APPLIED ELEMENT SIMULATION OF NON-LINEAR BEHAVIOR OF DIP-SLIP FAULTS FOR STUDYING GROUND SURFACE DEFORMATION

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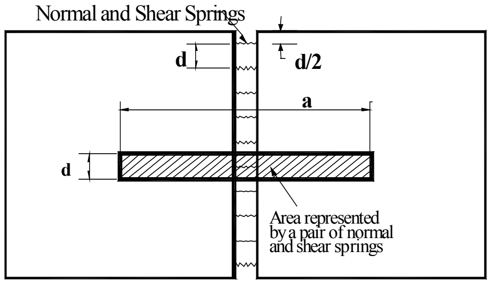
The recent strong earthquakes that have occurred in Turkey (M.7.4, 1999.8.17) and Taiwan (M.7.3, 1999.9.21), evidenced the effect of differential ground displacement on structural failure. Numerous researchers have attempted to study this phenomenon through experiments for understanding the effects of seismic fault mechanism and soil deposit parameters on surface deformation characteristics. However, from the widespread damage caused by the recent events, it is now clear that the earthquakes in different geological regions show drastic variations in their effects such as, large surface upliftment/displacements of unconsolidated soil deposits, commonly lying over the active and potentially active faults. For this reason, we attempted to develop a new application of Applied Element Method (AEM) to study the ground surface deformation near fault rupture zone.

Key Words : *AEM, Applied Element Method, dip-slip faults, surface rupture, upliftment*

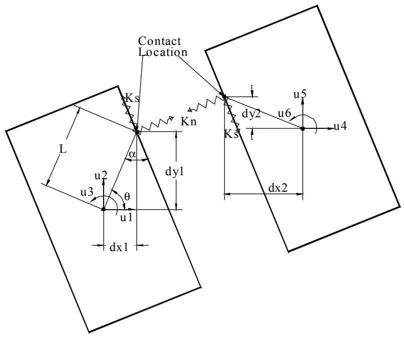
1. INTRODUCTION

Two enormously disastrous earthquakes hit the globe in 1999. The first one was an earthquake of magnitude 7.4 (Mw) occurred in Turkey on 17th August 1999 (JSCE (1999,a)), and immediately following that, another event of magnitude 7.3 (Central Weather Bureau, Taiwan) occurred in Taiwan on 21st September 1999 (see JSCE (1999, b)). Both these events caused immense loss to property and lives. The earthquake fault (North Anatolian Fault) in Turkey was traced over 100 km, and the damage was directly caused by the fault movement. The magnitude of right lateral movement of the fault on the ground surface was measured to be 2 to 4 m. Normal faults, which were caused secondarily, sunk huge area by a depth of 2-3 m. And in Taiwan, severer effects were observed. The earthquake fault (Cher-Lung-Pu fault) was traced for about 80 km, and here also the fault movement directly caused severe damage. The magnitude of maximum vertical differential moovement was measured to be nearly 10.0 m as shown in Fig.1. Though these earthquakes were tragic, also provided us the momentum to the process of improvement in understanding the behaviour of nature. From the above two events, it is clear that the severe damage can be caused not only by the strong ground motion but also due to large surface deformations lying directly over the seismic faults. Hence, it is necessary to direct our efforts to study the relation between seismic fault

Fig. 1. About 10 m vertical displacement is seen at the Shih-Kang dam site, Taiwan



(a) Element formulation in AEM



(b) Spring connectivity

Fig. 2. Element modelling in AEM

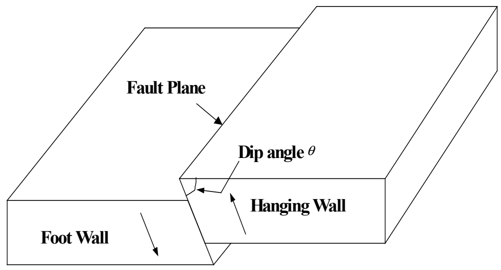


Fig. 3. Fault terminology

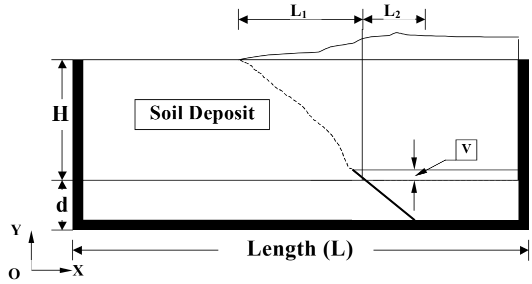


Fig. 4. Fault model

characteristics and resulting surface deformations due to the movement of seismic faults.

Many researchers conducted experiments to understand the phenomena of surface failure, Cole and Lade (1984) have tried to determine the location of surface fault rupture and width of the affected zone in alluvium over dip-slip fault using fault test box. Lade et al. (1984) studied to determine the multiple failure surfaces by conducting the experiments on sand using fault test box. Onizuka et al. (1999) have modelled the deformation of ground using aluminium rods. Through experiments, they investigated bedrock stresses induced by reverse dip-slip faults. Using the above experimental methods, we can find the influence length. However, replicating the actual field conditions using experiments is very difficult, especially, controlling the material properties and modelling the boundary conditions. Moreover, large amount of data is necessary to establish a relationship between seismic fault parameters and resulting surface deformation. On the other hand, studying this phenomenon using numerical model has the advantage of controlling the parameters like material properties, size of the model, boundary condition, dip angle, etc.

2. ELEMENT FORMULATION

Applied Element Method (AEM) (Meguro et al. (1997 and 2000) and Tagel-Din (1998)), which was developed recently as a general method for structural analysis in both small and large deformation ranges has shown good accuracy in predicting the structural behaviour from no loading till the complete collapse. In AEM, the media is modelled as an assembly of small elements which are made by dividing the structure virtually. Two elements shown in Fig. 2 (a) are assumed to be connected by pairs of normal and shear springs set at contact locations which are distributed around element edges. Stresses and strains are defined based on the displacements of the spring end points. Three degrees of freedom are assumed for each element in 2 dimensional model as shown in Fig. 2 (b). By using the advantage of AEM's simplicity in formulation and accuracy in non-linear range, fault rupture zone shown in Fig. 3 is modelled.

The mechanism as shown in Fig. 3 is called Reverse Dip-Slip Faulting. This is one of the types of faults where the hanging wall moves upward relative to the foot wall. If the direction of the movement of the hanging wall is downward then it is called normal faulting. In the study discussed in this paper, both normal and reverse dip-slip faults are considered. To analyse the mechanism of fault rupture zone near dip-slip faults, the model shown in Fig. 4 was prepared. In these numerical model, soil deposit of thickness, H (=140 m), is assumed to be overlay on the bedrock of

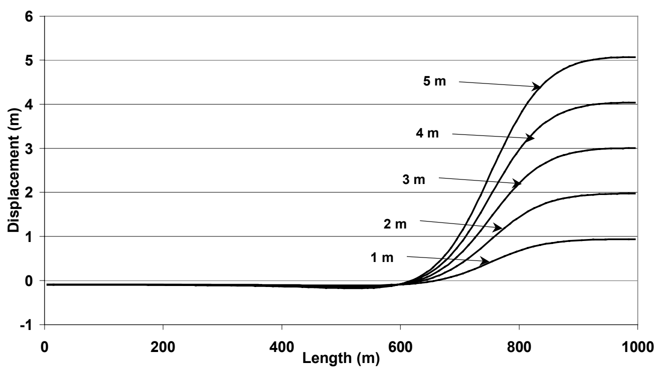


Fig. 5. Surface displacement at each 1-m displacement of hanging wall
(Case 1: elastic analysis, dip angle = 90^0)

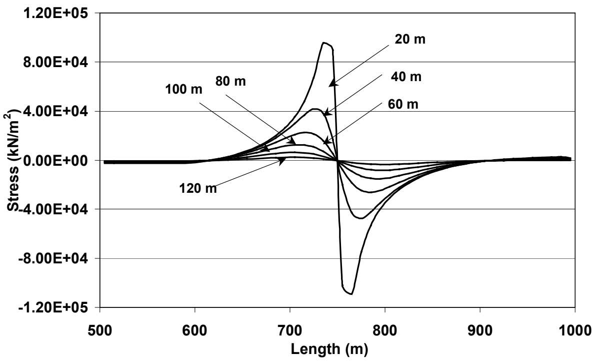


Fig. 6. Stresses in vertical direction in soil deposit at regular intervals (Case 1)

thickness, d (=10 m). The length of the model, L, is assumed as 1,000 m. Influence lengths, L_1 and L_2, in Fig. 4, on the surface towards left and right side of the point exactly above the seismic fault, respectively, are calculated by giving the hanging wall a displacement along the direction of dip angle.

3. BOUNDARY CONDITION

Generally, soil strata and bedrock extend upto tens of kilometres in horizontal direction. Numerical modelling of such a large media is a difficult task and moreover, for studying the surface behaviour near the active fault region, it is necessary to model the small portion of the region which will include all the effects when the bedrock moves. For studying the selected region numerically, we need to assume an appropriate boundary condition such that it will not affect the numerical results greatly. Since the present formulation is done for static case, we assume the boundary on left side to be fixed in horizontal direction, and free to move in vertical direction and can rotate. In order to avoid the interference of boundary condition on numerical results, left side boundary is kept at sufficient distance from the fault zone. The Bottom of the bedrock is assumed as fixed. We think that this kind of boundary condition is appropriate for this problem because more emphasis is given to the near fault behaviour of the formulated model. In case of dynamics, modelling of radiation condition is very important and the boundary condition discussed here can be easily replaced by viscous boundary condition or transmitting boundary (Wolf and Song (1996)).

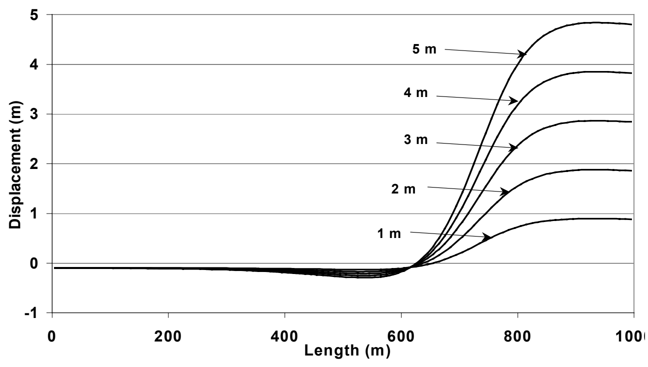


Fig. 7. Surface displacement at each 1-m displacement of hanging wall
(Case 2: elastic analysis, dip angle = 45^0)

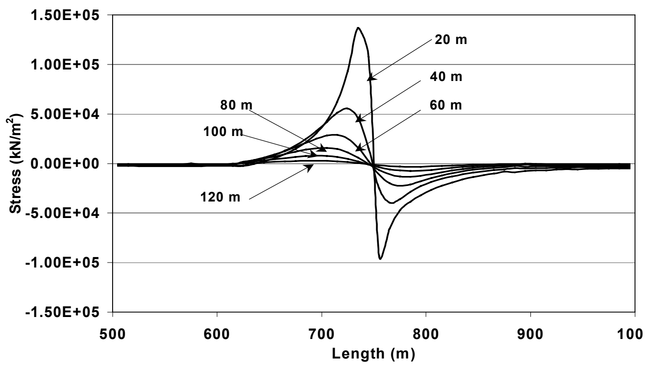


Fig. 8. Stresses in vertical direction in soil deposit at regular intervals (Case 2)

Table 1. Material Properties

	E (kN/m^2)	γ (kN/m^3)
Bedrock	$66x10^6$	26.5
Soil deposit	$20x10^5$	18.0

4. ELASTIC ANALYSIS

To verify the proposed model, analysis is carried out in elastic case by assuming two different dip angles. In Case 1, dip angle is assumed as 90^0 and in Case 2, it is assumed as 45^0. Density and Young's

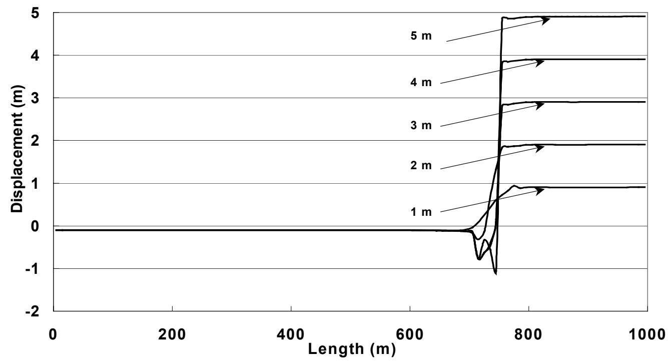


Fig. 9. Surface displacement
(Case 3a: non-linear analysis, dip angle = 90^0 reverse fault)

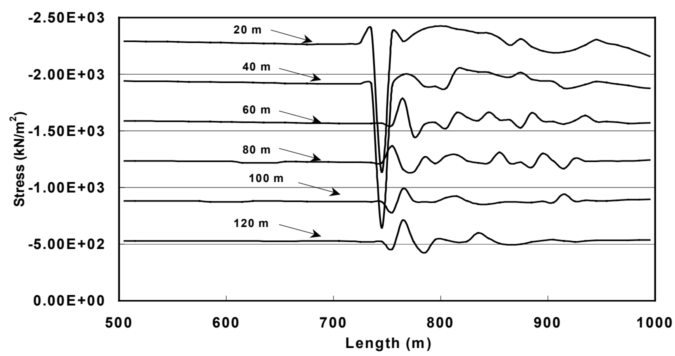


Fig. 10. Stresses in soil deposit (Case 3a)

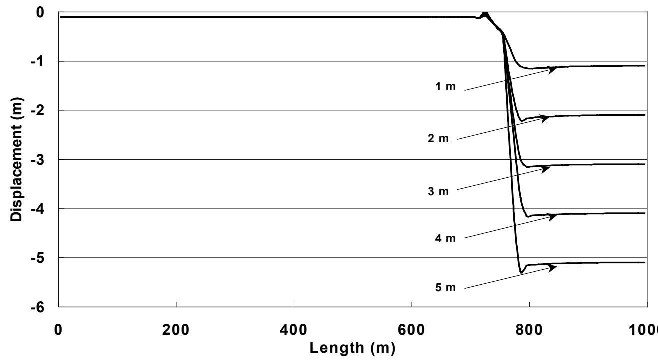


Fig. 11. Surface displacement
(Case 3b: non-linear analysis, dip angle = 90^0 normal fault)

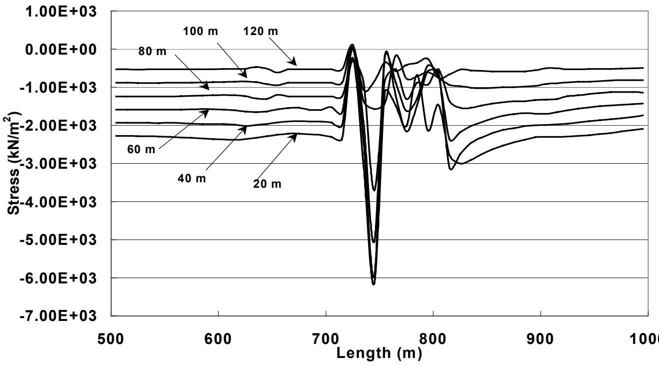


Fig. 12. Stresses in soil deposit (Case 3b)

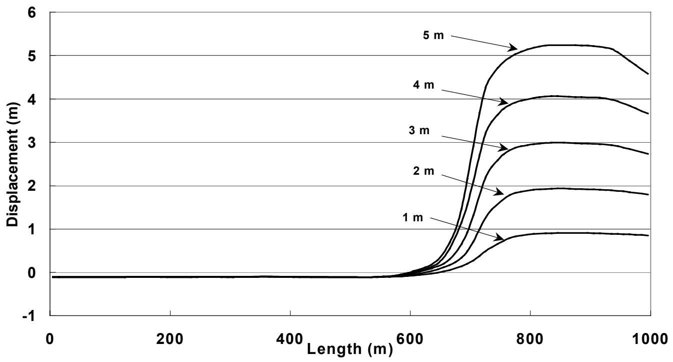


Fig. 13. Surface displacement
(Case 4a: non-linear analysis, dip angle = 90^0 reverse fault)

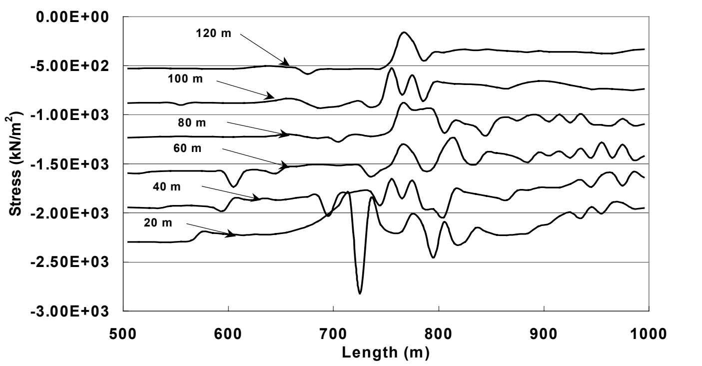


Fig. 14. Stresses in soil deposit (Case 4a)

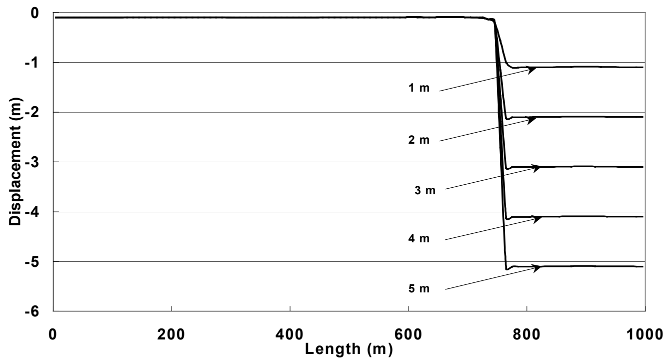


Fig. 15. Surface displacement
(Case 4b: non-linear analysis, dip angle = 90^0 normal fault)

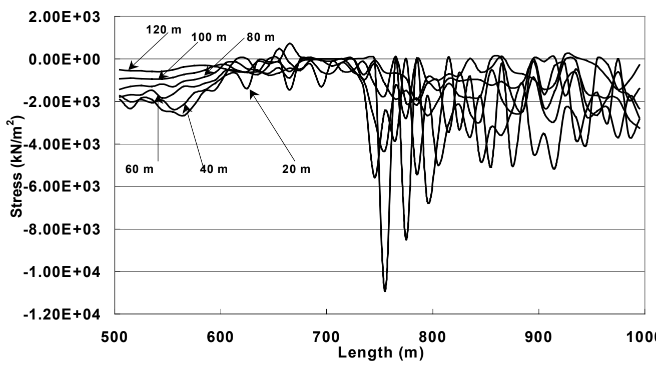


Fig. 16. Stresses in soil deposit (Case 4b)

modulus of bedrock and soil deposit are assumed as shown in Table 1. In Case 1, analysis is carried out by giving a displacement of 5 m to hanging wall in vertical direction. Displacement on the surface is plotted for every 1-m displacement of the hanging wall (Fig. 5). From this figure, it can be understood that the hanging wall portion on the surface is lifted in proportion to the hanging wall displacement. Figure 6 shows stresses in vertical direction taken along the horizontal lines at different depths in soil deposit are plotted. Here stresses show high values near the zone of rupture. As we can see clearly from the figure, that the stresses are reducing when we move near to the surface.

In Case 2, since the dip angle is 45^0, analysis is carried out by giving a displacement of 5 m to hanging wall both in vertical and horizontal directions. This means that the hanging wall is moving along the direction on dip angle. Displacement on the surface is plotted for every 1-m displacement of the hanging wall in horizontal and vertical direction (Fig. 7). From this figure also, it can be understood that the hanging wall portion on the surface is lifted in proportion to the hanging wall displacement. In this figure, we can observe the effect of horizontal movement of hanging wall between 500 m to 600 m. In Fig. 8, stresses in vertical direction taken along the horizontal lines at different heights in soil deposit are plotted. Here also stresses show high values near the zone of rupture. As we can see clearly from the figure, that the stresses are reducing when we move near to the surface.

5. NON-LINEAR ANALYSIS

Analysis is carried out for two cases (Case 3: dip angle = 90 (Figs. 9, 10, 11 and 12) and Case 4: dip angle = 45 (Figs. 13, 14, 15 and 16)). Figures 9, 10, 13 and 14 are drawn for reverse faulting where hanging wall is moving in upward direction and the stresses in the soil deposit are compressive. Figures 11, 12, 15 and 16 are drawn for normal faulting where the hanging wall is moving in down ward direction and the stresses in the soil deposit are tensile. The displacement on the surface is plotted for every 1-m displacement of the hanging wall along the direction of dip angle. Material properties for bedrock and soil deposit in case of non-linear analysis are shown in Table 2. Figures 9 and 10 shows the displacement and internal stresses for dip angle 90 degrees reverse faulting respectively. From the figures, it can be observed that the displacement on the hanging wall side is in proportion to the movement of the hanging wall movement and the effected zone is concentrated near the fault region only. From fig. 10, it can be seen that the stress near the zone of rupture are high and these stresses are reducing when we move towards the surface. Figures

Table 2. Material Properties

	E (kN/m^2)	γ (kN/m^3)	f_c (kN/m^2)	f_t (kN/m^2)
Bedrock	66×10^6	26.5	2.5×10^3	2.5×10^4
Soil deposit	20×10^5	18.0	1.5×10^4	1.5×10^3

11 and 12 are similar to Figs. 9 and 10 respectively except for the movement of hanging wall. In this case, hanging wall is moving in downward direction creating the tensile stresses in the bedrock. From fig. 11 we can easily observe that the influence length is lesser than in the case of reverse faulting. Figure 12 shows the stress distribution at regular intervals in soil deposit. From this figure also it is clear that the stresses are concentrated near the zone of faulting. Figures 13 and 14 are similar to figures 9 and 10 respectively except for the case of dip angle. Due to the change in dip angle the influence length has increased. Figures 15 and 16 are similar to figures 11 and 12 respectively. .

This kind of study is necessary to establish the possible locations of the faults appearing on the surface due to future earthquakes because engineers are more concerned about the damage that might be caused when the structures are located on the vulnerable area. According to seismological point of view, a small difference between the real fault and the expected fault line is acceptable but for the engineers, this difference might be sometimes of a major concern. Moreover, from the recent earthquakes, it was observed that the structures which are located very near to the zone of faulting have survived and the structures which are far have experienced major damage (JSCE (1999, a) and b)). This shows that there is a strong relation between site conditions and the dynamic characteristics of wave motion. Hence it is important to study the surface behaviour based on the local soil conditions and fault characteristics. This kind of study is difficult to perform experimentally because it is difficult to prepare a model similar to actual case. On the other hand, numerical models which can predict the behaviour of the media accurately in small and large deformation range and in non-linear range have the advantage of modelling any kind of soil and flexibility to change the parameters such as strength of soil, thickness of the deposit and dip angle.

6. CONCLUSIONS

A new application of Applied Element Method is proposed in this paper. A dip-slip fault zone is modelled numerically to study the influence of dip angle, bedrock displacement and the thickness of the soil deposit on the length of affected zone. Since this is preliminary model, dynamic aspects such as ground motion, slip rate of fault movement, etc, are not taken into consideration. The boundary condition discussed here can be improved for qualitative discussion since there will be some movement in the horizontal direction along the boundary. Although the discussion done here is for the static case, the method can be extended to dynamic case such as modelling of the unbounded media for studying more realistic phenomenon like wave propagation and dependence on soil parameters.

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