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Probabilistic hazard assessment of fault displacement under reverse fault considering effects of overlying soil layers

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Abstract

In modern constructions crossing a fault is inevitable for lifeline and infrastructure projects such as oil or gas pipelines, highway bridges, and tunnels. It is crucial to provide a reliable estimate of surface fault rupture displacement for their structural design or assessment. Generally, the method of probabilistic fault displacement hazard assessment (PFDHA) is applied to quantify the hazard. The prediction equations involved in the conditional PFDHA simply connect the surface fault displacement and earthquake magnitude without considering subsurface soil condition at the site. However, the overlying soil condition at site may significant affect surface rupture propagated from the bedrock dislocation. In this study, a numerical modelling is first developed to estimate surface rupture under the effects of overlying soils on the bedrock. A methodology of PFDHA is then proposed to evaluate the fault displacement hazard under reverse fault with the consideration of effect factors of overlying soils including the soil properties, thickness etc. Finally, an example is given to show the application of the proposed methodology.

Keywords: Probabilistic fault displacements hazard assessment; reverse fault; overlying soil effects.

1.Introduction

As a very destructive natural disaster, earthquakes will induce not only extensively dynamic ground motions, but also large permanent displacement(dislocations) near the surface at the fault, generally called fault displacement [1-2]. The latter has potential to cause severe damages to lifeline structures and infrastructures (such as tunnels, oil and gas pipelines, etc.) at the fault crossing location. Therefore, it is necessary to provide a reliable estimate of surface fault rupture displacement for their structural design or assessment.

Many studies have been conducted on the fault surface rupture, mainly including the following three methods. The first one is statistical method, in which statistical regression is adopted on seismic data to establish empirical relations between seismicity parameters such as moment magnitude and fault characteristics including surface rupture length, rupture width, rupture area and maximum surface displacement, etc.) [3-8]. The second one is the model test method in which testing equipment, such as shaking tables and centrifuge shakers, is used to study the failure pattern of overlying soil due to the fault movement, and to obtain the macroscopic rule of the surface rupture [9-14]. Numerical simulation is the third method. In this method, based on the finite element, finite difference and other computational theories, geological structures, ground motions and rock and soil mass are modelled to analyse the seismic response of overlying soil mass caused by fault dislocations [10-11,15-18]. Although the model test method can obtain scientific and reasonable results, the requirements to data acquisition and observation are very high along with a high cost. However, the numerical simulation method can simplify and model various sophisticated states of soil under fault induced dislocation with a low cost. It is conducive to study the rule of surface rupture and estimate the values of surface fault displacement under strong earthquakes. Therefore, this paper uses numerical simulation method to estimate the surface fault displacement.

Based on the conventional probabilistic seismic hazard analysis method (PSHA), Youngs et al. [19] proposed the probabilistic fault displacement hazard analysis (PFDHA) for the first time in the Yucca mountain nuclear waste disposal repository project. The method was used to calculate the annual probability of the fault displacement exceeding a given value. It can not only mitigate the limitation of deterministic method, but also consider comprehensive influences of the magnitude and the distance on seismic hazard analysis. After that, other researchers [20-22] have proposed various equations and methods to predict the surface rupture displacement and hazard for different types of faulting based on the framework of this methodology. For example, Moss and Ross [20] proposed the probabilistic fault displacement hazard analysis for reverse. In these conditional PFDHA methods, the prediction equations involved simply connect the surface fault displacement to earthquake magnitudes without considering subsurface soil condition at the site. However, the overlying soil condition at site may significantly affect surface rupture propagated from the bedrock dislocation.

Therefore, in this study we first establish the analysis models with finite element software ABAQUS to estimate surface rupture under the effects of overlying soils on the bedrock. We then test the rationality of the proposed models by comparing their results to the existing experimental data. And various scenarios with different factors, such as overlying soil thickness, fault dip angle and bedrock displacement are designed and computed. Furthermore, we developed the empirical equations to predict the surface rupture displacement under reverse fault based on and the bedrock displacement (dislocation) and these factors using regression analysis method. Finally, a methodology of PFDHA is proposed to evaluate the fault displacement hazard with the consideration of effect factors of overlying soils. An example is given to show the application of the proposed methodology in the end.

2 Finite element modelling

2.1 Modelling instructions and assumptions

Finite element software ABAQUS was used for numerical simulation and its implicit module was used for analysis. In order to obtain better simulation results, the influence of large deformations is considered here. In the analysis, the. fault dislocation is considered as a two-dimensional plane strain problem. Considering that the overlying soil and the bedrock is homogeneous or horizontal layered soil mass, the fault plane is a planar and reaches to the lower part of the overlying soil through the bedrock. The quasi-static elastoplastic finite element method is used to simulate the overlying soil deformation caused by bedrock dislocation without considering the reciprocating and the offset rate of the bedrock dislocation. Consequently, the response of the overlying soil when the fault dislocation can be well addressed.

2.2 Model dimension and mesh size

In order to minimize the influence of the accumulated plastic strain at the location of boundary conditions on the meshes around the faulting region, the width of the model should be much larger than the height. As suggested by previous tests, the width of the analysing model was set to be 10 times of the height (i.e., the thickness of the overlying soil layer). In order to ensure the calculation accuracy, the meshing grid should be as fine and regular as possible. Herein, we adopted square plane-strain elements with the side equal to the width*height of the whole model divided by 200.

2.3 Loading and boundary conditions

In this study, the analysis goes two steps: 1) obtain the balance of earth stress; 2) apply boundary displacement to simulate the fault offset. Fig. 1 is the schematic diagram of modelling a bedrock offset. In Fig.1(a), the overlying soil layer is modelled with the finite element, thus the bottom surface of the finite element modelling is the intersection surface of the bedrock and the overlying soil layer. And its plane is assumed to be horizontal. Considering the nonlinear deformation characteristics of the overlying soil layer, it is necessary to first balance the earth stress of the overlying soil in the model to create the initial geostress field and to ensure this field is input into finite element model with a state at which the surface displacement is approaching zero. Thus, gravity loads are applied, and the balance of earth stress is obtained in the Step1.

The boundary conditions of the analysing model are as follows: in Step 1 the displacement in X direction and Y direction is constrained of the left margin of the upper wall and the right margin of the foot wall; and the displacement in Y direction is constrained of the bottom margin of whole model; in Step 2, impose the bedrock displacement on the left and the lower margin of the upper wall, as shown in Fig.1(b); and the changing of fault dip angle is simulated by adjusting the ratio of the horizontal to vertical component of the displacement, while the foot wall remains immovable.

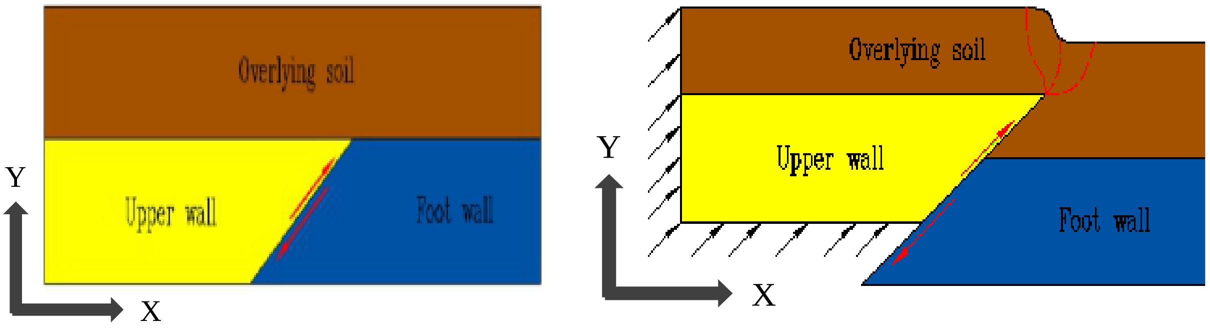

Fig. 1(a)Before the fault movement

Fig. 1(b) After the fault movement

Fig. 1 Schematic diagram of the bedrock movement

2.4 Verification of the numerical analysis model

In order to validate the finite element model in this study, we conducted a trail numerical test and compared its results to those from Baziar et al. centrifuge tests [12]. Baziar et al.[12] conducted centrifuge tests, shown in Fig 2(a). According to the test, a finite element model shown as Fig. 2 (b) is established to simulate the response of the overlying soil mass under the two loading conditions, namely, 2.4 and 4m upward movement (displacement) of the hanging wall along the fault face. The direction of the bedrock displacement is shown by the red arrow shown in Fig. 2 (b).The Mohr-Coulomb model was used to describe the soil constitutive model, and the values for soil parameters are set as follows: density $\rho = 1565\text{kg}/m^3$, elastic modulus $E = 20\text{MPa}$, poisson's ratio $\upsilon = 0.3$, cohesion ratio $c = 500\text{Pa}$, friction angle $\psi = 38°$ and dilation angle $\varphi = 10°$.

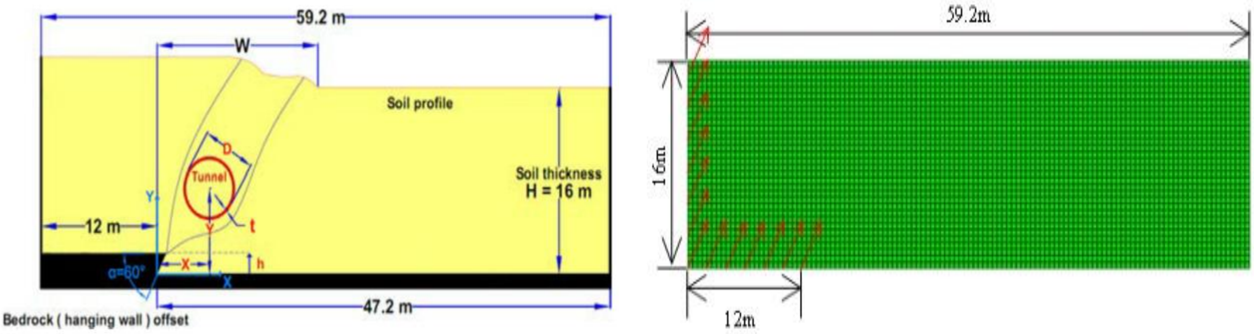

Fig. 2(a) Schematic diagram of test model (produced in the study [12])

Fig. 2(b) Finite element verification model diagram

Fig. 2 Schematic diagram of test model and Finite element verification model

The vertical displacements along horizontal position of the surface under two working conditions resulted from the experiment tests and the numerical simulation analyses in this study are compared in Fig. 3. It is observed that the both displacement curves are consistent with each other, validating the rationality of the numerical model proposed in this study. Therefore, we use the numerical analysis method established above to estimate the surface rupture displacement under the effects of overlying soils on the bedrock.

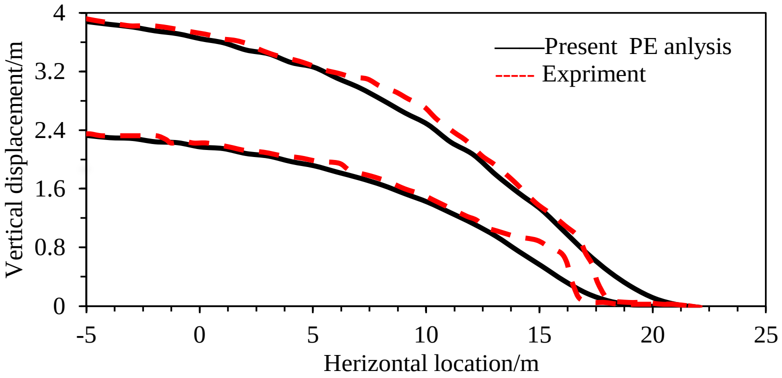

Fig. 3 Comparison curve between verification model and test model

3 Empirical relationship model of surface rupture

Previous studies[9-14] conclude that the rupture, expansion, and deformation of the overlying soil due to fault dislocation are mainly influenced by several main factors, such as faulting type, bedrock dislocation, fault inclination, the thickness and properties of the overlying soil, etc. Therefore, in this study the orthogonal design table based the above factors is used to establish the calculation condition table. In this section, the empirical prediction equations that give the maximum surface fault rupture displacement in terms of three factors (including: bedrock displacement, fault inclination and overlying soil thickness) for sandy overlying soil layer are proposed by regression analyses.

3.1 Numerical simulation experiment design

In order to fully explore the influence of three different factors on the surface rupture caused by fault bedrock dislocation, it is necessary to clarify the range of bedrock dislocation displacement (D), fault inclination (α) and overlying soil thickness (H), so as to facilitate the establishment of numerical analysis modelling. According to a large amount of global seismic data [23]and relevant empirical relationships, bedrock dislocation displacement ranges from 0.5m to 5.5m in the seismic zone of seismic intensity from VIII to X for Chinese codes. In the end, the range of bedrock vertical dislocation quantity (DV) was set to be 0 ~ 6m, considering the simplicity of modelling as well. The fault dip range was set to be 30°~ 80°, comprehensively considering the fact that 1) the low dip angle (≤45°) for the model test is limited by the model size; 2) the high dip angle (≥60°) is more likely to induce a surface rupture caused by bedrock dislocation. In addition, the thickness of overlying soil is set to be 0 ~ 100m according to previous studies [10].

Once the range of the above three factors is settled, it is necessary to select reasonable representative values for them to perform the numerical analyses. In this study, the orthogonal design method is used to select evenly distributed and uniformly representative values for these factors because it can ensure the reliability of regression analysis as well as greatly reduce the number of the modelling analysed. Table 1 gives designed values for three influencing factors under 20 working conditions from N1 to N20. Note that the bedrock dislocation displacement (D) and horizontal displacement (DV) can be calculated by means of vertical displacement (DH) and fault dip Angle (α).

Table 1 values for three influencing factors

Model (No.)	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**	**N10**

DV（m）	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3.0
α（°）	40	50	60	70	80	37.5	47.5	57.5	67.5	77.5
H (m)	20	45	70	95	15	40	65	90	10	35
Model (No.)	**N11**	**N12**	**N13**	**N14**	**N15**	**N16**	**N17**	**N18**	**N19**	**N20**
DV（m）	3.3	3.6	3.9	4.2	4.5	4.8	5.1	5.4	5.7	6.0
α（°）	35	45	55	65	75	32.5	42.5	52.5	62.5	72.5
H (m)	60	85	5	30	55	80	0	25	50	75

In the simulations, Mohr-Coulomb model is adopted as soil constitutive model, as it considers the strong nonlinear effects of soil, the selection of available soil parameters as well as the simplicity of the modelling. For simplicity, only the homogeneous sandy overlying soil layer is considered in this study. The values for soil parameters used for the analysis are shown in Table 2.

Table 2 Design values for soil parameters

Type	**Soil mass (kN/m^3)**	**Modulus of elasticity (MPa)**	**Poisson's ratio**	**Cohesion (kPa)**	**Friction angle (°)**	**Dilation angle (°)**	**Constitutive model**
Sandy soil	16.0	20.0	0.3	0.5	38.0	15.0	M-C

3.2 Analysis results

When the overlying soil is subjected to a thrust of the reverse fault, the surface of the overlying soil may uplift and rupture, resulting in a surface fault rupture displacement. Fig. 4 gives an example showing the displacement of the overlying soil when a reverse fault thrust occurs in the direction of the arrows. Due to the shear deformation of the overlying soil mass, the displacement of the surface soil mass may change dramatically, and the engineering structures underneath to the surface crossing the largest displacement tend to be unsafe due to relatively large displacements. Therefore, in this study the maximum displacement (MD) within 5m around the location of the maximum change per unit length for the surface fault rupture displacement in the analysis model is selected as the research index, which is defined as the surface fault rupture displacements in this study. The calculation results of MD for 20 finite element models are obtained and listed in Table 3.

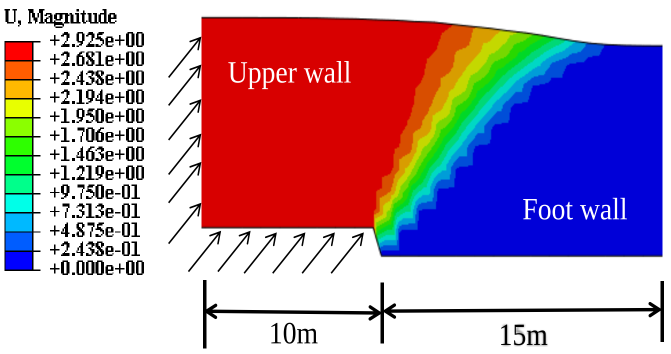

Fig. 4 Surface fault rupture displacement and deformation of the overlying soil for the model N9

Table 3 calculation results (i.e., MD) for 20 working conditions

Model (No.)	D_b(m)	DH(m)	DV(m)	α(°)	H(m)	MD(m)
N1	0.467	0.3	0.358	40	20	0.358
N2	0.783	0.6	0.503	50	45	0.551
N3	1.039	0.9	0.52	60	70	0.751
N4	1.277	1.2	0.437	70	95	0.878
N5	1.523	1.5	0.264	80	15	1.118
N6	2.96	1.8	2.346	37.5	40	1.875
N7	2.848	2.1	1.924	47.5	65	2.091
N8	2.846	2.4	1.529	57.5	90	1.982
N9	2.922	2.7	1.118	67.5	10	2.477
N10	3.073	3	0.665	77.5	35	1.973
N11	5.754	3.3	4.713	35	60	3.752
N12	5.091	3.6	3.6	45	85	3.516
N13	4.761	3.9	2.731	55	5	4.791
N14	4.634	4.2	1.958	65	30	3.285
N15	4.659	4.5	1.206	75	55	4.361
N16	8.933	4.8	7.534	32.5	80	5.735
N17	7.549	5.1	5.566	42.5	0	7.549
N18	6.807	5.4	4.144	52.5	25	5.007
N19	6.426	5.7	2.967	62.5	50	4.539
N20	6.291	6	1.892	72.5	75	5.054

3.3 Empirical prediction model for surface fault rupture displacements

In this section, we establish an empirical prediction model for surface fault rupture displacements under the influence of three factors. Based on the calculation results in Table 3, the empirical relationship between the surface fault rupture displacements (MD) and the amount of bedrock displacement (D), fault dip angle (α), and thickness of overlying soil (H) for the sandy overlying soil layer is obtained by the regression analysis. It is expressed in Eq.(1), for which $R^2 = 0.983$, indicating it has a strong goodness-of-fit, and standard deviation (σ) equals to 0.122, which can be used in the probabilistic hazard analysis.

$$\ln(\mathrm{MD}) = 1.0331 \cdot \ln\,(\mathrm{D}_b) + 0.21927 \sin\alpha - 0.00242H - 0.39345 \tag{1}$$

According to Eq. (1), some general conclusions can be drawn as follows: 1) MD increases with the increase of the bedrock displacement, which is also demonstrated in the study of Ramancharla et al. [13]; 2)

MD decrease with the increase of overlying soil thickness, which is due to the energy absorption effect of the overlying soil layer in the transferring process of the bedrock dislocation; 3) it is demonstrated that the fault dip angle has strong effects on the MD.

4 Probabilistic surface fault rupture displacement hazard analysis

The fault displacement hazard can be assessed in the deterministic and the probabilistic manner. The probabilistic method, known as the probabilistic fault displacement hazard analysis (PFDHA), produces the annual rate that a fault displacement exceeds a given value. PFDHA is generally divided into four parts: 1) identify seismic sources; 2) characterize earthquake frequency and distance distribution; 3) characterize displacement distribution; 4) obtain displacement hazard curves. Based on the existing PFDHA analysis, this study proposes a probabilistic analysis method of the fault displacement hazard considering effects of other factors, such as properties of overlying soil layer, fault dip angle, etc. The evaluation equation is as follows:

$$\gamma(D \geq D_0) = \nu_{min} \int_m \int_{D_b} P[D \geq D_0 | D_b, \boldsymbol{\beta}] f(D_b|m) f(m,s) d_{Db} d_m \qquad (2)$$

Where, $\nu_{\min}$ refers to the amount of earthquakes above an initial magnitude ($m_{\min}$) at the target fault. $f_M(m)$ is the probability density function for an earthquake of magnitude m. $f(D_b|m)$ is the conditional probability density function that the bedrock dislocation (D_b) equals to a certain displacement D_{b0} given an earthquake of magnitude m at source. Note that the D_{b0} herein can be the maximum displacement (offset) along the bedrock or an offset at a certain bedrock location. $P[D \geq D_0 | D_b = D_{b0}]$ is the conditional probability that the surface fault rupture displacement exceeds a level of D_0, given a bedrock displacement D_{b0} and other parameter $\boldsymbol{\beta}$ (such as the faulting type, fault dip angle, and the thickness and properties of the overlying soil layer, etc.

Here in an example of the proposed PFDHA method for the surface fault rupture displacement is presented. We assume a reverse fault with a characteristic magnitude of M_w=7 occurring every 140 years with a truncated distribution within magnitude 7.25±0.25 and standard deviation of 0.125. The empirical model of predicting bedrock displacement proposed by the study of Zhao Ying [24] is used to calculate $f(D_b|m)$. Its expression is given in Eq. (3), through which the maximum displacement (D_b) of bedrocks given a magnitude of a reverse faulting earthquake can be predicted. The empirical prediction of surface fault rupture displacement proposed in this study is used to calculate the $P[D \geq D_0|D_b = D_{b0}, \boldsymbol{\beta}]$, given the bedrock displacement obtained from Eq. (3), soil type of sandy soil, 10m thickness of the overlaying soil layer, reverse faulting type, fault dip angle of 50°. Through Eq.(2), the resulted seismic hazard curves of the surface fault rupture displacement is shown in Fig. 5. One should notice that the curve can change with different impact factors (fault dip angle, properties and thickness of overlaying soil, etc) while that resulted from conditional method will not change with them.

$$\ln(D_b) = 0.876M - 4.984 \qquad \sigma = 0.07351 \qquad (3)$$

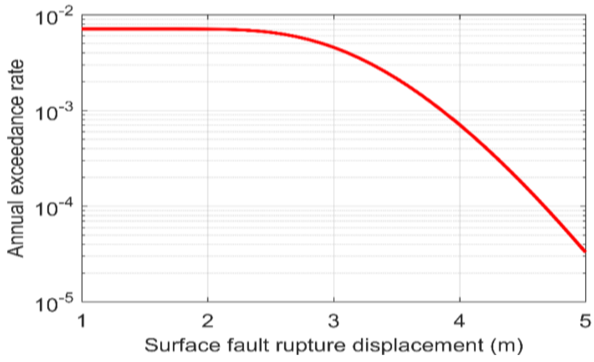

Fig. 5 Seismic hazard curves of surface fault rupture displacement

5 Summary and conclusion

In general, the probabilistic fault displacement hazard assessment (PFDHA) method is applied to quantify the hazard without considering subsurface soil condition at the site. However, the overlying soil condition at site may significant affect surface rupture propagated from the bedrock dislocation. In this study, a methodology is proposed for evaluating the seismic hazard of the surface fault rupture displacement considering various effecting factors such as properties and thickness of overlying soils, fault dip angle, bedrock dislocation, etc. Finite element models developed with software ABAQUS are first validated by comparing their results with those of the existing centrifuge test from literatures. They are then used to estimate surface rupture displacement under the effects of overlying soils on bedrocks based on the orthogonal experimental design. Furthermore, the empirical prediction model is proposed for the surface fault rupture displacement for reverse faulting based on the bedrock dislocation, fault dip angle, and thickness of sandy overlying soil layer. Finally, an example is given to show the application of the proposed methodology. Note that although this study only focuses on the reverse fault with sandy overlaying soil, the framework of the methodology proposed in this study can also be used in other types of faulting and overlying soil, e.g. strike-slip faulting type or clay overlying soil.

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