# Rupture characteristics of the overlaying soil with interlayer due to reverse faulting

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**Abstract**

In this paper, the rupture characteristics of the overlaying soil with soft/stiff interlayer were studied by plane-strain finite element method. From the results, it can be shown that the existence of soft layer separates rupture process of the overlaying soil into two phases. The depth of a buried soft interlayer will influence the rupture process and the rupture range of the overlaying soil. The deeply buried soft interlayer would bring about a wider range of surface failure. In addition, the thickness of the soft layer also has effect on the rupture process and rupture range of the overlaying soil. Comparing with the soft interlayer, influence of the stiff interlayer is smaller.

**Key words**: **fault**; **soft interlayer**; **stiff interlayer; overlaying soil**; **finite element method**

# Introduction

A sudden rupture of fault in the crust induces intensive earthquake, and brings about the overlaying soil moving and cracking, and the earth′s surface deforming and rupturing as well. When it crosses the foundations of buildings and the underground structures, the rupture close to the earth′s surface or surface fault would lead to direct destruction to these structures. The study on this problem has been paid more attention in recent years. From Kobe Earthquake, Izimit Earthquake and ChiChi Earthquake, the earthquake phenomena show that the rupture area of the earth’s surface is especially extensive, which results in havoc. We know a little about the response characteristics of the overlaying soil, which mainly comes from investigation reports of some earthquake and is only some qualitative references.

Based on the engineering requisition, the research emphases should be placed on studying the destroyed range and degree of the overlaying soil. The research results were applied to seismic hazard analysis of sites and would play a key role in determining safety keeping-away distance of structures. In the past, the research focuses on the rupture process and state of single homogeneous overlaying soil (Bray *et al*, 1994; Taniyama and Watanabe, 2000; GUO *et al*, 2002). In reality, soil layer is not generally formed by single homogeneous soil. With geological age evolving and nature environment varying, as well as diversified interior and external forces acting, overlaying soil is deposited by different sorts of soil. The rigidity is one of the classification standards of soil. Accordingly, in engineering practice, the shear wave velocity is often used to define the rigidity of soil, where the soft refers to a kind of soil whose shear wave velocity is less than 140 m/s, with low shear strength, high compressibility, small penetrability, and its strength reduced rapidly once being vibrated (HUANG, 1983).

In this paper, the rupture process and characteristics of the overlaying soil with soft/stiff interlayer was studied by plane-strain finite element methods.

## 1 Research method

By classifying, summing up and simplifying the information and the data from engineering geological report of some site and earthquake safety evaluation reports of its area, we established a nonlinear numerical model of overlaying soil with soft interlayer by plane strain finite element method. According to thickness and depth of the soft/stiff interlayer, four kinds of model are established. The model′s detailed data are given in Table 1 and the model′s sketch is shown in Figure 1. The sequence numbers in Table 1 are corresponding to these in Figure 1. The symbol

B'BCC' denotes the soft/stiff interlayer, F is fault rupture point, and the arrow represents the fault dislocating direction in Fig 1.

Table 1  Models of the overlaying soil with soft interlayer

| Models No. | Total thickness/m | Thickness of soft/stiff interlayer/m | Depth of soft interlayer/m |
|---|---|---|---|
| I | 50 | 5 | 30 |
| II | 50 | 2 | 35 |
| III | 50 | 5 | 5 |
| Ⅳ | 50 | 2 | 5 |

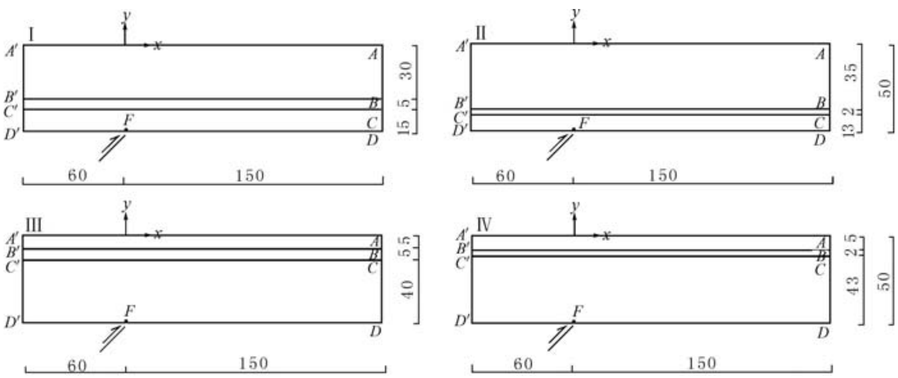


Fig 1  Overlaying soil models

Table 2  Physical parameters of soils

| Physical parameter | | Clay | Sand | Silt |
|---|---|---|---|---|
| Density ρ/ kg | | 1 940 | 2000 | 1 920 |
| Velocity of shear wave $v_S$/m·s$^{-1}$ | | 220.6 | 343.0 | 130.5 |
| Maximum shear modulus $G_{max}$/$10^8$ N·m$^{-2}$ | | 0.944 | 2.353 | 0.327 |
| Possion Ratio $v$ | | 0.3 | 0.3 | 0.4 |
| Mohr-Column criterion | Cohensive force /kN | 43.5 | | 13.0 |
| | Friction angle /(°) | 18.5 | 33.0 | 11.0 |
| Bearing stress $\sigma$/kPa | | 240 | 240 | 74.0 |
| Maximum shear stress $\Gamma_{max}$/Pa | | 123 800 | 155858 | 27 384 |

*F* is fault rupture point, and the arrows represent the fault dislocating direction in Figure 1. The thickness of the overlaying soil is 50 m, the soft interlayer is silt and the stiff is sand, whose thickness is 5 m and 2 m. The containing soil is clay. Their physical parameters are presented in Table 2.

Geological researches show that for reverse fault dislocating, the failure mainly occurs at footwall side, and the influence region is relatively extensive (GUO *et al*, 2002). To avoid influence of boundary constraints to compute precision, the length of the footwall side FD is lengthened, and determined by analyzing equivalent stress nephogram. The simulated type of the fault is reverse faulting. The length ratio of FD and D′F is 2.5, the footwall side FD is 150 m, and the overhanging side D′F is 60 m. Using pseudo-dynamic method, by giving D′F a with displacement and confining dip-slip angle (45° and 60°), the rupture process of the overlaying soil is analyzed.

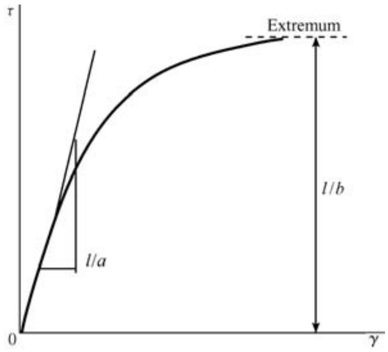


Fig 2 Soil stress~strain relation

The 1 m×1 m iso-parametric quadrilateral element is used in the finite element model. The soil stress-strain relation is hyperbola model (LI, 1993).

$$\tau = \frac{\gamma}{a + b\gamma} \qquad (1)$$

Where both $a$ and $b$ are parameters from the soil test, and are related to property of the soil. And $a=1/G_{max}$, $b=1/\tau_{max}$, where $G_{max}$ is the maximum shear modulus, *i.e.*, $G_{max} = \rho v_S^2$, with $\rho$, $v_S$ being the soil density and shear velocity respectively, and $\tau_{max}$ denotes the maximum shear strength, determined by Mohr-Column Formula.

The most widely used failure criterion in the engineering is applied: When the soil strain is up to 0.03~0.05 m, the load undergone by the soil reaches to its extremum and does not increase. Henceforth, the strain still goes on increasing, while the stress invariable. The soil element is failure when the strain is up to 0.03 m in this paper.

## 2 Conclusions

Having processed and analyzed the models, we find that the rupture process of the overlaying soil with sand interlayer is similar to the single homogeneous overlaying clay, the influence of the stiff can be ignored. The result are shown in Table 4. And using the same method, we analyze the rupture state of the single homogeneous overlaying clay. The result are shown in Table 3. But the process of that with the soft cannot be ignored. The process can be separated into two phases. For the convenience to explain the rupture process, we take advantage of Von Mises equivalent strain nephogram of the following two examples: for the first, overlaying soil with 2 m soft interlayer at the depth of 35 m; for the second, overlaying soil with 2 m soft interlayer at the depth of 5 m soft. The dip-slip angle of the bedrock fault is the same 60°.

Table 3 Results of single homogeneous overlaying clay

| Model | Dip-slip angle/(°) | Vertical dislocation when running through soil/m | Failure area of the earth′s surface/m |
|---|---|---|---|
| 50 m clay | 45 | 0.938 | 14.0 |
| | 60 | 1.100 | 14.0 |

Table 4 Results of overlaying soil with stiff interlayer

| Model No. | Dip-slip angle/(°) | Vertical dislocation when running through soil/m | Failure area of the earth′s surface/m |
|---|---|---|---|
| I | 45 | 1.074 | 15.0 |
| | 60 | 1.161 | 13.0 |
| II | 45 | 1.024 | 15.5 |
| | 60 | 1.128 | 14.0 |
| III | 45 | 1.011 | 14.5 |
| | 60 | 1.128 | 13.5 |
| IV | 45 | 0.956 | 15.0 |
| | 60 | 1.203 | 15.0 |

The first phase: Rupture runs through the soil under soft interlayer. With bedrock dislocation increasing, the soil under soft interlayer begins rupture, but the rupture trend is not always upward. However, the rupture starts from the bedrock and extends upward, when the rupture thickness is up to about 80% of the underside soil, the soil abutting on bottom of the soft layer appears rupture point, and then the point becomes a new rupture source. With dislocation increasing, the new rupture extends downward, and the original rupture extends upward. The first phase is finished when rupture runs through the underside soil. It can be seen from Figures 3 and 4 the depth of the soft interlayer has not effects on the rupture mode of the first phase.

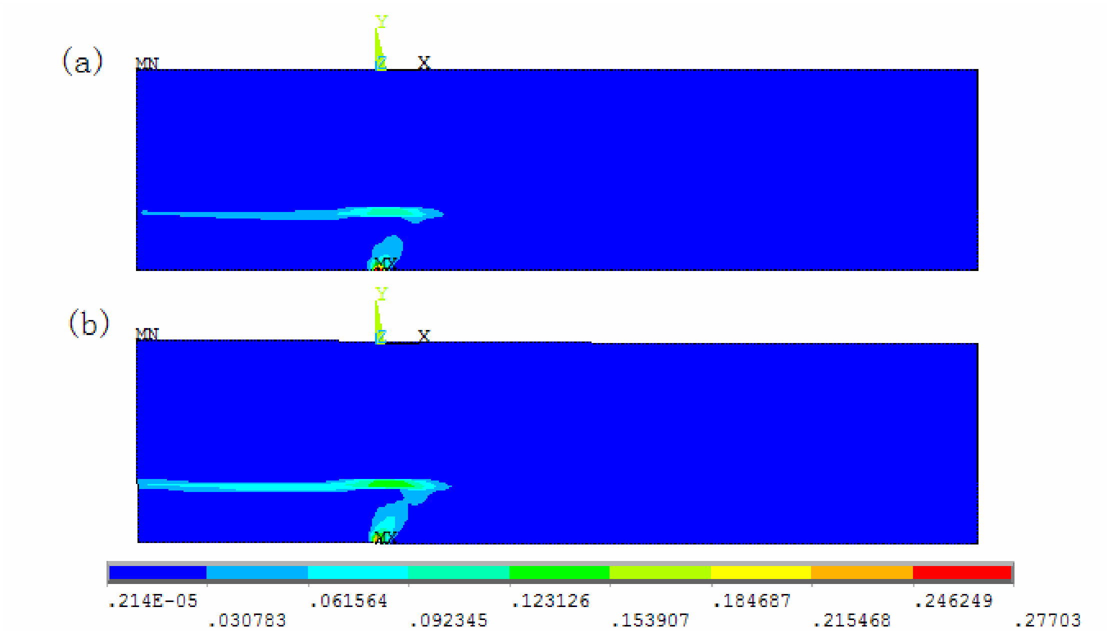


**Fig 3  The first rupture phase of the overlaying soil with thickness 2*m*, depth 35*m* soft interlayer**

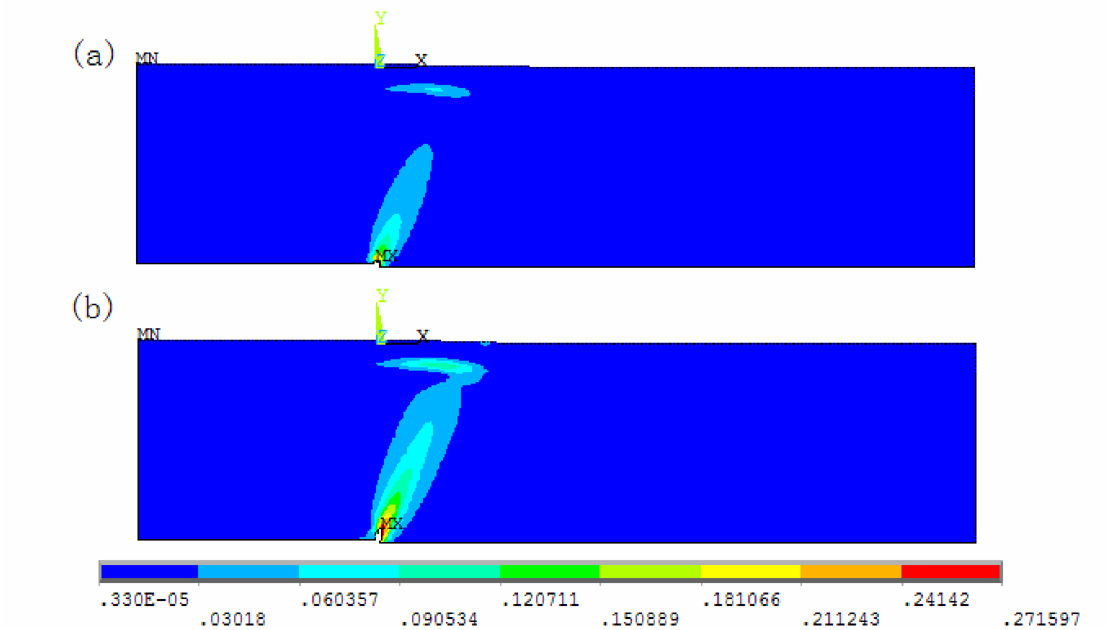


**Fig 4  The first rupture phase of the overlaying soil with thickness 2*m*, depth 5*m* soft interlayer**

The second phase: Rupture starts from soil on the soft interlayer, and then runs through the whole overlaying soil. With the depth of the soft interlayer changing, the rupture modes of the second phase take on two modes. The first mode: When the soft interlayer is buried shallowly, nearly at the same time of rupture runs through the underside soil, the earth′s surface appears rupture point, and it becomes a new rupture source, which extends downward. In the final, the rupture runs through the whole soil (Fig 5). The second mode: When the soft interlayer is buried deeply, the first rupture point appears at the low middle of the upper soil layer. It is a new rupture source at the upper soil. With the dislocation increasing, this rupture extends to the circumjacent soil like extensible stress bubble in soil mechanics. Soon after this, the earth’s surface appears a rupture point, and it becomes the second rupture source. With the dislocation increasing, rupture runs through the whole soil layer finally (Fig 6), The parts without color in the figures denote that the soil deformation is beyond the legend's scope) The whole rupture course shows strong rheology of the soft interlayer. The results of the above-mentioned models are in Table 5.

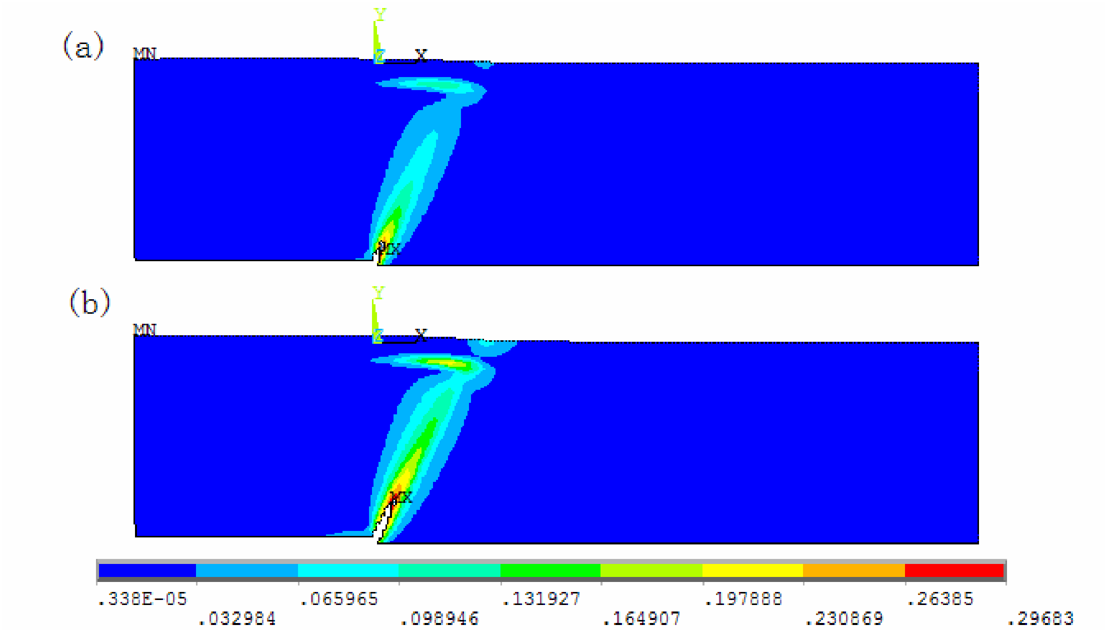


**Fig 5 The second rupture phase of the overlaying soil with thickness 2*m*, depth 5*m* soft interlayer**

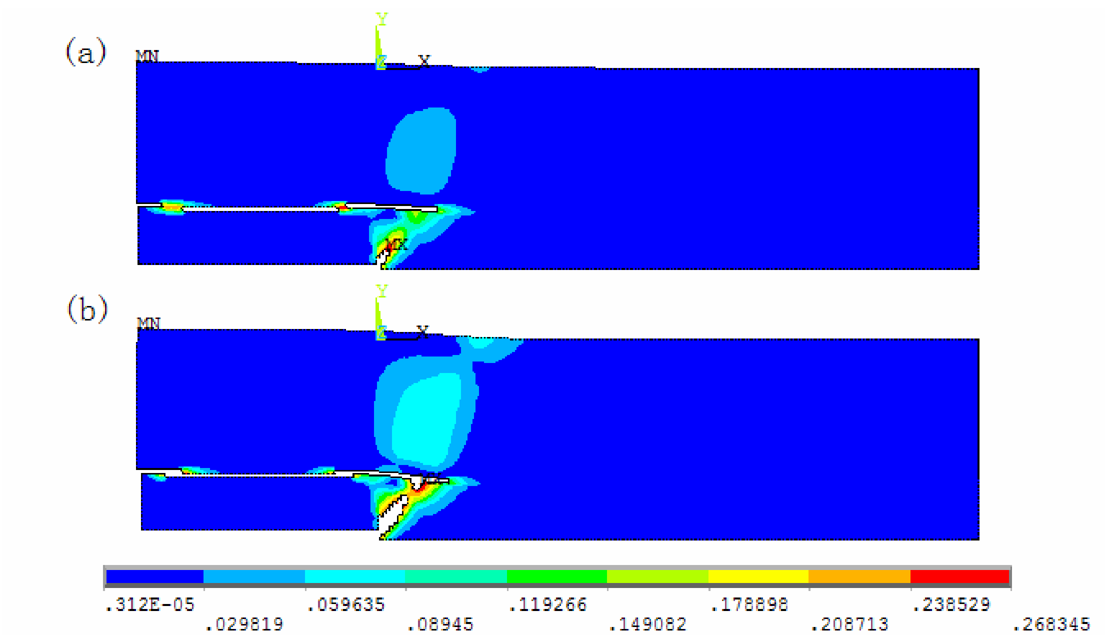


**Fig 6 The second rupture phase of the overlaying soil with thickness 2*m*, depth 35*m* soft interlayer**

Table 5 Results of overlaying soil with soft interlayer

| Model No. | Dip-slip angle/(°) | Vertical dislocation when running through soil/m | Failure area of the earth's surface/m |
|---|---|---|---|
| I | 45 | 2.500 | 21.0 |
| | 60 | 3.200 | 23.5 |
| II | 45 | 2.500 | 20.3 |
| | 60 | 2.500 | 19.5 |
| III | 45 | 1.275 | 13.0 |
| | 60 | 1.481 | 12.5 |
| IV | 45 | 1.247 | 14.0 |
| | 60 | 1.557 | 13.0 |

Comparing Table 3 with Table 5, the conclusions are summarized as follows:

1) To some extent, soft interlayer can obstruct or delay rupture of the overlaying soil. It can be seen from the column of vertical dislocation in Tables 3 and 4. Both the thickness and the depth of the soft interlayer could have effects on the rupture. The deeper and thicker the soft is, the more distinct obstructing action becomes. But the action of the thickness is less than that of the depth.

2) The soft interlayer buried deeply will bring about a wider range rupture of the earth′s surface and the shallow earth′s surface. If buried shallowly, the failure range is approximately equal to the range of the single homogeneous.

3) Thickness of the soft interlayer may affect the failure range of the earth′s surface. Buried deeply, the thicker soft bring about a wider failure range. Buried shallowly, the failure range is similar.

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# Reference

Bathe K J and Wilson E L. LIN Gong-yu and LUO En trans. 1985. *Numerical Method in Finite Element Analysis* [M]. Beijing: China Machine Press, 126~166.

Bray J D, Seed R B, Chang W S, *et al*. 1994. Analysis of earthquake fault rupture propagation through cohensive soil [J]. *Journal of Geotechnical Engineering*, *ASCE*, **120**(3): 562~580.

Bray J D, Seed R B, Chang W S, *et al*. 1994. Earthquake fault rupture propagation through soil [J]. *Journal of Geotechnical Engineering*, *ASCE*, **120**(3): 543~561.

GUO En-dong, SHAO Guang-biao, BO Jing-shan, *et al*. 2002 A method for earthquake rupture analysis of overlaying soil site [J]. *Earthquake Engineering and Engineering Vibration*, **22**(5): 122~126 (in Chinese).

HUANG Wen-xi. 1983. *Engineering Properties of Soil* [M]. Beijing: China Water and Electric Press, 321~334 (in Chinese).

LI Jie. 2005. *Lifelines Engineering Aseismic* [M]. Beijing: Science Press, 50~59 (in Chinese).

LI Xiao-jun. 1993. Study on the method for analyzing the earthquake response of nonlinear site [D] [Ph Dissertation]. Harbin: Institute of Mechanics, China Earthquake Administration, 112~126 (in Chinese).

LIU Shou-hua, DONG Jin-cheng, XU Guang-ming, *et al*. 2005. Influence on different overburden soils due to bedrock facture [J]. *Chinese Journal of Rock Mechanics and Engineering*, **24**(11): 1 868~1 873 (in Chinese).