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Non-Linear Modeling of Dip-Slip Faults Using Applied Element Method

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NON-LINEAR MODELING OF DIP-SLIP FAULTS USING APPLIED ELEMENT METHOD

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ABSTRACT

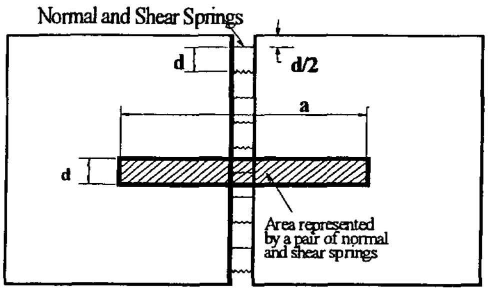
On observing the recent big earthquakes that have occurred in Turkey (M.7.4, 1999.8.17) and Taiwan (M.7.3, 1999.9.21), it is understood that the differential ground displacement is also responsible for the failure of structures. Now, it is understood that there is a need to channelize the research interests to study the failure propagating mechanism through the soil deposit. 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, lying commonly over the active and potentially active faults. Hence, there is a need to develop a numerical model which can give quantitative results to establish a relationship among characteristics of seismic fault rupture, soil parameters and location and area of affected zone. For this reason, we attempted to develop a new application of Applied Element Method (AEM) to study the fault rupture zone.

INTRODUCTION

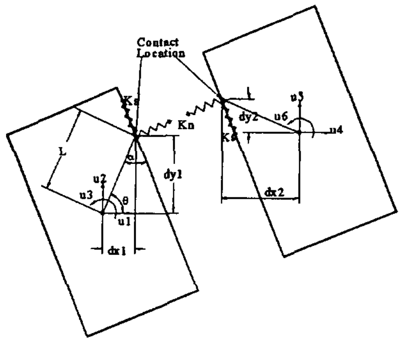
Two enormously disastrous earthquakes hit the globe in 1999. The first one was an earthquake of magnitude 7.4 (Mw) occurred in Turkey on 17th August 1999 (see JSCE (1999,a)), and immediately following that, another event of magnitude 7.3 (Central Weather Bureau, Taiwan) occurred in Taiwan on 21st September 1999 (see JSCE (1999, b)). Both of 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 (see 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 because of strong ground motion but also due to large surface deformations lying directly over seismic fault regions. Hence it is necessary to direct our ideas to study the relation between seismic fault characteristics and resulting surface deformations due to the movement of seismic faults.

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

Many researchers conducted experiments to understand the phenomena of surface failure, Cole and Lade (1984) have studied to determine the location of surface fault rupture



(a) Element formulation in AEM



(b) Spring connectivity

Fig. 2 Element modelling in AEM

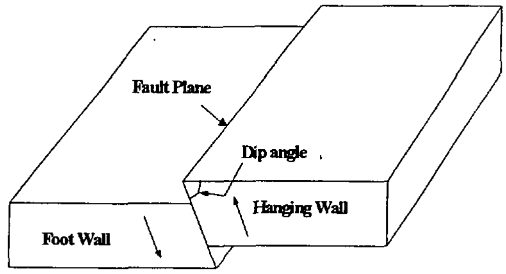


Fig. 3. Fault terminology

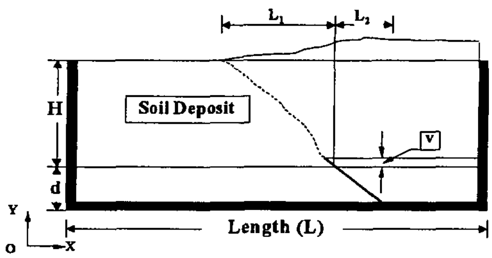
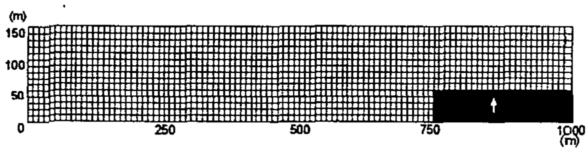
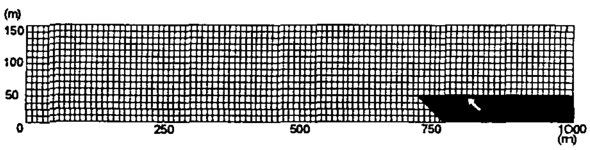


Fig. 4. Fault model



(a) Case 1 and Case 3



(b) Case 2 and Case 4

Fig. 5 Simulation models

and width of the affected zone in alluvium over dip-slip fault using fault test box. Cole 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. They investigated through experiments, bedrock stresses induced by reverse dip-slip faults. From the above experimental methods, we can find the influence length using simple experimental models. However, replicating the actual field conditions using experiments is very difficult, especially, controlling the material properties and modelling the boundary condition. 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 an advantage of controlling the parameters like material properties, size of the model, boundary condition, dip angle, etc.

ELEMENT FORMULATION

Applied Element Method (AEM) (see, 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 (see 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 kinds of faults where hanging wall moves upwards relative to foot wall. In the study discussed in this paper, reverse dip-slip fault is considered. To analyse the mechanism of fault rupture zone near dip-slip faults, the models shown in Fig. 5 are prepared. In these numerical models, soil deposit of thickness, H (=100 m), is assumed to be overlain on the bedrock of thickness, d (= 50 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

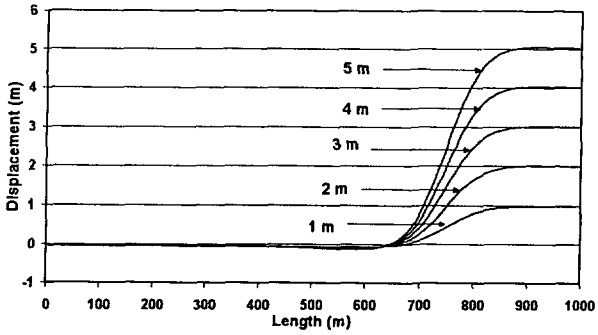


Fig. 6. Surface displacement at each 1-m displacement of hanging wall (Case 1: elastic analysis, dip angle = 90^0)

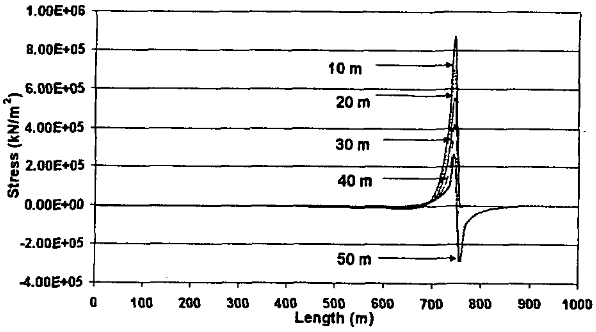


Fig. 7. Stresses in vertical direction in bedrock at regular intervals (Case 1)

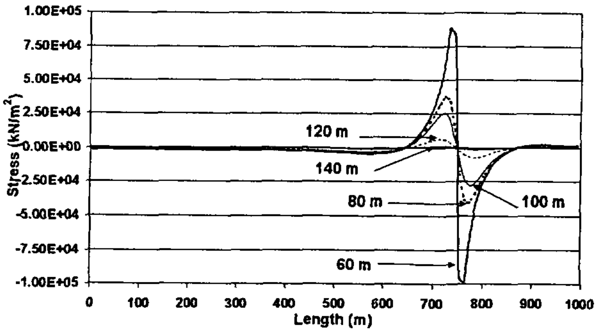


Fig. 8. Stresses in vertical direction in soil deposit at regular intervals (Case 1)

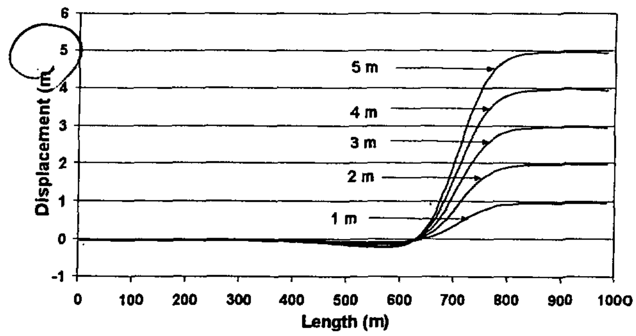


Fig. 9. Surface displacement at each 1-m displacement of hanging wall (Case 2: elastic analysis, dip angle = 45^0)

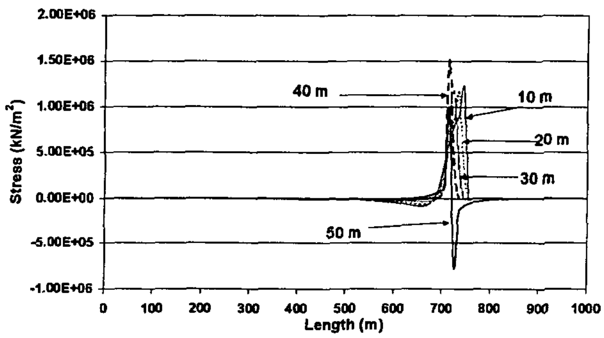


Fig. 10. Stresses in vertical direction in bedrock at regular intervals (Case 2)

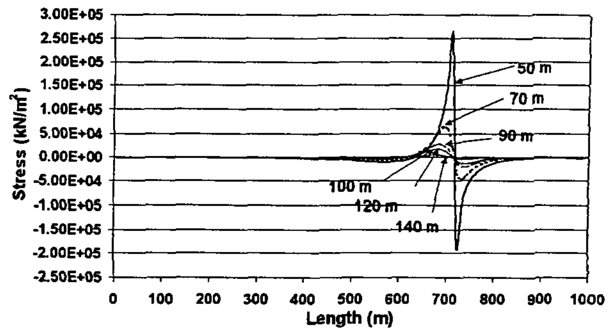


Fig. 11. Stresses in vertical direction in soil deposit at regular intervals (Case 2)

calculated by giving the displacement to the hanging wall along the direction of dip angle.

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 no effect of boundary will 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, 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. Bottom of the bedrock is assumed as fixed. We think that this kind of boundary condition is appropriate here 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 present boundary condition discussed here can be easily replaced by viscous boundary condition or transmitting boundary (see Wolf and Song (1996)).

ELASTIC ANALYSIS

To verify the proposed model, analysis is carried out in elastic case by assuming two different dip angles. In Case

Table 1. Material Properties

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

1, dip angle is assumed as 90^0 and in Case 2, it is assumed as 45^0. Density and Young's 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 (see Fig. 6). From this figure, it can be understood that the hanging wall portion on the surface is lifted in proportion to the hanging wall displacement and around 200 m of length is affected. In Fig. 7, stresses in bedrock at regular intervals of 10 m are plotted. This figure shows that the stresses are high around the location where the rupture is occurring. It can be seen that stresses are increasing as we move from upper layers to lower layer. From this figure, it can also be observed that no stress are developed from 750 m to 1,000 m. This is because the hanging wall portion of bedrock is moving as a whole and there is no relative displacement in it. 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.

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 (see Fig. 9). 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 and around 200 m of length is affected similar to the Case 1. In this figure, we can observe the effect of horizontal movement of hanging wall between 500 m to 600 m. Figure 10 is similar to Fig. 7 in Case 1. It shows stresses in bedrock at regular intervals of 10 m. This figure also shows that the stresses are high around the location where the rupture is occurring. Here we can easily see that the maximum stresses are developed at different points in different layers and this is due to the inclination of rupture surface which is 45 degrees in this case. Here also we can observe that no stresses are developed in the hanging wall. This is because the hanging wall portion of bedrock is moving as a whole and there is no relative displacement in it. In Fig. 11, 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.

NON-LINEAR ANALYSIS

Analysis is carried out for two cases (Case 3: dip angle = 90 (Figs. 12, 13 and 14) and Case 4: dip angle = 45 (Figs. 15, 16 and 17)). 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. Vertical displacement on the surface is shown in

Table 2. Material Properties

	E (kN/m^2)	γ (kN/m^3)	f_c (kN/m^2)	f_t (kN/m^2)
Bedrock	66x10^6	26.5	2.5x10^3	2.5x10^4
Soil deposit	20x10^5	18.0	1.5x10^4	1.5x10^3

Figs. 12 and 15. We can easily observe the difference in vertical displacements due to change in dip angle. It can be seen from the figures that the influence length on the surface is increasing as the displacement of the hanging wall increases. Figures 13 and 16 show the stress along different layers in vertical direction in soil deposit. We can observe in these figures that the stresses are concentrated near the zone of faulting. Figures 14 and 17 show the propagation of the failure surface through the soil deposit. In these figures, we can easily distinguish between the shear failure and the tension failure on the surface. In Case 3, the tension failure is almost vertical but where as in Case 4, the tension failure is inclined.

PARAMETRIC STUDY

A parametric study has been carried out to show the relationship between the bedrock displacement and influence length using two different dip angles (90^0 and 45^0). In both the cases, two different thicknesses of soil deposit are studied, one is 100 m thick and the other is 50 m thick. Figure 18 shows that r_1 ($=L_1/H$) and r_2 ($=L_2/H$) are plotted versus the percentage of bedrock displacement. Displacement of 10 m is given to bedrock and influence length on the surface is calculated both on left side (L_1) and right side (L_2) of the seismic fault. In Fig. 18, the two curves represented by r_1 show the increase in the influence length as the bedrock displacement percentage increases. The lower of these two curves is for thickness 100 m and the upper is for 50 m thickness. The curves represented by r_2 show the influence length on the right side. These two curves at the initial stage started raising but later they become constant. The reason for this is because they are being affected by tension cracks. As the crack starts reaching the surface the influence length will increase but once the crack reaches the surface, the influence length will remain same. And in Fig. 19, similar results are shown for dip angle 45 degrees. The trend of these curves is also same as of Fig. 18 except for the tension cracks in case where thickness is 100 m. This is because of the appearance of more tension cracks on the surface.

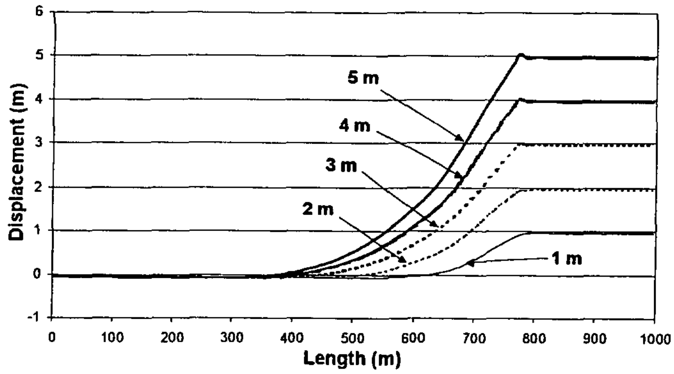


Fig. 12. Surface displacement
(Case 3: non-linear analysis, dip angle = 90^0)

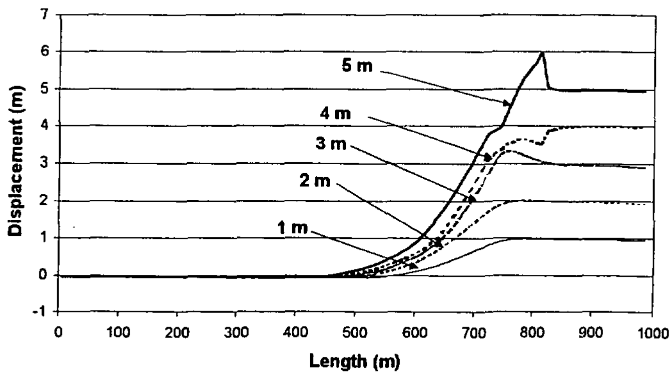


Fig. 15. Surface displacement
(Case 4: non-linear analysis, dip angle = 45^0)

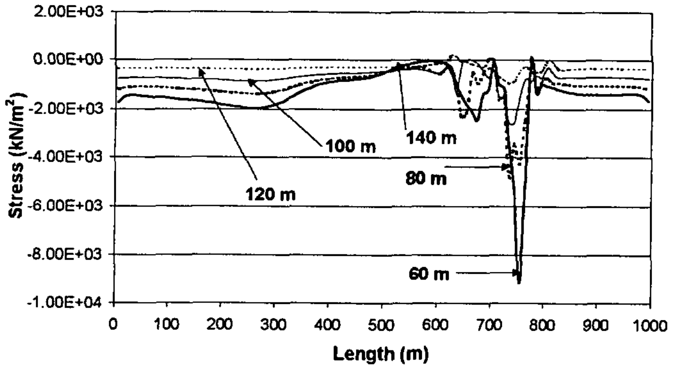


Fig. 13. Stresses in soil deposit (Case 3)

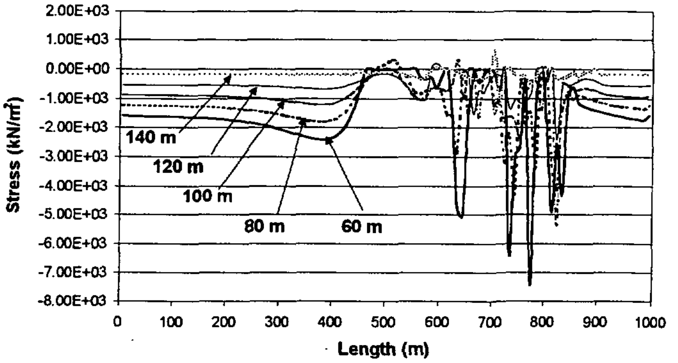
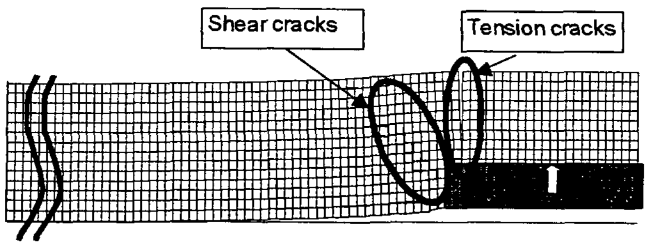
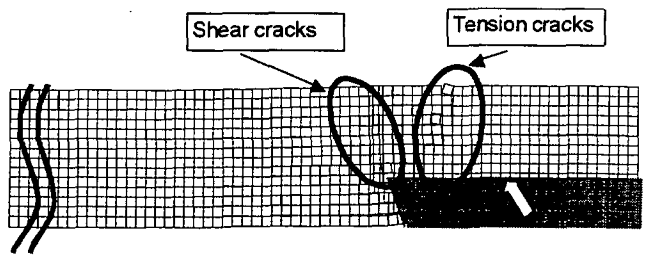


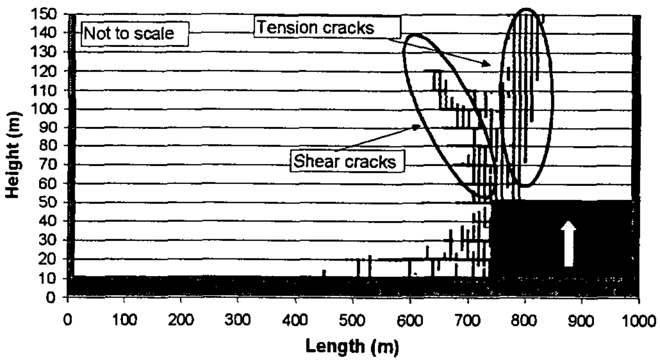
Fig. 16. Stresses in soil deposit (Case 4)



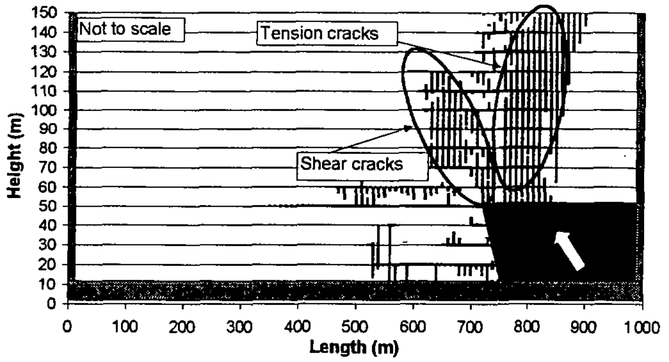
(a) Element distribution



(b) Element distribution



(b) Crack pattern



(b) Crack pattern

Fig. 14 Propagation of failure (Case 3)

Fig. 17 Propagation of failure (Case 4)

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

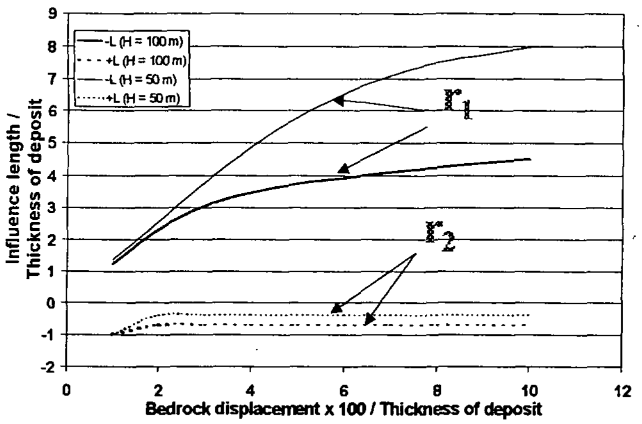


Fig.18. Influence length (dip angle = 90^0)

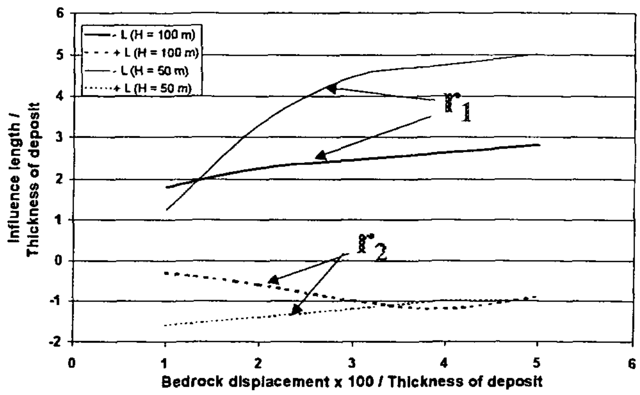


Fig. 19. Influence length (dip angle = 45^0)

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 (see 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.

CONCLUSIONS

A new application of Applied Element Method is proposed in this paper. A reverse 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 effected 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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