechanism of the projectile is a barrel fixed above the tank. After the propellant is detonated by the ignition head, the projectile is quickly pushed to move along the barrel, and finally the projectile impacts into the water. The projectile is a segmented hollow aluminum alloy cylinder, the tail section is a hollow cylinder structure, and a sealing groove is engraved on it to seal the propellant gas. Eight screws are used to connect the head and tail. The projectile is a cylinder with oblique head with length of 300mm, diameter of 80mm, the bevel angle of 45°, and the mass of 2kg. Figure 2 shows the projectile. The impact velocity of the projectile is set to 95m/s in the experiment.
3.2. **Velocity attenuation verification**

Figure 3 shows the comparison between the simulation results and the test results of the vertical velocity attenuation with the penetration depth of the projectile. From the perspective of velocity attenuation trend, when the penetration depth is less than 0.36m, the velocity of the projectile decays slowly; when the penetration depth is greater than 0.36m, the projectile decays faster. From the perspective of attenuation, the test results of the projectile decay slower than the simulation results in the first stage, and the test results of the projectile decay faster than the simulation results in the second stage. The relative error of the simulation result relative to the experiment is 11.5%. This may be due to the fact that the attitude of the projectile in the air has been deflected before it enters the water, causing the force acting in the vertical direction to become smaller, and the decay of velocity is slower than the simulation result. In the second stage, as the velocity of the test projectile decays to a small value, its gravity influence cannot be ignored, and the velocity decay is accelerated under the action of gravity.

![Figure 3. The curve of penetration depth of vertical velocity between test and simulation.](image)

3.3. **Cavitation verification**

As shown in figure 4, the cavity attitude is all deflected to the left, and the head of the projectile is lifted upward due to the head-up torque in the later stage of the movement. Since the tail of the projectile rests on the right side wall of the cavity, the width of the cavity gradually increases. In the later stage of the movement, the vertical velocity decays to a small value so that the cavity width no longer increase, and the upper and lower width of the cavity are almost the same. The comparison of the maximum width of the cavity at different time is shown in table 2. Compared with the experimental results, the maximum width of the cavity of the simulation results is slightly smaller, and the relative error is 9.8% as a result...
of ignoring the gravity effect in the simulation. In summary, the simulation results are in good agreement with experiment results.

![Image](image1.png)

**Figure 4.** The cavitation comparison between test and simulation.

| Time (ms) | Test results | Simulation results |
|----------|--------------|--------------------|
| 5.12     | 24.18        | 23.92              |
| 7.45     | 33.58        | 29.71              |
| 13.04    | 41.47        | 39.98              |
| 14.90    | 47.03        | 43.13              |

**Table 2.** The comparison of test and simulation cavity width results.

4. **Simulation results analysis**

4.1. *The velocity attenuation analysis*

The velocity attenuation of the projectile within 10 milliseconds is shown in figure 5. It can be seen that the trend of velocity attenuation remains almost the same. Until the vertical velocity attenuates to 70m/s, the bevel angle has little effect on the velocity attenuation. According to data fitting, it can be known that the relationship between vertical velocity and penetration depth satisfies the exponential formula, and the fitting formula is shown in table 3, where $v_0$ represents the impact velocity of the projectile; $v_y$ represents the vertical velocity; $y$ represents the penetration depth from the water surface; $a$, $b$, and $c$ are parameters related to the bevel angle $\alpha$. This formula is the same with the research conclusion of Guo [7].

The velocity attenuation curve corresponding to each working condition can be expressed by three exponential formulas, that is, the movement of the projectile is divided into three stages. The first stage of the movement is from the projectile touching water to the projectile body’s tail touches the cavity wall. The trajectory of the projectile has been deflected, but the tail of the projectile has not hit the cavity wall, so the projectile decays according to the same exponential decay law in the first stage of motion. When the tail of the projectile begins to contact the cavity wall, the second movement stage of the projectile begins. When the tail of the projectile hits the cavity wall, the wetted area of the projectile suddenly increases, the drag force increases, and its vertical velocity decays faster. When the side surface of the projectile completely touches the cavity wall, it begins the third stage, the wetted area remains constant, and the drag coefficient remains constant. When the vertical speed is less than 70m/s, there are obvious difference in velocity attenuation trend. The larger the bevel angle, the faster the vertical velocity decays.
Figure 5. The comparison of velocity attenuation curves under different working conditions.

Table 3. Velocity fitting formula.

| α   | a    | b    | c    |
|-----|------|------|------|
| 30° | 4.55 | -0.05| 4.20 | -1.10| 24.48| 2.22 | 0.79 | -34.78| -6.10|
| 25° | 4.54 | 1.05 | 3.75 | -0.92| 16.29| 3.36 | 0.55 | -20.65| -5.49|
| 20° | 4.53 | 1.84 | 4.59 | -0.91| 10.90| -0.31| 0.62 | -12.30| -1.06|

It is easily to found that the experimental data is in good agreement with exponential attenuation laws from Figure 3. In the first stage, parameter ‘a’ is between 4.53~4.55, parameter ‘b’ is between -1.10~0.91, and parameter ‘c’ is between 0.55~0.79. Nevertheless, there is no commonality both the second stage and the third stage, it may require some theoretical analysis.

4.2. Ballistic curve analysis

It can be seen from figure 6 that the trajectory of the projectiles with different bevel angles is bent when entering water, and the trend of bending remains the same. In this article, it is defined that when the attitude of the main body becomes horizontal, the penetration depth of the projectile is the maximum penetration depth. With the increase of the bevel angle, the head-up moment of the projectile increases, the curvature of the projectile trajectory increases, and the maximum penetration depth of the projectile decreases.

Figure 6. The comparison of the trajectory deflection under different working conditions.
4.3. Cavitation morphology analysis

Figure 7 shows the morphological development of cavity. It can be seen that the cavities are all asymmetrical. And the smaller the bevel angle is, the more slender the cavity is and the larger the maximum penetration depth of the projectile.

![Cavitation Morphology](image)

**Figure 7.** The comparison of cavity form development and trajectory under different working conditions.

5. Conclusion

This paper uses LS-DYNA to simulate and analyze the vertical entry process of three different truncated projectiles, and the test results is used to prove the reliability of the model. Through the data fitting of simulation results, it can be found that the attenuation of the vertical velocity of the projectile with the penetration depth conforms to the exponential attenuation law, \( \frac{v_y}{v_0} = e^{y^2 + by + a} \), and the bevel angle has little effect on the attenuation at the initial stage. It would be better to verify the law experimentally in the subsequent research. When the tail of the projectile touches the wall of the cavity, as the bevel angle increases, the velocity of the projectile in the vertical direction decays faster.

The projectile deflects when it enters the water. The larger the bevel angle, the greater the angle of deflection of the projectile at the same penetration depth. Also, the open cavity is asymmetrical, and the smaller the bevel angle is, the more slender the cavity is.

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