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Analysis on the Safety Margin and Damage Model for the Excavation Support Structure in a Very Deep Pit

LU Xinzheng SONG Erxiang & JIANG Jianjing
(Department of Civil Engineering, Tsinghua University, Beijing, 100084)

Abstract: The size of a very deep pit is about 69×50×50m. The excavation support structure in this pit is continuous concrete wall with internal support structure, and the continuous wall is embedded into bedrocks. In order to know the safety margin and the damage process of this pit, 3-D nonlinear finite element analysis with excavation simulation is carried out. The self-weight of soil in the finite element model is increased hypothetically until the support structure is destroyed. Comparing the assumed self-weight of soil to the real one, the safety margin of the pit can be obtained. The numerical results show that all the failure of the pit begins with the collapse of the internal supports and the failure models are different in various excavation depths.
Keywords: deep pit; spatial finite element analysis; damage model; safe margin

1 Introduction

For the safety of underground structures, exploring their possible failure modes and evaluating their safety margins are important, and the finite element (FE) method provides a useful tool to finish this task. By settling correct FE model and simulating the whole excavation procedure, the weakness of the pit can be predicted. And the construction or observation plan can be modified to avoid the weakness. This paper presents an example of simulating the excavation and failure of a very deep pit with 3D nonlinear FE model. And the FE results are useful for the safety of excavation.

2 Background information

A very deep pit is located near the Yangtze River, whose size is 69 ×50×50m. The strata of the field are[1]: 0~16m is silt stratification; 16~48m is sand stratification; and the bedrock lies under about 48m in depth. The mechanical parameters of the soil are list in table 1. The excavation structure of underground continuous concrete wall with internal supports is adopted for this pit. The average depth of the continuous wall embedded into the bedrock is 3m, and the thickness of the wall is 1.2m. There are 12 layers of internal supports in the pit, which are about 4m in space. The planar arrangement of internal supports is shown in Fig.1. The construction plan for this pit is: the continuous wall will be finished first before the excavation. Then the internal supports will be constructed parallel with the excavation. The time gap in building up neighborhood layer of supports is about 10~15 days. Since this pit is very complex, in order to know its safety margin and damage process, 3-D nonlinear finite element analysis with excavation simulation is carried out. The self-weight of soil in the finite element model is increased hypothetically until the support structure is destroyed. Comparing the assumed self-weight of soil to the real one, the safety margin of the pit should be able to obtain.

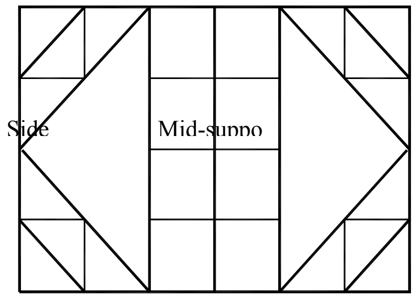

Fig.1 Planar arrangement of internal supports

Table 1. Mechanical parameters for the soil

Stratification	Density (Kg/m^3)	Yang's modulus (KPa)	Poisson ratio	C (KPa)	φ	Depth (m)
1	1810	3000	0.35	13	5	0～-16

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2	1790	8000	0.3	10	9	-12～-16
3	1900	15000	0.3	5	27	-16～-35
4	1900	30000	0.25	2	30	-35～-48
5	2200	2×10^6	0.25			

3 Numerical model

3.1 Finite element model

Nonlinear 3-D finite element model is built up for this pit with the common finite element software of ANSYS[2,3], in which the lateral pressure of soil and underground water are considered together[4~7]. 20 nodes solid element is adopted to model the soil, while 8 nodes shell element is adopted for continuous wall, spatial beam element for supports. Simulate the process of excavation with the “active/kill” function in the FEA software.

3.2 Soil parameters

The D-P elastic-plastic constitutive model[8~10] is adopted for soil material. Because the lateral pressure of soil and underground water is considered together, the Poisson ratio of soil is increased to 0.45, so that the total pressure applied on the wall is equal to the real conditions. In order to obtain the damage process of support structure, the self-weight of soil is increased hypothetically so that more pressure will be applied on the support structure. The self-weight of soil is increased step by step until the supports fails. And we select the following three typical load cases to illustrate the safety margin and damage process of the pit.

Load Case A (LS-A for abbreviation): the self-weight of soil is increased about 2 times.

Load Case B (LS-B for abbreviation): the self-weight of soil is increased about 2.2 times.

Load Case C (LS-C for abbreviation): the self-weight of soil is increased about 2.5 times.

3.3 Concrete parameters

In order to know the actual safety margin of the pit, not itemized parameters are multiplied on the material strength, and the standard strength of concrete is used.

The ideal elastic-plastic model is adopted for the concrete continuous wall. In the design draft, the yield bending moment for the continuous wall is 5762KNm. So the yield stress of the wall in numerical model is set to be 25MPa with equivalent bending moment method. The elastic-crush model is adopted for the concrete internal supports[11]. That is to say, when the stress in the supports is larger than the ultimate stress of concrete, the support will be crushed and removed from the model. From the field test results, the strength of concrete in most supports is higher than C40, and the average slenderness ratio of supports is 17. So considering the effect of bucking, the ultimate stress of concrete is descended to 26MPa, according to “Chinese Code for Concrete Structure” (GBJ10-89).

3.4 Simulate for the construction process

If there is no damage happening in the support structure, the simulation of construction process will be executed according to the original plan. However, once the supports begin to fail, then the excavation will stop and then the damage simulation will begin. The progress of damage process will be recorded step by step.

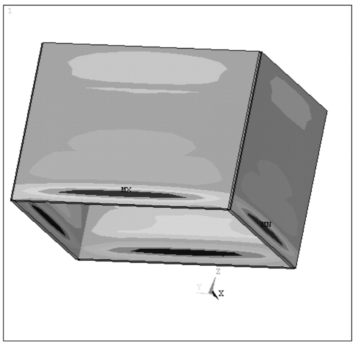

Fig.2 Strain in the wall (LS-A)

4 Results of Load Case A (LS-B)

In this load case, the self-weight of soil is doubled, which means the lateral pressure on the wall is about two times to the real condition.

The maximal stress in the internal supports is 25.6MPa, which is just a little smaller than the ultimate one. So there is no problem in the supports. The maximal displacement in the wall is 13.4cm, Δ/H=2.68‰; the maximal strain in the wall is 2.06‰, in which the plastic strain is 0.58‰, located in the zone embedded in the bedrocks, as shown in Fig.2. However, though the wall embedded in the rocks will crack and exceed its yield bending moment, the maximal compression strain in concrete is still smaller than 3.3‰, which is the ultimate strain for concrete in Chinese concrete code[12]. And usually there is some stress concentration in the FEA model. So we think that the wall should be no problem, too. From all these analysis above, we consider the support structure is safe in this load case, which means the safety margin of this pit is a little larger than 2.0.

5 Results of Load Case B (LS-B)

In this load case, the self-weight of soil is multiplied by 2.2. So the total lateral pressure acting on the wall is 2.2 times to the real one. The numerical results show that most internal supports in the pit will crush in this load case and the pit will be destroyed by global sliding of soil around.

In this load case, the maximal stress in the internal supports is still less than 26MPa before the excavation of the last layer. However, when the excavation of last layer is finished, the maximal stress in the supports is 27.2MPa, which is larger than the crush value of 26MPa. So it is suggested that the supports have reach their ultimate state in this load case and will be damaged when excavating the last layer. It also shows that the safety margin of this pit is about 2.0~2.2.

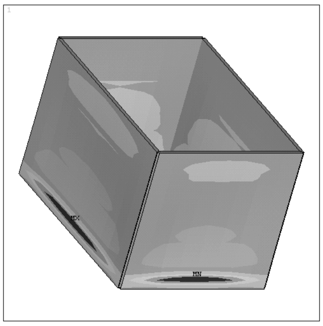

Fig.3 Strain in the wall (LS-B) before damage

At the same time, the maximal displacement in the wall is 14.9cm, Δ/H=3‰; the maximal strain in the wall is 2.5‰, in which the plastic strain is 1.02‰, located in the zone embedded in the bedrocks, as shown in Fig.3.

Using the method discussed in Chapter 2.3 to let the internal supports fail, and recording the axial force, displacement and strain in the damage process, the whole damage process of the pit will be obtained. The failure development of internal supports is shown in Fig.4.1~4.4. Only 1/4 of the model is shown in the figures, and failed supports will not appear, so as to make the figure clearer.

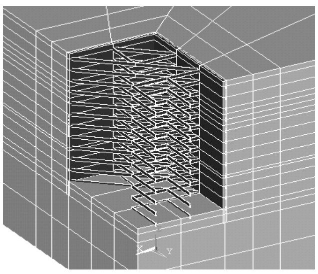

Fig.4.1 Internal supports before failure

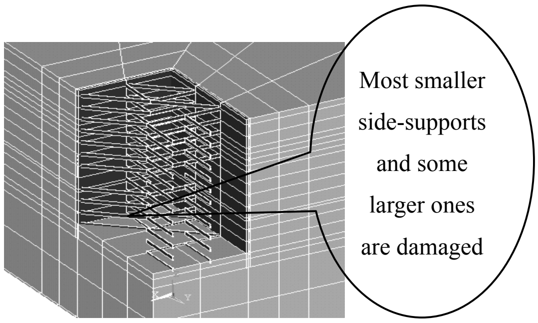

Fig.4.2. Lots of side-supports fail (7th step of damage)

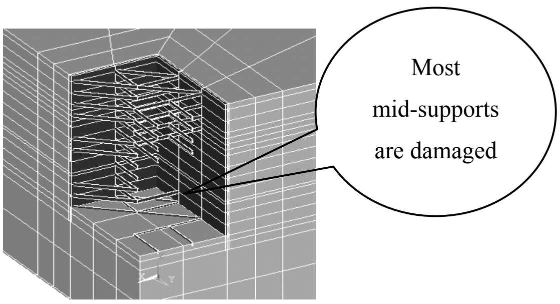

Fig.4.3. Lots of mid-supports fail (11th step of damage)

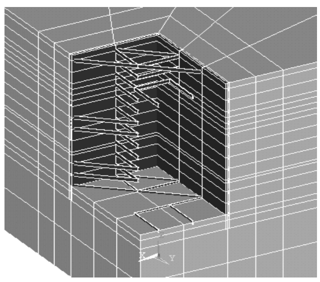

Fig.4.4. Survival supports (16th step of damage)

The probable damage process of the pit in this load case is: The smaller side-support in the 10th layer fails first because its internal force is the largest. The load in the failed support will transmit to the bigger side-support in the same layer and other side-supports of neighborhood layers quickly, which leads to the failure of these side-supports. Together with the failure of side-supports, the displacement in the short side is increasing quickly. The axial force in the mid-support is ascending quickly, too, with the failure of side-supports, especially to those in the middle layers. Then, these mid-supports are crushed and the displacement of long side increases suddenly and overcomes the displacement of short side. At last, all the internal supports except those in the first and last layer are destroyed entirely.

The development of displacement in the middle of long side and short side is shown in Fig.5.1, 5.2, respectively. The maximal displacement in the long side is larger than 60cm at last, and the iteration of FEA will not converge after that. In the practical project, the soil will collapse in such large displacement. So it means that the computation can satisfy the requirement of “damage analysis”. It also can be found in the figures that, because the side-supports fail first, while the mid-supports are still undamaged, the displacement development of long side is not obvious at first. Furthermore, because of the quick development of displacement in the short side, the displacement in the long side descends a little for a short while. However, when the mid-supports begin to fail, the displacement of long side will increase suddenly and will overcome the one in the short side. At the same time, the development of displacement in the short side will be influenced by the long side, so that the displacement increasing speed in the short side will be slowed.

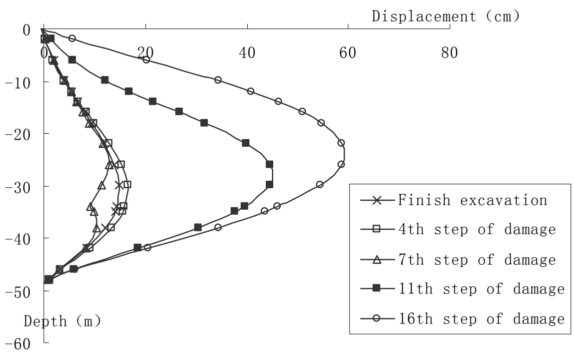

Fig.5.1 Displacement of long side

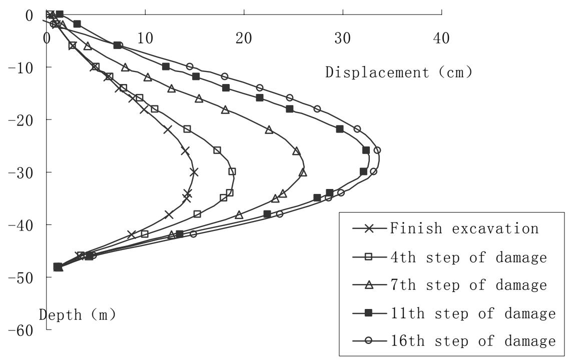

Fig.5.2 Displacement of short side

When damage analysis is completed, the last strain distribution in the wall is shown in Fig.6. It can be found that the maximal strain is no longer located in the zone embedded in the rocks. Because of the distinct strain development in the middle of the wall, the maximal strain in the wall is located there. The maximal strain is 0.0143, which is much larger than the ultimate strain of concrete. It means the wall is broken at that time.

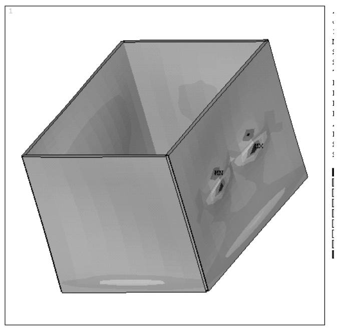

Fig.6 Strain in wall in the end

The development of plastic zone in the soil is shown in Fig.7 (a)~(d). It can be found that the plastic zone is located in the bottom of the pit before the damage starts. When the damage starts, the plastic zone will develop quickly in the middle of the pit edges, firstly in the short edge, then in the long edge. When the pit approaches to the entire failure, there is a plastic sliding surface in the middle of long side, which leads to the entire sliding damage of soil. Hence, the whole damage process of the pit is:

(1) Crushes in the internal supports
(2) The deformation of continuous wall increases continuously because lots of supports fail. At last the wall is broken in the middle of the long side.
(3) The soil above the middle of the pit slides entirely, and the whole pit is damaged.

Besides, the soil on the ground surface outside the pit will go into plasticity because of the too large deformation in the pit.

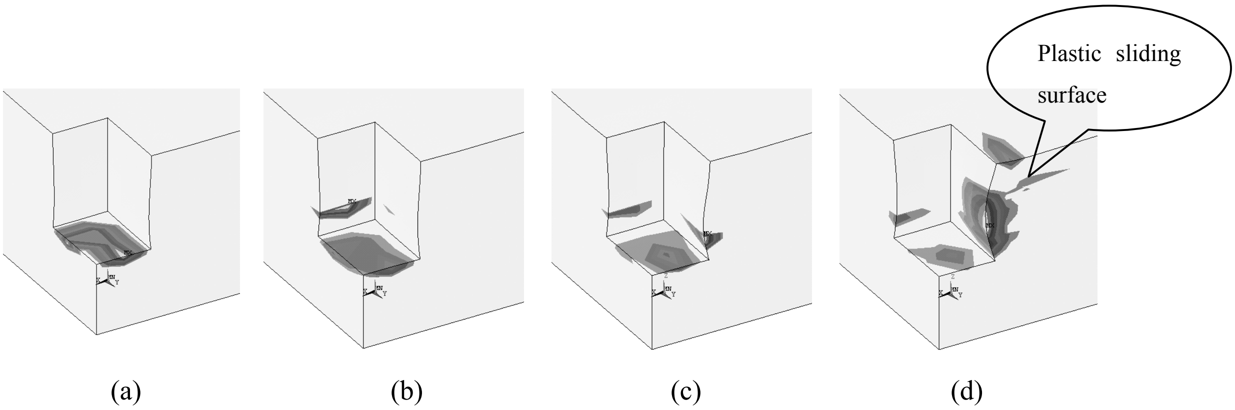

Fig.7 Development of plastic strain in the pit

(a) Plastic zone when excavation completed (b) Plastic zone appears in the short side

(c) Plastic zone appears in the long side (d) Plastic sliding surface which leads to the entire sliding damage of soil

6 Results of Load Case C (LS-C)

In this load case, the self-weight of soil is multiplied by 2.5, which means the lateral pressure acting on the wall is about 2.5 times to the real one. The numerical results show that the internal supports will begin to failure as early as excavating the shallow layers. However, since the excavation depth is not very deep, the lateral pressure difference on the wall is not very large. So the damage deformation will go to stable at last.

In this load case, the internal supports begin to failure when the 7th layer is being excavated. The damage takes place on the smaller side-supports of the 5th layer, firstly. Then the damage will expand to the neighborhood layers and at last most side-supports in the same side are crushed. However, as the excavation depth is not very deep, and the damage of side-supports releases the stress in the soil, so the damage deformation goes into stable at last. There is only a few side-supports fails in the other side of the pit, and almost all mid-supports are undamaged.

With the failure of supports, the deformation of pit is kept on developing. The displacement on the side where supports are damaged seriously increases from 14.3cm to 24cm. And the displacement on the long side will not develop too much because most of the mid-supports are still working, which will be stopped at about 15.6~17cm. The displacement development in long and short sides is shown in Fig.8.1, 8.2, respectively.

Before the damage happens, the maximal strain in the wall is 1.59‰, which is embedded in the bedrocks. And the plastic strain is very small. After the damage happens, when the displacement development stops at last, the maximal strain in the wall is 2.25‰, and the plastic strain is 1‰, which is still smaller than the ultimate compression strain of concrete (3.3‰). So the wall is not broken and still can hold the soil.

In this load case, the plastic zone of soil is located in the bottom of the pit. And no sliding surface like the one in Load Case B takes place in this load case.

Comparing Load Case B and Load Case C, we can find that if the damage takes place relatively earlier, there is more soil in the pit and the pressure difference on the wall is relatively smaller. So when some of the supports are destroyed, and the stress in soil is released, the displacement development will be stopped by survival supports and continuous wall in the end. In another words, with the excavation of the pit, there will be more risk for the entire damage like the one in Load Case B when excavating deep layers.

7 Conclusions

The safety margin and damage process of a very deep pit is obtained by increasing the self-weight of soil hypothetically in the 3-D FEA nonlinear model. The damage model of the pit is simulated, and the following conclusions can be obtained.

(1) From the computation we can see that the safety margin for this pit is about 2.0~2.2.

(2) Since the stiffness of supports in this pit is relatively large, and the total deformation in the pit is relatively small, the damage happens firstly on the supports. And most start from the smaller side-supports.

(3) It can be found from Load Case B and Load Case C that the probable damage types in the pit are the following two ones: when the excavation depth is relatively small, the damage will be concentrated on the internal supports and the continuous wall maybe can survive. However, when the excavation depth is relatively large, the pressure difference is large enough to break the continuous wall. Then the soil around the pit will slide down entirely and the whole pit will be destroyed at last.

(4) Since the continuous way is embedded in the bedrocks, the sliding surface of soil is located in the middle of the pit.

(5) There is no redundancy element in this support system. So the failure of any support may cause chain damage in the neighborhood supports, and the whole pit will be destroyed at last. That is to say, the supports should be built up very carefully.

(6) When the excavation of the pit is close to the bottom, the probability of entire failure in the pit will be increased a lot.

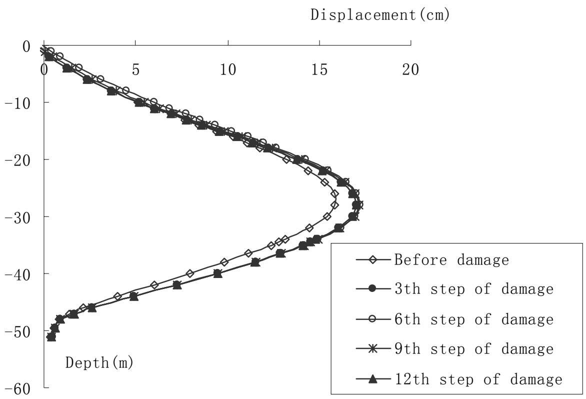

Fig.8.1 Displacement development of long side

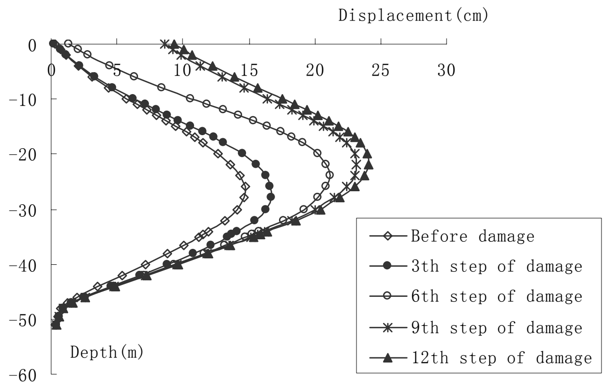

Fig.8.2 Displacement development of short side

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