Prediction of penetration depth of earth penetrator based on neural network

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Abstract. An artificial intelligence neural network model is established in this essay to seek a more general method for predicting penetration depth of earth penetrator, to comprehensively analyze the effect of various parameters on penetration depth as well as to predict the penetration depth of earth penetrator. This paper, by means of numerical simulation, determined the ordnance penetrator warhead curvature radius, the length of the projectile, the density of the projectile, the density of the target protective layer, the elastic modulus of the target protective layer and the hit velocity of the earth penetrator. This six key parameters as the input data of neural network model, and by using numerical simulation to obtain the data needed for training the neural network model samples. According to the characteristics of six input data and one output data of the neural network model, the possible structure of the neural network model is set, and the optimal model structure is selected through training. We built neural network model to forecast the ordnance penetrator penetration depth, analyzes the six key parameter's influence on the depth of penetration, the results show that reducing the warhead curvature radius, increasing the length and density of the projectile, properly increasing the impact velocity of the projectile can improve the penetration ability of the earth penetrating projectile, and increasing the density and elastic modulus of the target protective layer can improve the anti-penetration ability of the protective layer.

1. Introduction

Earth penetrator mainly used to strike key underground military targets, and it is one of the necessary weapons and equipment for strategic and precise strike in modern warfare[1]. The impact of the earth penetrator is mainly achieved through penetration and explosion, the projectile penetrates into the target's interior first, inserts or even penetrates the target's protective layer, and then the warhead detonates, causing damage to the target's protective layer and internal facilities and personnel. In order to improve the damage ability of the earth penetrator, it is necessary to study its penetration and explosion effects. At present, there are three main methods to predict penetration depth: experimental research, theoretical analysis and numerical simulation.

The experimental research is to carry out prototype test or model test, obtain relatively credible data through the test, and use the data to establish empirical formulas. The commonly used empirical formulas are Березаиъ Formula [2] proposed by Russia in 1912 and Young's Formula [3] proposed by Sandia National Laboratory in 1967. Theoretical analysis is to use analytical methods in-depth study penetration process shot target interaction, the physical mechanism of this method will allow researchers to more deeply understanding penetration problem, establish a target system, various parameters and the
penetration depth and other relation between damage index, and the relation between than empirical formula has better generality. Numerical simulation is a relatively new method. Its rapid development is mainly due to the development of modern computer technology, the increasing precision of computational mathematics and computational mechanics and the continuous emergence of large-scale finite element simulation software [4].

With the continuous development of new materials and technologies, earth penetrator are constantly upgraded and replaced. The usefulness of old empirical formulas and theoretical analysis is getting worse and worse. Artificial intelligence neural network is a kind of nonlinear dynamic system that simulates the thinking mode of human beings, imitates the neural network behavior of human brains and conducts distributed parallel information processing. Complex nonlinear mapping can be achieved without the establishment of specific mathematical expressions, so it is suitable for the penetration research of ground-penetrating projectile with complex mechanism. At present, relatively mature neural network algorithms have been developed, such as BP neural network, PID neural network, RBF neural network, GRNN neural network and SOM neural network, each algorithm is applicable to different fields, among which the most widely used is BP neural network [5].

2. Acquisition of training data

Because the penetration test of earth penetrating projectile is expensive and dangerous, it is theoretically impossible to obtain enough data to train the neural network through prototype test. This paper chooses to use numerical simulation method in ANSYS/LS-DYNA software to obtain the required sample data.

2.1 Establishment of numerical simulation model

2.1.1 Define cell types. SOLID164 is an explicit solid element for three-dimensional structure. It consists of eight nodes, namely I, J, K, L, M, N, O and P. The unit shape is shown in figure 1. When the nodes in the graph overlap, SOLID164 element can degenerate into triangular prism, tetrahedron, pyramid and other degenerate elements. When researchers apply loads on the surface of SOLID164 element, they should pay attention to the area number, which is determined by the node. The order is: face (J-I-K-L), face (I-J-N-M), face (J-K-O-N), face (K-L-P-O), face (L-I-M-P), face (M-N-O-P).

![Figure 1. Structure of SOLID164 element](image)

Unit SOLID164 contains two unit options. KEYOPT (1) is used to select the unit algorithm, KEYOPT (1) = 0 or 1 is used to represent the unit algorithm as the constant stress entity unit algorithm, KEYOPT (1) = 2 is used to reduce the entity unit algorithm by complete integration selection, KEYOPT (5) is used to specify the unit type, KEYOPT (5) = 0 is the Lagrangian unit, KEYOPT (5) = 1 is the ALE (Arbitrary Lagrangian-Eulerian) unit. In this case, KEYOPT (1) option takes the default value of 0, KEYOPT (5) option takes the earth penetrator mode as 1, and target protective layer model takes 0.

2.1.2 Definition of material model. In this case, the earth penetrator is defined as a rigid material model, using Rigid Material model [6], and the target protective layer is defined as an elastic-plastic material model, using Mat-Johnson-Cook model [7]. The parameters of the two material models are shown in table 1 and 2. The unit system adopts the default unit system of software.
Table 1. Parameters of earth penetrator material model

| Parameter | DENS | EX | NUXY | CON1 | CON2 |
|-----------|------|----|------|------|------|
| Numerical value | 8.93 | 1.17 | 0.35 | 4 | 7 |

Table 2. Parameters of target's protective covering material model

| Parameter | DENS | EX | NUXY | A | B | N | C | M | TM |
|-----------|------|----|------|---|---|---|---|---|----|
| Numerical value | 7.83 | 2 | 0.32 | 7.92e-3 | 5.1e-3 | 0.26 | 1.4e-2 | 1.03 | 1793 |

| Parameter | TR | EPSO | CV | PC | D1 | D2 | D3 | D4 | D5 |
|-----------|----|------|----|----|----|----|----|----|----|
| Numerical value | 294 | 1e-6 | 4.77e-6 | -9 | 0.8 | 0 | 0 | 0 | 0 |

| Parameter | C | S1 | S2 | S3 | GAM | A | E0 | V0 |
|-----------|---|----|----|----|-----|---|----|----|
| Numerical value | 0.4569 | 1.49 | 0 | 0 | 2.17 | 0.46 | 0 | 1 |

2.1.3 Define contact and boundary conditions. Firstly, the geometric model is established according to the entity. Then, considering the factors of calculation accuracy and efficiency, the geometric model is meshed and the finite element model is generated. PART is created on the basis of finite element model. The software automatically creates PART for the earth penetrator model and the target protective layer model. ESTS is defined as the contact mode between the earth penetrator and the target protective layer, i.e. the erosion contact type[8]. In this case, both the earth penetrator and the target protective layer are symmetrical structures. In order to observe the relative movement and deformation between the warhead and the protective layer of the ground penetrating projectile during the penetration process, a quarter of the whole entity is modeled. In order to eliminate the influence of symmetrical plane on the calculation results, it is necessary to add non-reflective symmetrical constraints on the symmetrical plane. In fact, the targets attacked by earth penetrator are not isolated. They are surrounded by surrounding rocks or soil layers, which can be regarded as semi-infinite targets. In order to eliminate the influence of the boundary in the model, a non-reflective boundary surface is defined for the model. Before creating a non-reflective boundary surface, it is necessary to establish a non-reflective boundary node component named Component.

2.1.4 Solution control settings and results analysis. Set the analysis time, this example set to 200, to ensure the completion of penetration; set the output file to LS-DYNA file, this example uses LS-PREPOST, the post-processor of LS-DYNA, to process and analyze the results; set the output step of the result file, this example sets the output step of the binary result file and the time history file to 20; energy control options, this example needs to activate Stonwall Energy, Hourglass Energy and Sliding Interface single options. After the numerical simulation, the state of the earth penetrator and the target protective layer is shown in figure 2. The penetration terminates after the earth penetrator reaches a certain depth. The displacement of point A in the vertical direction is observed by taking the node A on the warhead of the earth penetrator. As shown in figure 3, the final penetration depth is about 5.1m.
2.2 Acquisition of training data samples

In the process of establishing the numerical simulation model, it is found that the key variables are the curvature radius of the warhead, the length of the projectile body, the density of the projectile body, the density of the target protective layer, the elastic modulus of the target protective layer and the impact velocity of the earth penetrator. Taking these six parameters as input variables of the neural network model, it is necessary to modify the corresponding parameters in the numerical simulation model and calculate the penetration depth under the corresponding conditions. In order to fully reflect the penetration law of the earth penetrator, and taking into account the time required for numerical simulation calculation, according to the actual situation, three values of each parameter are selected, as shown in table 3.

| $r$  | $l$  | $\rho_1$ | $\rho_2$ | $E$     | $v$  |
|------|------|----------|----------|---------|------|
| 0.15 | 2    | 6000     | 1800     | 3.41E+10| 400  |
| 0.30 | 4    | 8000     | 2100     | 4.01E+10| 600  |
| 0.45 | 5    | 10000    | 2500     | 4.32E+10| 800  |

According to the data in the table, there are six parameters. Each parameter takes any of the three values in the interval and traverses all combinations. It needs 729 times of numerical simulation. Each time, it only needs to modify the parameters in the command stream file. A total of 729 sets of sample data can be obtained.

3. Establishment of BP Neural Network Model

3.1 Setting up the Model Structure of BP Neural Network

BP neural network is a multi-layer feedforward neural network trained by error back propagation algorithm. Its basic idea is gradient descent method. Gradient search technology is used to minimize the mean square error of the actual output value and the expected output value of the network[9]. BP feedforward neural network has unique advantages in function approximation. By training a large number of data, a complex implicit mapping relationship can be established between key parameters such as projectile length, projectile density, target strength and penetration depth, as shown in figure 4.
Figure 4. Structure of neural network

In figure 4, $X_1, X_2, L, X_n$ are the input values of BP neural network, $Y_1, Y_2, L, Y_m$ are the predicted value of BP neural network, $\omega_{ij}$ and $\omega_{jk}$ are the weights of BP neural network. When the number of input nodes is $n$ and the number of output nodes is $m$, BP neural network expresses the functional mapping relationship from $n$ independent variables to $m$ dependent variables. The selection of the optimal number of nodes $h$ in the hidden layer can be referred to the following formula [10]:

$$h < n - 1$$  \hspace{1cm} (1)

$$h < \sqrt{(m + n) + a}$$  \hspace{1cm} (2)

$$h = \log_2 n$$  \hspace{1cm} (3)

In formula, $a$ is a constant between 0 and 10. In practical problems, the choice of the number of nodes in the hidden layer first determines the approximate range of the number of nodes by referring to the above formula, and then determines the optimal number of nodes by trial and error method. For general problems, the prediction error of BP neural network increases first and then decreases with the increase of the number of nodes.

The prediction of penetration depth of earth penetrator requires six parameters as input, so $n=6$, the output is penetration depth, so $m=1$, substituting (1) (2) (3) formula, the number of nodes in the hidden layer can be obtained as follows:

$$h < 5$$ \hspace{1cm} (4)

or $h < 12$ \hspace{1cm} (5)

or $h = 3$ \hspace{1cm} (6)

Because the penetration mechanism is complex, the neural network structure with 1, 2 or 3 hidden layers is chosen, and the number of nodes in each layer is 3-6.

3.2 Training of BP neural network

Before the data is input into the neural network, it is usually necessary to normalize the data. The main purpose is to eliminate the influence of dimension and order of magnitude, so as to avoid large errors caused by the difference of order of magnitude of data. There are two main methods of data normalization, the maximum and minimum method and the mean variance method [11]. The function form of the maximum and minimum method is as follows:

$$x'_k = \left( x_k - x_{\text{min}} \right) / \left( x_{\text{max}} - x_{\text{min}} \right)$$  \hspace{1cm} (7)

In the formula, $x_{\text{min}}$ is the minimum value in the data sequence and $x_{\text{max}}$ is the maximum value in the data sequence. The function form of the mean variance method is as follows:

$$x'_k = \left( x_k - x_{\text{mean}} \right) / \sigma$$  \hspace{1cm} (8)

In the formula, $x_{\text{mean}}$ is the mean of the data sequence and $\sigma$ is the variance of the data.
sequence. The output data need to be de-normalized, that is, the reverse derivation of the above two functions.

According to BP neural network theory, the software of MATLAB includes a toolbox specially used for BP neural network. The three main functions are the parameter setting function of neural network `newff`, the training function of neural network and the prediction function of neural network `sim` [12]. Their function forms are as follows:

\[
\text{net} = \text{newff}(P,T,S,TF,BTF,BL,F,PF,IPF,OPF,DDF) \\
[\text{net},\text{tr}] = \text{train}(\text{NET},X,T,P,A) \\
y = \text{sim}(\text{net},x)
\]

Through these functions, the multi-hidden layer BP neural network can also be established. Compared with single hidden layer, multi-hidden layer has strong generalization ability, high prediction accuracy, and can achieve more complex mapping relationship. However, multi-hidden layer training takes a long time and needs more training data samples.

After numerical simulation, 729 sets of data have been obtained as data samples. Data samples are normalized and disorderly processed in Matlab software. 36 groups of data (5% of the data samples) are randomly selected as validation data. Each set of neural network model structure is trained to compare the errors between validation data and prediction results, and then the best model structure is determined. Tansig function is used for the transfer function between layers of the neural network model, and `trainindm` function is used for the training function [13]. The upper limit of training times is 10,000, the target error is 0.0001, and the learning efficiency is 0.0001. After training, it is known that the double hidden layer structure has the best prediction effect.

After repeated attempts, the optimal network structure is finally determined to be a 3-5 double hidden layer structure. It can be seen that the double hidden layer neural network with 3-5 structure can accurately penetrate the penetration depth of the earth penetrator, but when the penetration depth is large, there are obvious errors.

4. Prediction of penetration depth of earth penetrator

The trained neural network model can be used to predict the penetration depth of the earth penetrator. By controlling variables, the influences of the curvature radius of the warhead, the length of the projectile, the density of the projectile, the density of the target protective layer, the elastic modulus of the target protective layer, and the velocity of the projectile hitting the ground penetrating surface on the penetration depth can be studied respectively. According to the input data set in table 4, the unit system adopts the unit system, and the prediction results are shown in figure 5.

| Table 4. Value range of each parameter |
|---|---|---|---|---|---|
| $r$ | $l$ | $\rho_1$ | $\rho_2$ | $E$ | $v$ |
| (a) | 0.12-0.6 | 1.8 | 7000 | 2000 | 3.41E+10 | 500 |
| (b) | 0.2 | 0.5-2.5 | 7000 | 2000 | 3.41E+10 | 500 |
| (c) | 0.2 | 1.8 | 5000-10000 | 2000 | 3.41E+10 | 500 |
| (d) | 0.2 | 1.8 | 7000 | 1500-2500 | 3.41E+10 | 500 |
| (e) | 0.2 | 1.8 | 7000 | 2000 | 2.50E+10-4.50E+1 | 500 |
| (f) | 0.2 | 1.8 | 7000 | 2000 | 3.41E+10 | 250-1000 |
According to figure 5 (a), with the increase of warhead curvature radius, the penetration depth decreases sharply at first and then slows down. The main reason is that when warhead curvature radius increases, the warhead area increases and its force increases, which leads to the decrease of penetration capability of ground penetrating projectile. According to figure 5 (b), with the increase of the length of the projectile, the penetration depth also increases. The main reason is that the quality of the earth penetrator is increased while the warhead area is not increased, and the penetration capability of the earth penetrator is improved. According to figure 5 (c), the penetration depth increases with the increase of projectile density. The main reason is the same as the increase of projectile length. According to figure 5 (d), the penetration depth decreases with the increase of the density of the protective layer, and the anti-penetration ability of the protective layer increases with the increase of the density of the protective layer. According to figure 5 (e), the penetration depth decreases with the increase of the elastic modulus of the protective layer. The main reason is the same as that when the density of the protective layer increases. According to figure 5 (f), with the increase of the velocity of the projectile hitting the target, the penetration depth increases first and then decreases. The main reason is that the kinetic energy increases and the penetration ability increases with the increase of the velocity of the projectile.

![Figure 5. The influence of the parameters on the depth of penetration](image-url)
However, with the increase of the velocity, the mass erosion of the projectile becomes more and more serious and the penetration ability decreases. In this case, the penetration effect is the best when the velocity of the projectile is about 800m/s. The maximum penetration depth is 21.5m.

To sum up, in practical engineering, the methods to improve penetration capability of earth penetrating projectile are: (1) Reducing the radius of warhead curvature and appropriately reducing the radius of warhead curvature can achieve significant results, reduce excessive effect decline, and easy to bend during penetration.(2) To increase the length and density of the projectile, the main purpose is to increase the mass of the projectile, especially for kinetic earth penetrator.(3) The kinetic energy increases with the increase of the impact velocity of the projectile properly, but it is easy to cause the erosion of the projectile. The methods to improve the anti-penetration ability of the protective layer are: (1) Increasing the density of the target protective layer.(2) To increase the elastic modulus of the target protective layer, the essence of both methods is to increase the strength of the protective layer. In addition, methods such as increasing the thickness of the protective layer and setting the shelter layer can be adopted.

5. Conclusion
In this paper, the penetration depth of earth penetrator is predicted ideally by establishing artificial intelligence neural network model. Based on the BP neural network model, the influence of six different parameters on penetration depth of earth penetrator is studied. The conclusion is drawn that the ways to improve penetration ability of earth penetrator are to reduce warhead curvature radius, increase projectile length and density, properly increase projectile impact velocity and enhance the anti-penetration ability of protective layer by increasing the density and modulus of elasticity of protective layer.

Because of the high cost and danger of penetration test, the data used to train the neural network in this paper are obtained by numerical simulation. Compared with the prototype test, the reliability of the data is not high enough.

References
[1] Liang B, Chen X W, Ji Y Q, Huang H J, Gao H Y and Li X L 2008 Experimental study on deep penetration of reduced-scale advanced earth penetrating weapon. Expl Shock Wave, 28(1), 1-9.
[2] Zhou J N, Jin F N and Wang B 2008 Discussion on Projectile Parameters in Bepezaux Formula. J Ball,(02),20-23.
[3] Jin F N, Xu H Z and Liu L 2004 Depth Calculation of GBU-28 Penetrating Surrounding Rocks with Young Formula. Journal of PLA University of Science and Technology. (06),33-36.
[4] Wu G S 2009 Development of numerical simulation in geotechnical engineering. Science & Technology Information, (30),708-709.
[5] Jiao L C, Yang S Y and Liu Fang 2016 Seventy Years Beyond Neural Networks, Retrospect and Prospect. Chinese Journal of Computers.39 (08),697-1716.
[6] Huang M R 2011 Penetration and perforation mechanism of rigid projectile into the concrete target. Nanjing University of Science & technology.
[7] Gao G F, LI Y C and ZHAO K 2016 Influence of material constitutive parameters on penetration depth and optimization for them. Ordn Mater Sci Eng.39(02),1-9.
[8] Zheng H 2013 Study on the effect of mass abrasion of ogive-nose projectile during penetration into concrete targets. Nanjing University of Science & technology.
[9] Li Y K 2012 Analysis and improvement applications of BP neural network. AnHui University of Science and Technology.
[10] Wang R B, XU H Y and Li B 2018 Research on Method of Determining Hidden Layer Nodes in BP Neural Network. Comput Technol Dev.28(04),31-35.
[11] Liu X T 2010 Study on Data Normalization in BP Neural Network. Mechanical Engineering and Automation.(03),122-123+126.
[12] Shi Y 2010 Realization of BP Neural Network Based on Matlab. Journal of Xiangnan University.
31(05), 86-88+111.

[13] Shen L and Wu K J. *Hybrid Genetic Algorithm to Improve the BP Neural Network*. Machine Design & Research. (02), 10-12+6.