Finite Element Analysis of Overlying Soil Failure Based on Fault Dip Angle

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Abstract. When the strong earthquake occurs, the deformation response and rupture of the overlying soil are very complicated. In this paper, the influence of fault dip angle on the surface deformation and rupture of overlying soil is analyzed by means of finite element numerical simulation. When the vertical dislocation of the fault is about 3~5% of the thickness of the overlying soil layer, the surface rupture occurs only when the fault dip angle is 45°. When the vertical displacement of the fault increases to 10% of the thickness of the overlying soil layer, surface rupture occurs under three working conditions of 45°, 70° and 90° of fault dip angle. With the increase of the dip angle from 45°, 70° to 90°, the surface equivalent strain is gradually smaller, the deformation of the overlying soil is smaller, and the deformation width of the upper wall will change from about 2 times that of the lower wall to the same as the lower wall. The deformation and rupture of the overlying soil first begin with the fracture of the soil mass at the interface between the fault bedrock and the soil. With the increase of the dislocation quantity, the surface also will appear 1 breakpoint when the fault angle is 45° and 70°, the ground surface will appear 2 breakpoints when the fault angle is 90°, and at last overlying soil is broken through.

1. Introduction
Several historical strong earthquake damage phenomena indicate that the destruction of ground surface and the permanent large deformation caused by the earthquake faults make the destruction of the ground buildings, structures and lifeline engineering very serious. In recent years, the research personnel pay attention to the problems about the deformation and fracture of the overlying soil caused by fault dislocation. So the formation and development of overlying soil deformation and fracture caused by fault dislocation can further understand the failure mode of overlying soil and the failure mechanism of the near fault structure.

During the occurrence of strong earthquakes, the deformation and fracture of overlying soil are very complicated. Previous studies show that the deformation process and rupture characteristics of the overlying soil are affected by many factors. On the one hand, it is the factors of soil itself: such as different formation combinations [1], soil layer thickness [2-4], the physical and mechanical properties of different stratum soil and soil composition [5], weak intercalation or hard intercalation [3], etc. The two aspects are earthquake and its seismic fault factors, such as seismic amplitude, frequency spectrum characteristics and duration, seismic fault type, fault dip angles [6], fault displacement [7-8] and other factors. Based on the above research results, it is concluded that the fault dip angle has a great influence on the deformation and fracture of overlying soils, and it is worth further analysis and discussion.
Therefore, on the basis of previous research results, this paper uses finite element numerical simulation method to analyze the influence of fault dip angle on the surface deformation and fracture of the overlying soil layer, and discusses its influence law, which is used to provide reference basis for prediction of permanent deformation of the ground, active fault seismic hazard and risk and the seismic fortification of engineering structure.

2. Calculation Conditions
Using the plane strain finite element method, combined with the nonlinear constitutive relation of the soil, under the condition of fault vertical dislocation of 2m, different overlying soil thickness (60m, 40m, 20m), the influence of dip angle change on the deformation and rupture of the overlying soil layer and and its regularity analysis are analysed by changing fault dip angle. Nine operating conditions are calculated (Table 1).

| Table 1. Calculation condition table |
|-------------------------------------|
| working condition number | overlying soil thickness(m) | fault dip angle(°) | working condition number | overlying soil thickness(m) | fault dip angle(°) | working condition number | overlying soil thickness(m) | fault dip angle(°) |
|---------------------------|----------------------------|------------------|---------------------------|----------------------------|------------------|---------------------------|----------------------------|------------------|
| NO.1                      | 60                         | 45               | NO.4                      | 40                         | 45               | NO.7                      | 20                         | 45               |
| NO.2                      | 60                         | 70               | NO.5                      | 40                         | 70               | NO.8                      | 20                         | 70               |
| NO.3                      | 60                         | 90               | NO.6                      | 40                         | 90               | NO.9                      | 20                         | 90               |

3. Establishment of Finite Element Model

3.1. Basic Assumptions
In the model establishment, it is assumed that: 1 plane strain state; 2 considering the elastoplastic material of rock and rock, all adopting Drucker-Prager yield criterion; 3 the contacts between upper and lower disk of reverse fracture is assumed to be nonlinear contact.

3.2. Determination of Material Model

3.2.1. Original geological model. The observation point of Xiaoyudong Town in Sichuan is taken as the original geological model. It is located in the northwestern edge of the Sichuan Basin, the heart of the Yujiang River. The lithology of the strata exposed on the west side of Xiaoyudong Street Road in the study area are:

Triassic (T3x): mainly argillaceous limestone sandstone with a thickness of 100m-120m.

Quaternary alluvial deposit (QAL+PL): covered in the Xujiahe Formation, with a thickness of 30-40m, consisting of sub-clay, sand and gravel.

According to field survey and comprehensive analysis of relevant literature [9], it is preliminarily determined that the fault dip angle is about 70°.

3.2.2. Determination of material model. In the establishment of bedrock fault and overburden model, considering the nonlinear stress-strain characteristics of rock and soil, the Drucker-Prager elastoplastic model is applied to both bedrock and soil, and the Drucker-Prager yield criterion is followed.

The yield criterion is an approximation of the Mohr-Coulomb criterion to correct the Von Mises yield criterion, which includes an additional term in the Von Mises expression. Its equivalent stress expression is:

\[ \sigma_i = 3\beta \sigma_{\varepsilon} + \left[ \frac{1}{2} \left( \frac{\sigma}{\sigma_{\varepsilon}} \right)^T \left( \frac{\sigma}{\sigma_{\varepsilon}} \right) \right]^{\frac{2}{3}} \]  

(1)
3.2.3 Selection of material calculation parameters. The model bedrock is argillaceous limestone, and there are Quaternary alluvial deposits and residual slopes on the surface. The main reference is to the "Engineering Geology Handbook" and a large number of previous numerical simulation experience. The mechanics parameters of the material is determined by engineering geology analogy method. The parameters are shown in Table 2.

| material Name          | elastic modulus (Mpa) | Poisson's ratio | volumetric weight (KN/m\(^2\)) | cohesion (Mpa) | friction angle (°) |
|------------------------|-----------------------|-----------------|----------------------------------|---------------|-------------------|
| bedrock                | argillaceous limestone| 2.0e4           | 0.2                              | 23            | 0.15              | 30                |
| overlying soil         | Quaternary alluvial deposits | 1.5e2     | 0.35                             | 19            | 2.5e-2            | 15                |

3.3. Determination of Geometric Models

A geometric calculation model is established by taking into account the boundary effects and the amount of calculation. The bottom of the model is 300m wide and the is 20m thick. In the different cases of fault vertical dislocation of 2m and overlying soil layers of 60m, 40m and 20m, fault dip angles are changed by 45°, 70° and 90°; and frictional nonlinear contact is adopted between the upper and lower faults. Taking vertical dislocation of 2m, overlying soil layer of 40m, and fault dip angle of 70° as an example, a geometric model is established and meshed as shown in Fig.1.

3.4. Boundary Conditions And Loading

3.4.1 Boundary conditions. The upper boundary is the surface free surface, without constraint. The left boundary is free and unrestrained; the right boundary is fixed and completely bound; the footwall of bedrock is fixed and completely restrained.

3.4.2. Loading. As the near field of the fault is simulated, the dislocation displacement of bedrock at the A interface of the soil layer is consistent with the fault rupture of bedrock. In different working conditions, certain displacement values in X and Y directions were applied to the upper wall of bedrock in different models, that is, the movement of the reverse fault was simulated through upper and lower dislocation respectively.

4. Preliminary Analysis and Discussion of Finite Element Results

4.1. Finite Element Simulation Results of Deformation and Fracture of Overlying Soil Caused by Fault Dislocation

Taking the model of overlying single soil layer on bedrock of thrust fault, with vertical dislocation of 2m, overlying soil thickness of 40m and fault dip angle of 45 degrees as example, the process and characteristics of overlying soil deformation and fracture caused by fault dislocation are preliminarily analyzed. In this model, the displacement in the X and Y directions (vertical dislocation 2m) is applied to the upper wall of bedrock, so that the upper and lower walls stagger to simulate the movement of thrust faults. Fig.2 (a) and (b) show the deformation cloud map of overlying soil layer and its 4-fold magnification. At the same time, the node horizontal displacement distribution diagram of overburden layer, the node vertical displacement distribution diagram of overburden layer, the node total displacement distribution diagram of overburden layer and the node equivalent strain distribution diagram of overburden layer are respectively drawn as shown in Fig 3-Fig.6 for further comparative analysis.

Through the calculation of a large number of conditions, it can be concluded that the deformation of the overlying soil first will appear in the boundary surface of bedrock and soil, with the increment
of fault dislocation, scaling up of deformation, when the bedrock dislocation value reaches a certain value, the topsoil appear deformation, scaling down, the last through the reach soil (When the surface deformation exceeds 0.02, it is considered that surface rupture can be caused).

Next, through the calculation and comparison of the working conditions of different dip angles, the influence and rule of the variation of fault dip angle on the deformation and fracture of overlying soil are analyzed.

Figure 1. Geometric model and mesh division

![Figure 1](image1.png)

(a) original proportion  
(b) 4-fold magnification

Figure 2. Deformation cloud map of overlying soil

![Figure 2](image2.png)

Figure 3. Horizontal displacement distribution of nodes in overlying soil (2m-40m-45°)

![Figure 3](image3.png)

Figure 4. Vertical displacement distribution of nodes in overlying soil (2m-40m-45°)

![Figure 4](image4.png)

Figure 5. Total displacement distribution of nodes in overlying soil (2m-40m-45°)
Figure 6. The equivalent strain distribution of nodes of overlying soil (2m-40m-45°)

4.2. Influence of Fault Dip Angle on the Deformation of Overlying Soil

4.2.1 Vertical dislocation amount of 2m and overlying soil thickness of 60m. In the case of vertical dislocation of 2m and overlying soil thickness of 60m, fault dip angle is increased in turn to 45°, 70°, 90°. The equivalent strain distribution of the overburden layer under three different working conditions is obtained as shown in Fig.7.

By comparison in Fig.7, it can be obtained:
① Under the condition of the thickness of overlying soil is 60m, when the vertical dislocation of the fault is about 3.3% of the thickness of the overlying soil, the overlying soils are deformed in different degrees under the above three working conditions. Among them, in the operation condition of the fault dip angle is 45°, the surface is in the critical state of rupture, in the working condition of fault dip angle is 70°, 90°, neither the surface rupture occurred.
② As the fault dip angle increases from 45°, 70° to 90°, the surface of the equivalent strain is gradually become smaller, the overlaying soil deformation is smaller, which indicates that the amount of dislocation required for the same deformation is increased.

4.2.2 Vertical dislocation amount of 2m and overlying soil thickness of 40m. In the case of vertical dislocation of 2m and overlying soil thickness of 40m, fault dip angle is increased in turn to 45°, 70°, 90°. The equivalent strain distribution of the overburden layer under three different working conditions is obtained as shown in Fig.8.

By comparison in Fig. 8, it can be obtained:
① Under the condition of the thickness of overlying soil is 40m, when the vertical dislocation of the fault is about 5% of the thickness of the overlying soil, the overlying soils are deformed in different degrees under the above three working conditions. Among them, in the operation condition of the fault dip angle is 45°, surface rupture occurred; in the working condition of fault dip angle is 70°, 90°, no surface rupture occurred, but compared to the operation condition of the overlying soil thickness of 60m, deformation increased obviously.
② As the fault dip angle increases from 45°, 70° to 90°, the surface of the equivalent strain is gradually become smaller, the overlaying soil deformation is smaller, which indicates that the amount of dislocation required for the same deformation is increased.
③ According to the operation condition results which fault dip angle is 45° and 70° (Fig.7, Fig.8), it can be seen: when the fault dip angle is 45°, 70°, first of all, the soil at the interface between the fault bedrock and the soil is fractured, and as the increase of dislocation amount (that is, the overlying soil thickness decreases under same conditions), a rupture point appeared on the surface, and finally formed a transfixion fracture of the overlying soil.
④ According to the results of different dip angle (Fig.7, Fig.8), it can be obtained: as the fault dip angle increases from 45°, 70° to 90°, the deformation width of the upper wall will change from about 2 times of the lower wall to close to the lower wall. When the fault dip angle is 45°, as for the range of the overlying soil deformation, upper wall of fault is greater than the lower wall; when the fault dip angle is 90°, overlaying soil deformation is basic symmetric distribution.
**Figure 7.** Comparison of equivalent strain distribution of overlying soil layer under different fault dip angles with 2 m vertical dislocation and 60 m thickness of overlying soil layer

**Figure 8.** Comparison of equivalent strain distribution of overlying soil layer under different fault dip angles with 2 m vertical dislocation and 40 m thickness of overlying soil layer

4.2.3 **Vertical dislocation amount of 2m and overlying soil thickness of 20m.** In the case of vertical dislocation of 2m and overlying soil thickness of 20m, fault dip angle is increased in turn to $45^\circ$, $70^\circ$, 


90 °. The equivalent strain distribution of the overburden layer under three different working conditions is obtained as shown in Fig.9.

By comparison in Fig. 9, it can be obtained:

① Under the condition of the thickness of overlying soil is 20m, when the vertical dislocation of the fault is about 10% of the thickness of the overlying soil, under the above three conditions, surface rupture all occurred.

② As the fault dip angle increases from 45 ° to 90 °, the surface of the equivalent strain is gradually become smaller, the overlaying soil deformation is smaller, which indicates that the amount of dislocation required for the same deformation is increased.

③ As the fault dip angle increases from 45 ° to 90 °, the deformation width of the upper wall will change from about 2 times of the lower wall to close to the lower wall.

④ According to the operation condition results which fault dip angle is 90 °(Fig.7, Fig.8, Fig.9), it can be seen: when the fault dip angle is 90 °, first of all, the soil at the interface between the fault bedrock and the soil is fractured, and as the increase of dislocation amount(that is, the overlaying soil thickness decreases under same conditions), two rupture points appeared on the surface(is different from one rupture point which dip angle is 45 °, 70 °), and finally formed a transfixion fracture of the overlying soil.

![Figure 9](image)

**Figure 9.** Comparison of equivalent strain distribution of overlying soil layer under different fault dip angles with 2m vertical dislocation and 20m thickness of overlying soil layer

5. Conclusions and Recommendations

In the process of strong earthquake, the deformation and fracture of overlying soil are very complicated. The deformation process and fracture characteristics of the overlying soil in the fault of earthquake are affected by the overlying soil thickness, soil property, fault type and fault dip angle. In this paper, the effect of fault dip angle on surface deformation and fracture of overlying soil is analyzed by means of finite element numerical simulation.

① When the amount of vertical fault dislocation is about 3-5% of the thickness of the overlying soil, only in the operation condition of the fault dip angle is 45 °, surface rupture occurred; in the working condition of fault dip angle is 70 °, 90 °, no surface rupture occurred. When the amount of vertical fault dislocation is about 10% of the thickness of the overlying soil, under the above three conditions(fault dip angle is 45°, 70°, 90°), surface rupture all occurred.
② As the fault dip angle increases from 45°, 70° to 90°, the surface of the equivalent strain is gradually become smaller, the overlaying soil deformation is smaller, which indicates that the amount of dislocation required for the same deformation is increased.

③ As the fault dip angle increases from 45°, 70° to 90°, the deformation width of the upper wall will change from about 2 times of the lower wall to close to the lower wall. When the fault dip angle is 45°, as for the range of the overlaying soil deformation, upper wall of fault is greater than the lower wall; when the fault dip angle is 90°, overlaying soil deformation is basic symmetric distribution.

④ The deformation and fracture of overlying soil first begins with the fracture of soil at the interface between fault bedrock and soil. As the increase of dislocation amount (that is, the overlaying soil thickness decreases under same conditions), when the fault dip angle is 45° and 70°, a rupture point appeared on the surface; when the fault dip angle is 90°, two rupture points appeared on the surface, finally a transfixion fracture of the overlying soil is formed.

⑤ This paper is a preliminary study on the influence of fault dip angle on the surface deformation and fracture of overlying soil. In the future, the working condition of fault dip Angle can be increased to further refine the value of influencing factors, so as to further control the critical value of surface rupture.

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