Parameters sensitivity analysis of underground excavation impacting on slope stability based on Vector Sum Method

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Parameters sensitivity analysis of underground excavation impacting on slope stability based on Vector Sum Method

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Abstract. The impact of underground excavation on slope stability is controlled by many parameters, including the shape of slope, the mechanical property of soil and rock, the relative position of excavation zone and slip surface, and so on. The factor of safety (FOS) base on limit equilibrium method (LEM) and strength reduction method (SRM) is not suitable to evaluate the impact. Vector sum method (VSM) and orthogonal experiment are used to evaluate the impact by doing parameters sensitivity analysis. The result shows that the VSM could be used to in this research field, and the gradient of a slope, the relative position between a excavation area and a slope, the cohesion are the top three factors which impact the stability significantly.

1. Introduction

The impact of underground excavation on slope stability is very common is geotechnical, for example, the tunnel excavation in a mountainous area, or mining near a slope. The property of soil and rock, the relative position, the structural characters of a slope, the excavation size and the original geological structure of the slope will all impact the slope stability after excavation [3,4,6]. The excavation will remove the material which support the slope before, and will cause the stress concentration, reduce the resistance force of potential slip surface.

Usually, the index of slope stability is the factor of safety (FOS), which is computed by limit equilibrium method (LEM) or strength reduction method (SRM). LEM introduce a rigid body assumption, so it can not reveal the stress redistribution after excavation. Based on numerical method such finite element method, the SRM could consider the stress change, but when the excavation cause highly stress concentration, is very hard to get the reasonable FOS of SRM because the poor numerical convergence. Because of the large number of impact factors and the lack of suitable analysis methods, it is rarely to see studies on the basic law of the impact of underground excavation on slope stability by numerical method. Most of the studies are focus on a specific geotechnical engineering.

2. Vector Sum Method

The Vector Sum Method is a newly developed method. The slip and resistance force on a slip surface are calculated by numerical method like FEM, so all kinds of process, natural or artificial can be consider, so it is suitable to analysis the impact of excavation on slope stability. The FOS is define as follow [1,2,5]:

\[ F = \frac{\Sigma R}{\Sigma T} \]  


Where $\sum R$ is the potential resistance force on slip surface, $\sum T$ is the slip force on slip surface.

Different from other method, VSM will use the vector sum of slip force to compute a slip direction. The resistance force is the vector sum of the projection, which is the resistance force all along the slip surface project to the slip direction. The analysis steps are as follow:

Build a numerical model, compute the stress distribution.

Compute the slip force all along the slip surface, and the vector sum of the forces will be the slip direction.

Compute the potential resistance force all along the slip surface base on the failure criteria, project to slip direction, then get the FOS.

![Fig. 1 Concept of Vector Sum Method](image)

3. Orthogonal experiment on parameters sensitivity analysis

3.1. Orthogonal experiment design

We use orthogonal experiment [7] to study the impact of underground excavation to slope stability. The analysis model is a two-dimension homogeneous slope model with a circle excavation area, whose diameter labeled as $D$. In order to build some physical models in a two-dimension slope model experiment rig to verify the compute results, so the size of the analysis model are quite small.

Seven factors and three levels are chosen in the orthogonal experiment, the factors and levels are shown in table 1. The height, the gradient, the cohesion and the friction angle are the internal factor of a slope stability. The relative position of a excavation area and a slip surface, the distance from slip surface to the excavation area, the diameter of excavation area are external factors. The experiment design is shown in Table 2.

| Number | Factors Description | Level 0 | Level 1 | Level 2 |
|--------|---------------------|---------|---------|---------|
| 1      | Height of the slope | 650 mm  | 700 mm  | 750 mm  |
| 2      | Gradient of the slope | 1:1.07 | 1:0.84  | 1:0.67  |
| 3      | Cohesion            | 6 kPa   | 8 kPa   | 10 kPa  |
| 4      | Friction angle      | 24.9°   | 31.8°   | 37.78°  |
| 5      | Relative position ($\angle ACO$) | 0.25° $\angle ACB$ | 0.5° $\angle ACB$ | 0.7° $\angle ACB$ |
| 6      | Distance to the slip surface | 0.5° $D$ | $D$ | 1.5° $D$ |
| 7      | Diameter of excavation area ($D$) | 50mm | 65mm | 80mm |
**Fig. 2** Concept graph of orthogonal experiment

**Table 2. Orthogonal Experiment Table**

| NO. | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 | Factor 6 | Factor 7 |
|-----|----------|----------|----------|----------|----------|----------|----------|
| 1   | 0        | 0        | 0        | 0        | 0        | 0        | 0        |
| 2   | 0        | 0        | 0        | 1        | 1        | 1        | 2        |
| 3   | 0        | 0        | 0        | 2        | 2        | 2        | 1        |
| 4   | 0        | 1        | 2        | 0        | 1        | 2        | 0        |
| 5   | 0        | 1        | 2        | 1        | 2        | 0        | 2        |
| 6   | 0        | 1        | 2        | 2        | 0        | 1        | 1        |
| 7   | 0        | 2        | 1        | 0        | 2        | 1        | 0        |
| 8   | 0        | 2        | 1        | 1        | 0        | 2        | 2        |
| 9   | 0        | 2        | 1        | 2        | 1        | 0        | 1        |
| 10  | 1        | 0        | 2        | 0        | 2        | 1        | 2        |
| 11  | 1        | 0        | 2        | 1        | 0        | 2        | 1        |
| 12  | 1        | 0        | 2        | 2        | 1        | 0        | 0        |
| 13  | 1        | 1        | 1        | 0        | 0        | 0        | 2        |
| 14  | 1        | 1        | 1        | 1        | 1        | 1        | 1        |
| 15  | 1        | 1        | 1        | 2        | 2        | 2        | 0        |
| 16  | 1        | 2        | 0        | 0        | 1        | 2        | 2        |
| 17  | 1        | 2        | 0        | 1        | 2        | 0        | 1        |
| 18  | 1        | 2        | 0        | 2        | 0        | 1        | 0        |
| 19  | 2        | 0        | 1        | 0        | 1        | 2        | 1        |
| 20  | 2        | 0        | 1        | 1        | 2        | 0        | 0        |
| 21  | 2        | 0        | 1        | 2        | 0        | 1        | 2        |
| 22  | 2        | 1        | 0        | 0        | 2        | 1        | 1        |
| 23  | 2        | 1        | 0        | 1        | 0        | 2        | 0        |
| 24  | 2        | 1        | 0        | 2        | 1        | 0        | 2        |
| 25  | 2        | 2        | 0        | 0        | 0        | 0        | 1        |
| 26  | 2        | 2        | 0        | 0        | 0        | 1        | 2        |
| 27  | 2        | 2        | 2        | 2        | 2        | 2        | 2        |
Before the experiment, use LEM to get the slip surfaces of the 27-slope model, which will be used in VSM to compute the FOS before and after excavation. To verify the slip surfaces, some of the slope models are chosen, and build real physical slope models. We compared the slip surface of LEM and real physical model, results show that this two slip surfaces are fit each other, so the LEM slip surfaces can be used as the input of the VSM.

![Fig. 3 Real slip surface of a physical model and corresponding slip surface of LEM](image)

**3.2. Analysis on the VSM FOS change and parameters sensitivity analysis**

The changes of VSM FOS are shown in Table 3. The rate of change are between 0.15% and 21.28%, the largest change appear at experiment No.21, and the smallest change belongs to experiment No.27, as shown in figure 4

**Table 3. VSM FOS changes**

| NO. of experiments | VSM FOS Before excavation | VSM FOS After excavation | Rate of change | NO. of experiments | VSM FOS Before excavation | VSM FOS After excavation | Rate of change |
|--------------------|---------------------------|--------------------------|----------------|--------------------|---------------------------|--------------------------|----------------|
| 1                  | 0.895                     | 0.874                    | 2.35%          | 15                 | 1.324                     | 1.313                    | 0.83%          |
| 2                  | 1.098                     | 1.076                    | 2.00%          | 16                 | 0.964                     | 0.959                    | 0.62%          |
| 3                  | 1.226                     | 1.229                    | 0.33%          | 17                 | 0.954                     | 0.967                    | 1.47%          |
| 4                  | 1.161                     | 1.138                    | 1.98%          | 18                 | 1.063                     | 1.072                    | 0.85%          |
| 5                  | 1.304                     | 1.297                    | 0.54%          | 19                 | 1.132                     | 1.044                    | 7.77%          |
| 6                  | 1.462                     | 1.447                    | 1.03%          | 20                 | 1.305                     | 1.224                    | 6.21%          |
| 7                  | 0.922                     | 0.940                    | 1.95%          | 21                 | 1.471                     | 1.157                    | 21.28%         |
| 8                  | 1.054                     | 1.069                    | 1.42%          | 22                 | 0.923                     | 0.926                    | 0.33%          |
| 9                  | 1.193                     | 1.221                    | 2.26%          | 23                 | 1.037                     | 0.989                    | 4.63%          |
| 10                 | 1.259                     | 1.199                    | 4.77%          | 24                 | 1.194                     | 1.171                    | 1.93%          |
| 11                 | 1.455                     | 1.302                    | 10.45%         | 25                 | 1.070                     | 1.037                    | 3.08%          |
| 12                 | 1.642                     | 1.549                    | 5.72%          | 26                 | 1.221                     | 1.217                    | 0.33%          |
| 13                 | 1.009                     | 0.931                    | 7.73%          | 27                 | 1.367                     | 1.365                    | 0.15%          |
| 14                 | 1.167                     | 1.155                    | 0.94%          |                     |                           |                           |                |
The result of range analysis on the FOS change are shown in table 4 and figure 5, from largest influence to smallest influence on the FOS change, the 7 factors are sorted as follow: the gradient, the relative position, the cohesion, the height, the diameter of excavation area, the friction angle, the distance to slip surface.

As shown in figure 5, the relationship between the change of FOS and the following factors are quite simple: the height, the gradient, the relative position, the diameter of excavation area. The higher the slope is, the larger the diameter of excavation area is, the larger the FOS changes. The larger the gradient is, the closer the excavation area to the bottom of the slip surface is, the smaller the FOS changes.

| Number | Factors Description | Meaning value (level 0) | Meaning value (level 1) | Meaning value (level 2) | Range |
|--------|----------------------|-------------------------|-------------------------|-------------------------|-------|
| 1      | Height of the slope  | 0.0154                  | 0.0371                  | 0.0508                  | 0.0354 |
| 2      | Gradient of the slope| 0.0676                  | 0.0221                  | 0.0135                  | 0.0542 |
| 3      | Cohesion             | 0.0161                  | 0.0560                  | 0.0312                  | 0.0399 |
| 4      | Friction angle       | 0.0340                  | 0.0311                  | 0.0382                  | 0.0071 |
| 5      | Relative position    | 0.0587                  | 0.0262                  | 0.0184                  | 0.0403 |
| 6      | Distance to the slip surface | 0.0348 | 0.0372 | 0.0313 | 0.0059 |
| 7      | Diameter of excavation area | 0.0276 | 0.0307 | 0.0449 | 0.0173 |

Fig. 4 Rate of VSM FOS change

Fig. 5 relation between the change of FOS and 7 factors
4. Conclusion

Vector sum method (VSM) and orthogonal experiment are used to do parameters sensitivity analysis of underground excavation impacting on slope stability. The result shows that the VSM can be used in this research field, and shows a good prospect in relative geotechnical engineering.

The range analysis shows that the gradient of a slope, the relative position between an excavation area and a slope, the cohesion are the top three factors which impact the stability significantly. The higher the slope is, the larger the diameter of excavation area is, the larger the FOS changes. The larger the gradient is, the closer the excavation area to the bottom of the slip surface is, the smaller the FOS changes.

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