Explosion force and shape fitting based modelling of dynamic virtual crater deformation

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Abstract. The dynamic deformation of virtual terrain is an important research content to improve the dynamic adaptability of virtual geographic environment, which can support the research of disaster simulation, combat simulation and so on. It is also a novel method to support human-environment interaction research in the community of geographic information science. In this paper, the dynamic generation of bomb crater is taken as an example to study the construction method of virtual terrain deformation model. Starting from the formation process of crater in explosive mechanics, the deformation model is coupled with the calculation method to control the radius and depth of crater shape. Through the method of geometric fitting, the shape of crater is modeled in different regions and the basic crater model is established. On the basis of the basic model, the incidence angle of projectile is introduced to build the relationship model between crater deformation and incidence angle of projectile. Based on the Digital Terrain Model (DTM), the terrain data model is improved by coupling the radius coefficient and depth coefficient related to the geological characteristics, and the crater shape algorithm reflecting the geological characteristics is proposed. Finally, the Perlin noise is added to realize the disturbance of the elevation value of each position point in the crater zone. The simulation environment of crater deformation is established by Unity, and the crater model is simulated and verified. The results show that the crater model can basically reflect the impact of different projectile incidence angle, explosion equivalent and geological characteristics. The deformation state of crater is similar to the actual situation. The research results can provide support for the simulation of the dynamic process of the crater produced by the projectile touch-down explosion in the virtual battlefield environment.

Keyword. virtual terrain; dynamic terrain; crater model

1. Introduction

Environment is the carrier of military action. It interacts and couples with weapon equipment and warfighter, and presents a variety of process and results.

Operational simulation is an important means to study modern war. To simulate war, we must consider the interaction among the three core elements of "equipment-environment-human". The change of terrain, as an important manifestation of the results of three factors, is an important environmental issue that must be considered in the simulation of land warfare. Crater, as a typical representative of terrain change, its size and depth directly affect the operation route of ground weapon equipment and the operation behavior of personnel. The study and construction of crater model to simulate the dynamic change of battlefield terrain is an important basis for improving the fidelity and feasibility of land warfare simulation.
At present, there are two kinds of algorithms for terrain deformation model building, namely, the method based on non-physical process and the method based on physical process. The first method abandons the physical attributes and complex calculation accuracy of terrain, and specifies some parameters to control the terrain change, so as to achieve the visual effect. At present, the main method is to establish the surface model through the particle system. However, the simulation of different soil properties is limited. Because of the small particle size, the large number of particles, the large amount of calculation and the difficulty of large terrain simulation, it is difficult to achieve dynamic change. For example, in 1999, Sumner et al. [1] established a terrain surface simulation model based on granular materials to describe the effect of object movement on the surface. In 2003, Onoue et al. [2] based on Sumner's research, used particle system in the process of constructing terrain model to achieve the effect of soil particles piling up on the entity. In 2014, Leach [3] developed large particles terrain real-time simulation and rendering system based on GPU (graphics processing unit). The dynamic terrain based on the physical process fully combines the physical properties of the terrain itself when simulating the surface. And in the process of calculating the mathematical model after the terrain is deformed, the relevant contents of soil mechanics and physical engineering are considered, which not only enhances the reality of dynamic terrain simulation, but also makes the calculation complex. For example, in 1993, Li et al. [4] put forward a scheme of dynamic terrain realization based on physical model. In 2006, Cai Xingquan et al. [5] realized the simulation of ruts. In 2012, Wang Da [6] improved the crater physical model of half ellipse proposed by Cai [7], and realized the dynamic simulation of crater generation. In 2013, Chen et al. [5] put forward a dynamic terrain rendering method. In 2014, Zhang Huijie et al. [8] proposed a method of real-time generation of crater physical model. In 2016, Zheng Guping [9] proposed a crater generation and drawing method based on Geometry Clipmaps algorithm.

Based on the comprehensive analysis of the existing crater model construction methods, the following problems are found: the crater model lacks the description of the condition of crater constraints, the crater model does not consider the impact of different geological characteristics of the crater zone on the crater shape, and in the calculation process, the corresponding relationship between a certain position point in the crater and the geological characteristics is not clear, which is not convenient to add the geological characteristics parameters.

In view of the above problems, this study starts from the explosive force and the foundation of geometry model of crater shape, and describes the formation process of different zones of crater. According to the basic model of explosive force, the calculation method of radius and depth which control crater shape is studied, and the crater shape is modeled in different regions by geometric fitting method. Based on the Digital Terrain Model (DTM), the terrain data model is improved, and the crater shape algorithm is proposed to reflect the geological characteristics. Finally, by adding Perlin noise and changing the elevation value of each position point, the disturbance of the crater zone is realized and the details of the crater are further enriched.

2. Explosion force and geometrical model foundation of crater shape

The projectile hits the ground and explodes, under the action of shock wave and high-temperature and high-pressure air mass, it transmits energy to the surrounding through expanding work, generating irreversible deformation to the surrounding medium, and then producing crater.

According to the research results of Academician Qian Qihu (as shown in Figure 1) [10], the damage zone produced by the explosion can be divided into four stages: the first stage is the expansion stage of the explosion cavity, because the pressure of the explosion product in the cavity is greater than 0.1 times of the rock side limit deformation modulus \( \rho \alpha_0^2 \) (\( \rho \) is the density of the rock, \( \alpha_0 \) is the propagation speed of the longitudinal wave in the rock), the influence of the shear stress can be ignored, similar to the expansion in the incompressible fluid, and the cavity radius is \( R_1 \); then it enters the impact crushing stage, the rock stress exceeds the crushing strength, and the crushing rock movement between the cavity and the destructive wave is only affected by internal friction, and the radius is \( R_2 \); the third stage is the cavity wave free expansion stage, the destructive wave is slower than
the leading elastic wave, and the stress condition of medium between the cavity and the destructive 
wave is the same as that in the second stage, the radius is $R_4$; the fourth stage is elastic wave 
propagation stage, the elastic wave starts with the stop of the development of the destruction zone, and 
the movement of the elastic medium will not exceed the external elastic zone.

![Figure 1. Schematic diagram of explosion damage zone in rock.](image)

Through the above physical process, the whole destruction zone is divided into explosion cavity, 
fracture zone, radial crack zone and elastic deformation zone. The explosion cavity and fracture zone 
are different from radial crack zone and elastic deformation zone, because these two zones involve the 
change of terrain elevation value. Therefore, the geometry fitting of crater shape in explosion cavity 
and fracture zone is mainly studied. Among them, the radius of the final formed explosion cavity is $R_1$ 
and the depth of the crater is $H_1$. According to the trend of the elevation value, the crushing zone is 
further divided into internal deformation zone and external deformation zone, with the radii of $R_2$ and $R_3$ respectively.

3. Crater shape control and partition modeling

Next, according to the basic model of explosive force, the calculation method of parameters (radius of 
explosion cavity $R_1$, crater depth $H_1$, radius of internal deformation zone $R_2$ and radius of external 
deformation zone $R_3$) controlling the shape of crater is determined, and the partition modeling is 
realized on the basis of region division.

3.1. Crater shape control method and regional division

In order to facilitate the coupling of geological characteristics data, combined with the basic model 
of explosive force, the cavity zone, internal deformation zone and external deformation zone are 
respectively modeled by different geometric shapes, as shown in figure 2 and figure 3, which are the 
profile of the crater model in the horizontal and vertical directions, where $H_1$ is the crater depth. The 
shape of crater is controlled by eight parameters, which are radius coefficient $C$ and depth coefficient $D$ related to medium characteristics, explosive equivalent $Q$, region critical influence factors ($f_1$ and $f_2$), 
proportion control factor $k$, peripheral height $h$ of internal deformation zone and incident angle $\theta$.

First of all, we need to determine the range of each zone through the above control parameters. A 
large number of experiments show that [11], the explosion cavity radius $R_1$ and crater depth $H_1$ are 
closely related to the explosion equivalent $Q$ and the properties of the medium near the explosion.
center (such as the rock side limit deformation modulus, the crushing stress limit of the medium, the Young's modulus of the medium, etc.), even in the same medium, in the case of different water content, the crater parameters are also very different. In the case of the same medium, the crater parameters are approximately in proportion to the explosive equivalent 1/3.4 power. Therefore, the calculation equation of the cavity radius $R_1$ and the crater depth $H_1$ can be determined as follows:

$$R_1 = CQ^{\frac{1}{3.4}}$$

$$H_1 = DQ^{\frac{1}{3.4}}$$

There is a proportional relationship between the radius $R_2$ of internal deformation zone and the radius $R_3$ of external deformation zone and $R_1$. Therefore, the regional critical influence factors $f_1$ and $f_2$ are introduced, and the equations for calculating $R_2$ and $R_3$ are as follows:

$$R_2 = f_1 R_1$$

$$R_3 = f_2 R_1$$

3.2. Cavity region morphology modeling

The section of the explosion cavity is approximately elliptical. Therefore, the explosion cavity is modeled by using an ellipsoid as the prototype. The coordinates of the explosion center point are $(x_0, y_0, z_0)$, $(x, y, z)$ represents the coordinates of any point on the surface of the ellipsoid, then it satisfies:

$$\frac{(x-x_0)^2}{R_1^2} + \frac{(y-y_0)^2}{H_1^2} + \frac{(z-z_0)^2}{b_1^2} = 1$$

$$\Delta y = H_1 \left[ 1 - \left( \frac{(x-x_0)^2}{R_1^2} + \frac{(z-z_0)^2}{b_1^2} \right) \right]^{1/2}$$

3.3. Internal deformation zone morphological modeling

The internal deformation zone has a variety of curves for the radial section. In order to ensure the authenticity, at the same time, considering the smooth transition of the internal deformation zone with the cavity zone and the external deformation zone, and the peripheral height of the internal...
deformation zone is controllable, so the section extending radially in this zone selects the elliptical surface, which rotates around the y-axis in the x-z plane to form a closed surface, as shown in Figure 4. It can be seen that the peripheral boundary of each section is one quarter of the elliptic curve, and the short semi-axis is the controllable height h, and the long axis varies with the polar angle θ. When θ=0° or 180°, the long semi-axis is the longest R2-R1, when θ=90° or 270°, the long semi-axis is the shortest b2-b1, b2 is the short semi-axis length of the ellipse projected on the x-z plane by the internal deformation zone, and the calculation method is the same as the length of the short semi-axis of ellipsoid in the cavity region, that is, b2=kR2.

The points on the interface between the cavity region and the internal deformation zone and between the internal deformation zone and the external deformation zone are respectively taken (x1, y1, z1) and (x2, y2, z2), and any point on the elliptic curve (x, y, z). If the polar angle θ is selected, the following equations are available:

\[
\frac{z_1-z_0}{x_1-x_0} = \tan \theta \tag{7}
\]
\[
\frac{z-z_0}{x-x_0} = \tan \theta \tag{8}
\]
\[
\frac{z_2-z_0}{x_2-x_0} = \tan \theta \tag{9}
\]

Due to the points (x1, z1) and (x2, z2) that the points (x1, y1, z1) and (x2, y2, z2) projected to the x-z plane, are on the boundary line of cavity region and internal deformation zone and the boundary line of internal deformation zone and external deformation zone respectively, they satisfy the ellipse equation, and thus:

\[
\frac{(x_1-x_0)^2}{R_1^2} + \frac{(z_1-z_0)^2}{b_1^2} = 1 \tag{10}
\]
\[
\frac{(x_2-x_0)^2}{R_2^2} + \frac{(z_2-z_0)^2}{b_2^2} = 1 \tag{11}
\]

The long axis of the section ellipse is: \(\sqrt{[(x_2-x_1)^2+(z_2-z_1)^2]}\). Therefore, the ellipse equation for the section is:

\[
\frac{(x_2-x)^2}{(x_2-x_1)^2+(z_2-z_1)^2} + \frac{\Delta y^2}{h^2} = 1 \tag{12}
\]

And then:

\[
\Delta y = h \left[1 - \frac{(x_2-x)^2+(z_2-z)^2}{(x_2-x_1)^2+(z_2-z_1)^2}\right]^{\frac{1}{2}} \tag{13}
\]

Take:

\[
t = \tan^2 \theta \tag{14}
\]
\[
k_1 = \left(\frac{R_1^2 b_1^2}{b_1^2 + R_1^2 t}\right)^{\frac{1}{2}} \tag{15}
\]
\[
k_2 = \left(\frac{R_2^2 b_2^2}{b_2^2 + R_2^2 t}\right)^{\frac{1}{2}} \tag{16}
\]

Then, the amount of change in the elevation value of any point (x, y, z) in the internal deformation zone can be calculated:

When \(0^\circ \leq \theta < 90^\circ\):
\[
\Delta y = h \left[ 1 - \left( \frac{(x_0 + k_2 - x)^2 + (z_0 + k_3 t^{1/2} - z)^2}{(k_2 - k_1)^2 + t(k_2 - k_1)^2} \right)^{1/2} \right]
\]

When \(0^\circ \leq \theta < 90^\circ\):
\[
\Delta y = h \left[ 1 - \left( \frac{(x_0 - k_2 - x)^2 + (z_0 + k_3 t^{1/2} - z)^2}{(k_2 - k_1)^2 + t(k_2 - k_1)^2} \right)^{1/2} \right]
\]

When \(180^\circ < \theta < 270^\circ\):
\[
\Delta y = h \left[ 1 - \left( \frac{(x_0 - k_2 - x)^2 + (z_0 - k_3 t^{1/2} - z)^2}{(k_2 - k_1)^2 + t(k_2 - k_1)^2} \right)^{1/2} \right]
\]

When \(270^\circ < \theta < 360^\circ\):
\[
\Delta y = h \left[ 1 - \left( \frac{(x_0 + k_2 - x)^2 + (z_0 - k_3 t^{1/2} - z)^2}{(k_2 - k_1)^2 + t(k_2 - k_1)^2} \right)^{1/2} \right]
\]

When \(\theta = 90^\circ\), the ellipse equation of the section is:
\[
\frac{[b_2 - (z - z_0)]^2}{(b_2 - b_1)^2} + \frac{\Delta y^2}{h^2} = 1
\]

When \(\theta = 270^\circ\), the ellipse equation of the section is:
\[
\frac{[b_2 - (z_0 - z)]^2}{(b_2 - b_1)^2} + \frac{\Delta y^2}{h^2} = 1
\]

3.4. External deformation zone morphological modeling

This zone is considered to be linearly modeled, that is, a part of the straight line is selected for the section extending radially in this zone, and rotates around the y-axis to form a closed curved surface, as shown in Figure 5.

The point on the interface between the internal deformation zone and the external deformation zone and the point on the interface between the external deformation zone and the outer explosion region
are respectively taken \((x_1, y_1, z_1)\) and \((x_2, y_2, z_2)\), \(y_1 = h, y_2 = y_0\), all of which are fixed values. Take any point \((x, y, z)\) on the elliptic curve, and if the polar angle \(\theta\) is selected, the following equations are available:

\[
\frac{z_1 - z_0}{x_1 - x_0} = \tan \theta \tag{25}
\]

\[
\frac{z - z_0}{x - x_0} = \tan \theta \tag{26}
\]

\[
\frac{z_2 - z_0}{x_2 - x_0} = \tan \theta \tag{27}
\]

Due to the points \((x_1, z_1)\) and \((x_2, z_2)\) that the points \((x_1, y_1, z_1)\) and \((x_2, y_2, z_2)\) projected to the x-z plane, are on the boundary line of internal deformation zone and external deformation zone and the boundary line of external deformation zone and outer explosion region respectively, they satisfy the ellipse equation, and thus:

\[
\frac{(x_1 - x_0)^2}{R_x^2} + \frac{(z_1 - z_0)^2}{b_z^2} = 1 \tag{28}
\]

\[
\frac{(x_2 - x_0)^2}{R_x^2} + \frac{(z_2 - z_0)^2}{b_z^2} = 1 \tag{29}
\]

The points \((x_1, y_1, z_1), (x_1, y_0, z_1)\) and \((x_2, y_2, z_2)\) form a triangle, and according to similar triangles:

\[
\frac{h}{(x_1 - x_0)^2 + (z_1 - z_0)^2} = T \tag{30}
\]

\[
\frac{\Delta y}{(x_1 - x_0)^2 + (z_1 - z_0)^2} = T \tag{31}
\]

\(T\) is the temporary coefficient. From the above equations, the amount of change in the elevation value of any point \((x, y, z)\) in the external deformation zone can be calculated:

\[
\Delta y = \frac{(W_2 - 1)h}{W_2 - W_1} \tag{32}
\]

Among them:

\[
W_1 = \left[ \frac{R_x^2 b_z^2}{b_z^2 (x - x_0)^2 + R_x^2 (z - z_0)^2} \right]^{1/2} \tag{33}
\]

\[
W_2 = \left[ \frac{R_x^2 b_z^2}{b_z^2 (x - x_0)^2 + R_x^2 (z - z_0)^2} \right]^{1/2} \tag{34}
\]

3.5. Asymmetric crater shape calculation method

Under actual conditions, when the projectile hits the ground, it is not only perpendicular to the incident, it must have an incidence angle with the surface of the impact point zone. This causes the explosion impact force to produce a component in the horizontal direction, which pushes the crater to expand in the corresponding direction, thus changing the shape of the crater. So the shape, can not be simply simulated with symmetrical geometry. In order to simulate this detail, an improved physical model of the crater is constructed based on the introduction of the incident angle. Take the interior of the cavity as an example, as shown in Figures 6 and 7, which are the horizontal and vertical sections respectively.
The improved crater physical model consists of two semi-ellipsoids connected together. \( R_{L1} \) corresponds to the long semi-axis of the large ellipse part (zone II) in the crater profile, and \( R_{S1} \) corresponds to the long semi-axis of the small ellipse part (zone I), and \( b_1 \) is the common short semi-axis, the same as the short semi-axis of the cavity zone of the basic crater model, \( H_{LS1} \) is the depth of the crater, and \( \theta \) is the angle between the projectile incident direction and the surface normal of the impact point. Combined with the fact that the cause of crater asymmetry is the horizontal component of explosion impact force and characterizing the influence of incident angle \( \theta \) on crater shape, the calculation equations of \( R_{L1} \), \( R_{S1} \) and \( H_{LS1} \) are as follows:

\[
R_{L1} = R_1 + H_1 \sin \theta \\
R_{S1} = R_1 - H_1 \sin \theta \\
H_{LS1} = H_1 \cos \theta
\]

In order to calculate the variation of elevation values of different positions \((x, y, z)\) in the cavity zone, first determine the angle between the vector determined from the explosion point to the point and the incident direction of the projectile, and then determine whether the position is in zone I or zone II. If it is in zone I, replace \( R_1 \) and \( H_1 \) in equation (6) with \( R_{S1} \) and \( H_{LS1} \) respectively. If it is in zone II, replace \( R_1 \) and \( H_1 \) in equation (6) with \( R_{L1} \) and \( H_{LS1} \) respectively. In the calculation of the two regions, \( b_1 \) is the same as the basic crater model, and then the variation of the elevation value of the position is calculated.

For the internal deformation zone and the external deformation zone, the regional critical influence factors \( f_1 \) and \( f_2 \), the proportional control factors \( k, b_2 \) and \( b_3 \) are unchanged, and the \( R_{S2}, R_{L2}, R_{S3} \) and \( R_{L3} \) are calculated as follows:

\[
R_{S2} = f_1 R_{S1} \\
R_{L2} = f_1 R_{L1} \\
R_{S3} = f_2 R_{S1} \\
R_{L3} = f_2 R_{L1}
\]

First of all, it is necessary to determine the zone where \((x, y, z)\) is located. When calculating the internal deformation zone, \( R_{S1}, R_{S2} \) (corresponding to the part of small ellipse) or \( R_{L1}, R_{L2} \) (corresponding to the part of large ellipse) are used to replace \( R_1 \) and \( R_2 \) in equation (15) and (16); when calculating the external deformation zone, \( R_{S2}, R_{S3} \) (corresponding to the part of small ellipse) or \( R_{L2}, R_{L3} \) (corresponding to the part of large ellipse) are used to replace \( R_2 \) and \( R_3 \) in equation (33) and (34).

4. Crater morphology modeling coupled with geological characteristics

The crater model established by the above method can well simulate the crater shape. However, the whole process of crater modeling is based on the uniform geological conditions in the crater zone. In
the case of non-uniform media in the crater zone, the crater shape will inevitably change with the different geological conditions, and the crater details are more abundant than the uniform geological conditions. Therefore, how to characterize the geological characteristic parameters related to crater formation and how to add the geological characteristic parameters in the process of crater shape simulation are studied.

4.1. Improved Digital Terrain Model of coupling radius and depth coefficient

In the calculation of cavity radius \( R_1 \) and crater depth \( H_1 \), the abstract geological characteristics that control the shape of crater are specified to radius coefficient \( C \) and depth coefficient \( D \) related to geological characteristics. When the explosive equivalent \( Q \) is fixed, if \( C \) and \( D \) are changed, \( R_1 \) and \( H_1 \) will change accordingly. The radius \( R_2 \) of the internal deformation zone and the radius \( R_3 \) of the external deformation zone will also change, which will affect the shape of the crater. Therefore, in the terrain data, we consider adding radius coefficient \( C \) and depth coefficient \( D \) related to geological characteristics for each coordinate position, and the Digital Terrain Model gives us enlightenment.

The selection of multi-dimensional ground features is provided in Digital Terrain Model, and the selection of specific ground features varies according to different applications. Therefore, we can build a five-dimensional ground feature vector model: \((X, Y, Z, C, D)\), where \( X \) and \( Y \) indicate the position, \( Z \) represents the elevation value of the position, \( C \) and \( D \) are the radius coefficient and depth coefficient of the position. In the calculation of crater shape, for each coordinate position, the corresponding parameters in the calculation process are updated according to the radius coefficient and depth coefficient of the position to reflect the influence of geological characteristics on crater shape.

The five-dimensional data model is constructed by taking the radius coefficient and depth coefficient of typical geological characteristics. For wet soil (wet soft rock), the radius coefficient and depth coefficient of touch-down explosion are 25 and 9.3 respectively. For dry soil (dry soft rock), the radius coefficient and depth coefficient of touch-down explosion are 19 and 8.4 respectively. In hard rock, the size of explosion crater is reduced. Under the conditions of dry and wet, the radius coefficient shall be multiplied by factors 0.8 and 0.7 respectively. And the depth coefficient shall be multiplied by factors 0.8 and 0.9 [11], as shown in Table 1.

| Typical geological characteristics data  | Radius coefficient C | Depth coefficient D |
|-----------------------------------------|----------------------|---------------------|
| Dry soil                                | 19                   | 8.4                 |
| Wet soil                                | 25                   | 9.3                 |
| Dry hard rock                           | 15.2                 | 6.72                |
| Wet hard rock                           | 17.5                 | 8.37                |

4.2. Crater shape algorithm reflecting geological characteristics

Radius coefficient \( C \) and depth coefficient \( D \) related to geological characteristics affect cavity radius \( R_1 \) and crater depth \( H_1 \), and then affect \( b_1, R_2, b_3, R_3 \) and \( b_3 \). First of all, each geological zone in the crater zone will inevitably have an impact on the overall shape of the crater. The weight value of each geological zone is used to reflect its impact on the crater. That is, in the initial crater zone, the influence weight value is determined according to the zone occupied by each geological zone, and then the radius coefficient and depth coefficient of each geological zone are respectively weighted and averaged to realize the update of the overall radius coefficient and the depth coefficient. Then, it is necessary to highlight the influence of each geological zone on the elevation value at its coordinate position, that is, double calculation shall be carried out when calculating the change of elevation value in different positions \((x, y)\). The updated overall radius coefficient and depth coefficient shall be used firstly to calculate the change of the primary elevation value, and then the radius coefficient and depth
coefficient of the position shall be used to calculate the change of elevation value. Finally, the mean value of the two calculations is taken as the change of the final elevation value of the position. The specific process is as follows.

(1) Determine the explosive equivalent Q, the regional critical influence factors f1 and f2, the proportional control factor k, and the incident angle θ.

(2) According to the radius coefficient C0 and depth coefficient D0 of the explosion point O, the initial R1, b1, R2, b2, R3 and b3 are calculated, and determine the initial crater zone range.

(3) Traverse all positions (x, y, z) in the initial crater zone, record the number of position vertices Count[i] of different media (each i corresponds to a medium), and read the radius coefficient Ci and depth coefficient Di of the corresponding medium.

(4) Obtain C1 and D1 for the overall calculation. Since the crater zone may contain multiple media, in order to reflect the influence of different media on the crater, the weighting method is used to calculate. The specific calculation equation is as follows:

\[ C_1 = \frac{\sum_{i=0}^{\text{Count.Length}-1} \text{Count}[i]C_i}{\sum_{i=0}^{\text{Count.Length}-1} \text{Count}[i]} \]  \hspace{1cm} (42)

\[ D_1 = \frac{\sum_{i=0}^{\text{Count.Length}-1} \text{Count}[i]D_i}{\sum_{i=0}^{\text{Count.Length}-1} \text{Count}[i]} \]  \hspace{1cm} (43)

Count.Length is the number of types of media in the crater zone, and then R1, H1, R2, b2, R3, b3 can be calculated.

(5) According to the crater model, determine the crater zone where any point position (x, y, z) is located, select the calculation equation of the elevation value change, and determine the crater shape control parameters involved, which need to be updated in step (6) according to the radius coefficient Ci and depth coefficient Di of the location.

(6) Update parameter and calculate the change of elevation value \( \Delta y \) of any point (x, y, z). In order to reflect the influence of different media characteristics of each location on the crater, double calculation is needed: first, according to C1 and D1 calculated in step (4), substitute the corresponding equation to get the change of elevation value \( \Delta y_1 \) of this position. If \( C_i \) and \( D_i \) is equal to \( C_1 \) and \( D_1 \) of this position, then \( \Delta y = \Delta y_1 \). If not, the second calculation is performed. The second calculation is based on \( C_i \) and \( D_i \) of the position, the corresponding equation will be substituted to obtain the change of elevation value \( \Delta y_2 \) of the position, then \( \Delta y \) will take the mean value of the two calculations. Finally, the elevation value of the position will be updated.

(7) Cycling step (5) and step (6), updating the elevation values of all positions in the crater zone, and the algorithm ends.

5. Regional disturbance method of crater based on Perlin noise

In terms of overall effect, the shape of the crater can be controlled by the above method. However, the shape of the whole or partial zone of the crater is still relatively smooth. Due to the different crushing effect of the explosion on different geology, the interior of the crater will present fluctuating details. In order to make the constructed crater more realistic, Perlin noise is considered to be added. In a certain range, the elevation value of every coordinate position is changed based on the overall crater model to increase the disorder of local details.

Perlin noise was proposed by Ken Perlin in 1980s [12-13], and was mainly used to generate continuous noise. Perlin noise is widely used in the simulation of terrain generation, combustion
effects, water surface effects and clouds. Moreover, Perlin noise can be applied in one-dimensional, two-dimensional, three-dimensional and even four-dimensional levels.

For the input of any position point \((x, y, z)\), the output value is between 0-1 after Perlin noise processing. So it is necessary to add the proportional coefficient \(n\) to multiply it to control the output range of Perlin noise, and the result is superimposed on the variation of the calculated elevation value. Finally, the effect of Perlin noise on the elevation value of each coordinate point in the crater zone is realized, and the effect is shown in Figure 8. Among them, the dotted line is the original crater outline, and the solid line is the crater outline after adding Perlin noise.

![Figure 8. Schematic diagram of the influence of Perlin noise on the crater model.](image)

6. Experimental verification
In the experiment, Unity 5.5.0 is used for crater simulation, and Visual Studio 2017 is used as the language development tool. The hardware platform is Intel (R) core (TM) i7-7700k CPU @ 4.20 GHz, memory 8GB, and GPU is NVIDIA GeForce RTX 2080 SUPER.

In Unity, the terrain component of the system and the model prefabrication of the missile are added, at the same time complete the setting of the basic terrain parameters and the C# script is added. According to table 1, radius coefficient and depth coefficient are added for each position point and saved to the Comma-Separated Values (CSV) file. At the beginning of simulation, the file is read firstly to obtain multidimensional data of terrain.

![Figure 9. Crater effect diagram with incident angle of 0 (uncombined geological characteristics).](image)
The effect verification includes the verification of crater model under different incident angles, the verification of crater model after adding geological characteristics and the verification of regional disturbance of crater after adding Perlin noise. Figure 9, 10 and 11 are respectively the effect diagrams of the crater without combined geological characteristics produced by the projectile at three incident angles of 0 °, 15 ° and 30 °, and Figure 12, 13 and 14 are respectively the effect diagrams of the crater with combined geological characteristics of 0 °, 30 ° and 45 ° incident angles. Figure 15 shows the crater effect after adding Perlin noise. (In order to more clearly reflect the crater effect combined with geological characteristics and the crater effect after adding Berlin noise, the texture map of crater area is not added to the renderings of Figures 12, 13, 14 and 15.)
It can be observed from the renderings that the crater model has clear explosion cavity zone, internal deformation zone and external deformation zone. Comparing Figures 9, 10 and 11, the shape of the crater can be changed according to the different incident angles of projectiles; comparing Figures 9, 10, 11 with Figures 12, 13 and 14, the shape of the crater is further adjusted according to the geology after coupling the geological characteristics data, and the effect is obvious; through the comparison between figure 15 and the above effect diagrams, it is not difficult to find that the crater
zone is disturbed by adding Perlin noise, the elevation value of coordinate points fluctuates up and down, and the effect of details is more abundant.

7. Conclusion
Taking the crater simulation in the land warfare environment as an example, this study deeply explores the dynamic terrain modeling algorithm, which is the improvement of the dynamic terrain generation and simulation technology field, and is helpful to the construction of land warfare simulation system, and to improve the fidelity, scientificity and credibility of warfare simulation. The research results can be further improved in the following aspects: enrich the parameters of crater force and crater shape control, making the crater formation process more scientific and reasonable.

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