Energy-Saving Technology in Finite Element Calculation

Feng Wang1,2, Qianwen Han1*,2, Yurong Ma1, Yaqiong Jiang1, Dan Li1 and Wei Zhou1
1School of Urban Construction, Anhui Xinhua University, Hefei 230088, China
2Key Laboratory of Building Structure of Anhui Higher Education Institutes, Anhui Xinhua University, Hefei 230088, China
*Corresponding author’s e-mail: hanqianwen@axhu.edu.cn

Abstract. In the finite element calculation of three-dimensional impact mechanics, there are usually such problems as large memory consumption and more machine consumption, which leads to a great waste of power resources. Based on the analysis of the calculation process of three-dimensional penetration sliding surface, a method of improving the calculation efficiency is proposed, which is the cell search method, based on the comparison calculation and without affecting the calculation accuracy. This method only judges the main elements in the cell involved by the slave nodes in the penetration channel area, greatly reduces the calculation amount of the elements, and improves the efficiency of the program calculation. The method is applied to the programming of finite element, and the results are satisfactory. The application of cell search method has played a good role in promoting the development of energy-saving technology.

1. Introduction
When the finite element method is used to calculate three-dimensional impact mechanics problems, in order to ensure sufficient accuracy, a large number of element meshes are needed to generate the geometric model. The number of grid elements is usually tens of thousands, even hundreds of thousands, so the calculation of all elements is considerable. Therefore, the problem of large memory consumption and machine time consumption in finite element calculation has been troubling engineers, resulting in a great waste of power resources, which also limits the application of finite element.

Over the years, many scholars have improved the efficiency of finite element method through various methods, and achieved a lot of results. Zhou Jie et al discrete the two-dimensional shallow water equation by using the step-by-step finite element method, and preliminarily explored the efficiency of the row index matrix compression storage sparse matrix method and the preconditioned biconjugative gradient method in solving the large-scale linear equations formed in the finite element method[1]. Niu Shanting et al respectively analyzed the calculation efficiency of the golden section method, the successive quadratic interpolation method and the hybrid method of them in the three-dimensional inverse heat transfer problem during quenching and cooling process[2]. Feng Qingsong et al improved the traditional energy method and reduced the amount of calculation through the calculation method of periodic structure band gap based on artificial spring model[3]. Zhu Hongping et al developed the response sensitivity method based on substructure for finite element model updating of large structures[4]. Zhao Mi et al proposed an efficient time history analysis method for soil deep underground structure interaction under earthquake action[5]. Chai Xianghai et al used explicit dynamic sub model method in parallel calculation of transient impact of aeroengine, which
can ensure the calculation accuracy and greatly improve the calculation efficiency[6]. These methods are generally to improve the numerical calculation method, to a certain extent, improve the calculation efficiency of the finite element method, but there are few such research results as through the optimization of the number of elements calculation to improve the efficiency.

Aiming at the finite element calculation of three-dimensional impact mechanics problems, this paper puts forward the cell search method on the basis of not affecting the calculation accuracy. The effect of this method to improve the computational efficiency is very significant.

2. Cell search method

The amount of finite element calculation of three-dimensional impact mechanics is quite huge. It is far from enough to improve the numerical calculation method. How to optimize the number of elements participating in the finite element calculation on the basis of not affecting the calculation accuracy is the key to improve the operation efficiency.

2.1. Introduction to calculation of 3D penetration sliding surface

In the numerical simulation of three-dimensional penetration, the calculation of the sliding surface of the projectile in the target plate is often the key and difficult problem in the numerical calculation. In order to avoid the difficulty of program logic design and calculation caused by the mutual invasion of main-slave elements when the sliding surface becomes a space surface, a simple calculation idea of sliding surface is adopted. Only main elements and no slave elements are set, but the nodes on the slave elements are reserved, which is called slave nodes.

Before the calculation of sliding surface, each time step is calculated $\Delta t$. First, according to the coordinates of the slave node, we can judge whether the slave node invades into the main element. If it invades, calculate the sliding surface. For each slave node, if we want to search all the main elements once to judge whether the slave node invades the main element, the amount of calculation is very huge. In fact, for each slave node, only a few main elements near its location are likely to invade, while most of the other main elements are useless. In order to improve the computational efficiency, the program adopts another simple and effective method, the cell search method.

2.2. Determination of the cells region

The region $\Omega_C(x,y,z)$ involved in the calculation of the sliding surface is estimated according to the approximate range of the penetration channel in the penetration process, which satisfies the following conditions,

$$ x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}, z_{\min} \leq z \leq z_{\max} $$

(1)

Where $x_{\min}, x_{\max}, y_{\min}, y_{\max}, z_{\min}$ and $z_{\max}$ are the boundary coordinates of the region $\Omega_C$ respectively. In fact, $\Omega_C$ is only a virtual area attached to the target plate. According to the different types of penetration, $\Omega_C$ should also be different, that is, $\Omega_C$ of oblique penetration is larger than that of normal penetration.

2.3. Determination of the cells number

The region $\Omega_C$ is further subdivided into many "cells". Figure 1 is a cross-sectional schematic diagram of the target cells. If the size of each cell is $x_{DIS} \times y_{DIS} \times z_{DIS}$, then the number of cells in the region $\Omega_C$ is,

$$ N = \left\lfloor \text{Int}\left(\frac{x_{\max} - x_{\min}}{x_{DIS}}\right) + 1\right\rfloor \times \left\lfloor \text{Int}\left(\frac{y_{\max} - y_{\min}}{y_{DIS}}\right) + 1\right\rfloor \times \left\lfloor \text{Int}\left(\frac{z_{\max} - z_{\min}}{z_{DIS}}\right) + 1\right\rfloor $$

(2)

where $\text{Int}(\ )$ is an integer function. We sort the cells in the region $\Omega_C$ in the order of 1, 2, 3... $N$ according to the size of their coordinates.
In this way, each cell has its fixed space position, and contains several slave nodes and main elements. Before calculating the sliding surface of elements, all the main elements contained in each cell are determined, that is, all the main elements in the region $\Omega_C$ are assigned to the corresponding cell. To solve this problem, we first check whether the formula (1) is satisfied according to the coordinates of the eight nodes (i.e. the main node) of the main element. If any main node meets the conditions, we allocate it. Let the coordinates of the main node be $(x, y, z)$, then the number of the cell where the main node is located is

$$N_{cell} = (I_z - 1) \times N_{cx} \times N_{cy} + (I_y - 1) \times N_{cx} + I_x$$  \hspace{1cm} (3)

where,

$$I_x = \text{Int}\left(\frac{x - x_{\text{min}}}{x_{DIS}}\right) + 1, \quad I_y = \text{Int}\left(\frac{y - y_{\text{min}}}{y_{DIS}}\right) + 1, \quad I_z = \text{Int}\left(\frac{z - z_{\text{min}}}{z_{DIS}}\right) + 1$$

$$N_{cx} = \text{Int}\left(\frac{x_{\text{max}} - x_{\text{min}}}{x_{DIS}}\right) + 1, \quad N_{cy} = \text{Int}\left(\frac{y_{\text{max}} - y_{\text{min}}}{y_{DIS}}\right) + 1$$  \hspace{1cm} (4)

2.4. The principle of the cell search method

Obviously, $1 \leq N_{cell} \leq N$. Then, the main element containing the main node will be assigned to the cell with serial number. When all the main elements in the region $\Omega_C$ are allocated, each cell is allocated all the main elements it contains. In this case, a main element may be assigned to several different cells at the same time, but the main elements contained in each cell are determined.

In the calculation of sliding surface, only the slave nodes in the cells enter into the calculation logic of sliding surface. For each slave node, if its coordinates satisfy formula (1), that is, the slave node is in the region $\Omega_C$, and then the serial number $N_{cell}$ of its cell is calculated according to formula (3). In this case, the main element that the slave node may invade into must also be included in the cell $N_{cell}$, that is, one of the main elements allocated in the cell $N_{cell}$. Then, all the main elements in the cell $N_{cell}$ can be judged according to the coordinates of the nodes, and the main element that is invaded can be determined.

3. Example analysis

A simple example is given to illustrate the advantages of this method. The projectile body with size 20mm×20mm×40mm is taken as the main body, and the target plate with size 300mm×300mm×90mm
is taken as the slave body. The meshes are generated according to the element size of 1mm×1mm×1mm and 3mm×3mm×3mm respectively. The size of the region $\Omega_C$ is $x_{\text{max}} - x_{\text{min}} = 24\text{mm}, y_{\text{max}} - y_{\text{min}} = 24\text{mm}, z_{\text{max}} - z_{\text{min}} = 44\text{mm}$, and the size of the body package is $x_{\text{DIS}} \times y_{\text{DIS}} \times z_{\text{DIS}} = 5\text{mm} \times 5\text{mm} \times 5\text{mm}$. Then the number of projectile elements is,

$$\frac{20}{1} \times \frac{20}{1} \times \frac{40}{1} = 16000$$

The number of target plate elements is,

$$\frac{300}{3} \times \frac{300}{3} \times \frac{90}{3} = 300000$$

In the case of no cell search method, the amount of calculations to judge whether the slave nodes invade into the main elements is,

$$300000 \times 16000 = 4.8 \times 10^9$$

After using the cell search method, the amount of calculations used to allocate the main elements to the cells is,

$$8 \times 16000 = 1.28 \times 10^5$$

The amount of computations used to determine whether the slave node is in the region $\Omega_C$ is,

$$300000 = 3 \times 10^5$$

According to formula (2), the number of cells contained in the region $\Omega_C$ is,

$$N = \left[ \text{Int}\left(\frac{24}{5}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{24}{5}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{44}{5}\right) + 1 \right] = 225$$

The maximum number of slave nodes in region $\Omega_C$ is,

$$N_{\text{max}} = \left[ \text{Int}\left(\frac{24}{3}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{24}{3}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{44}{3}\right) + 1 \right] = 1215$$

The maximum number of main elements in each cell is,

$$N_{\text{max}} = \left[ \text{Int}\left(\frac{5}{1}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{5}{1}\right) + 1 \right] \times \left[ \text{Int}\left(\frac{5}{1}\right) + 1 \right] = 216$$

The maximum amount of computations is to judge all the main elements in the cell $N_{cell}$ where the slave node is located,

$$N_{\text{max}} \times N_{\text{max}} = 1215 \times 216 \approx 2.62 \times 10^5$$

Therefore, according to formula (8), (9) and (13), the total amount of computations used by the cell search method at most is,

$$1.28 \times 10^5 + 3 \times 10^5 + 2.62 \times 10^5 = 6.9 \times 10^5$$

Compared with formula (7) and (14), the computations amount of the two schemes is $4.8 \times 10^9 / 6.9 \times 10^5 \approx 7000$ times different. It can be seen that the improvement of computational efficiency by using the cell search method is very significant.
Of course, in addition to element calculations, program operation also includes pre-processing, post-processing, data input and output, so the total efficiency of program operation can not be increased by thousands of times. However, according to the calculation results of practical examples, the operation time of the program can be reduced to at least one tenth of the original by using the above method.

4. conclusion

It can be seen from the comparison calculation that the volume package search method proposed in this paper can greatly reduce the calculation amount of finite element analysis, and is very effective in improving the efficiency of program operation. This method has been applied to the finite element programming and satisfactory results have been obtained. It can be said that it solves the problems of large memory consumption and time-consuming in the finite element calculation of three-dimensional impact mechanics to a certain extent, and plays a good role in promoting the development of energy-saving technology. It is believed that with the improvement of computer hardware level and the development of finite element method, the calculation efficiency of finite element method will be better solved.

Acknowledgments

This paper is one of the phased achievements of the key project of Natural Science Research in Universities of Anhui Province "Study on dynamic mechanical properties of heterogeneous materials based on extended finite element method" (KJ2019A0882), Anhui Province Quality Engineering Project "Teaching team of civil engineering" (2019jxtd118), the school level key laboratory project "Mechanical performance analysis of prefabricated concrete member joints based on ANSYS" (KLBSZD201907), the key project of Humanities and Social Sciences in Universities of Anhui Province "Research on digital restoration and protection technology of Huizhou colour painting" (SK2020A0607), and the school level key laboratory project "Study on aseismic behaviour of prefabricated beam column joints" (KLBSZD202006).

References

[1] Zhou J., Wang D.F. (2004) Exploration on memory requirement and operation efficiency of finite element method in flow calculation. Advances in Water Science, 15: 593-597.
[2] Niu S.T., Zhao G.Q., Li H.P. (2006) Study on the Influence of Optimization Methods on the Computation Efficiency in Inverse Heat Conduction Analysis with 3D FEM during Quenching Process. China Mechanical Engineering, 17(S1): 318-322.
[3] Feng Q.S., Yang Z., Guo W.J., Lu J.F., Liang Y.X. (2021) Research on band gap calculation method of periodic structure based on artificial spring model. Chinese Journal of Theoretical and Applied Mechanics. http://kns.cnki.net/kcms/detail/11.2062.O3.20210327.1443.002.html.
[4] Zhu H.P., Li J.J., Tian W., Weng S., Peng Y.C., Zhang Z.X., Chen Z.D. (2021) An enhanced substructure-based response sensitivity method for finite element model updating of large-scale structures. Mechanical Systems and Signal Processing, 154: 107359.
[5] Zhao M., Li X.D., Gao Z.T., Du X.L. (2021) An efficient time history analysis method for soil deep underground structure interaction under earthquake action. Journal of disaster prevention and mitigation engineering, 41: 39-45 + 54.
[6] Chai X.H., Hu S.F., Zhang Z.N., Hou L. (2020) Application of Explicit Dynamic Sub-Model Method in Parallel Calculation of Aero-Engine Transient Impact. Frontiers of Data&Computing, 2: 11-20.