研 究 速 報

Non-Linear Static Modeling of Dip-Slip Faults for Studying Ground Surface Deformation Using Applied Element Method

Pradeep Kumar RAMANCHARLA* and Kimiro MEGURO**

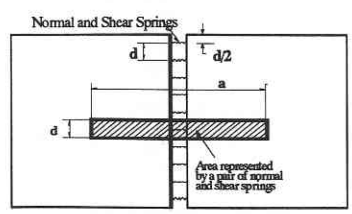
1. Introduction

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.

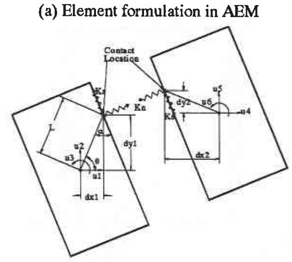
2. Element Formulation and Boundary Condition

Applied Element Method (AEM)[1,2,3], 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 the AEM, the media is modelled as an assembly of small elements which are made by dividing the structure virtually. Two elements shown in Fig.1 (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. 1 (b). By using the advantage of AEM's simplicity in formulation and accuracy in non-linear range, fault rupture zone shown in Fig. 2 is modelled.

The mechanism as shown in Fig. 2 is called Reverse Dip-Slip Faulting. This is one of the kinds of faults where hanging wall moves upwards relative to foot wall. To analyze the mechanism of fault rupture zone near dip-slip faults, the models shown in Fig. 3 is 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. 3, on the surface towards left



(a) Element formulation in AEM



(b) Spring connectivity

Fig. 1 Element modelling in AEM

*PhD Student, Institute of Industrial Science, The University of Tokyo
**Associate Professor, Institute of Industrial science, The University of Tokyo

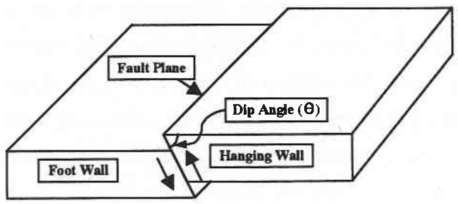


Fig. 2　Fault terminology

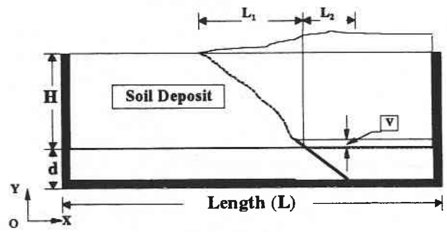


Fig. 3　Fault model

and right side of the point exactly above the seismic fault, respectively, are calculated by giving the displacement to the hanging wall along the direction of dip angle.

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.

3. Linear Analysis

To verify the proposed model, analysis is carried out in elastic case by assuming dip angle as 45^0. Density and Young's modulus of bedrock and soil deposit are assumed as shown in Table 1. 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 of dip angle. Displacement on the surface is plotted for every 1-m displacement of the hanging wall in horizontal and vertical direction (see Fig. 4). 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. Figure 5 shows stresses in bedrock at regular intervals of 10 m. This figure 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 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. 6, stresses in vertical direction taken along the horizontal lines at different heights in soil deposit are plotted. Here stresses show high values near the zone of rupture.

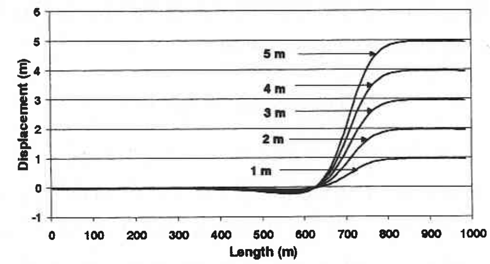


Fig. 4　Surface displacement at each 1-m displacement of handing wall
(Case 1: elastic analysis, dip angle = 45°)

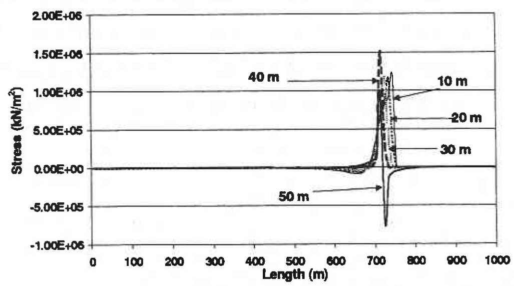


Fig. 5　Stresses in vertical direction in bedrock at regular intervals (Case 1)

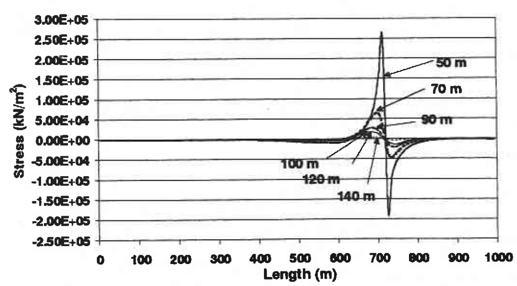


Fig. 6　Stresses in vertical direction in soil deposit at regular intercals (Case 1)

As we can see clearly from the figure, that the stresses are reducing when we move near to the surface.

4. Non-linear Analysis

Analysis is carried out for two cases (Case 2: dip angle = 90 (Figs. 7, 8 and 9) and Case 3: dip angle = 45 (Figs. 10, 11 and 12)). 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 1. Vertical displacement on the surface is shown in Figs. 7 and 10. 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.

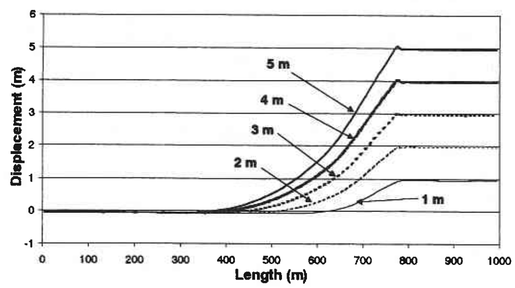


Fig. 7 Surface displacement
(Case 2: non-linear analysis, dip angle = 90°)

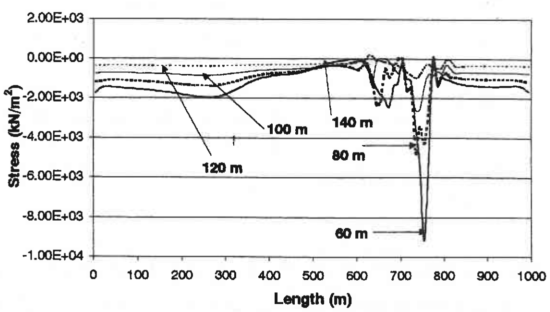
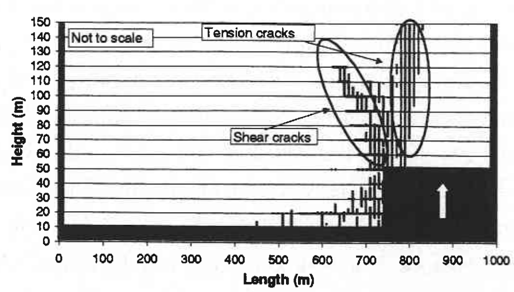


Fig. 8 Stresses in soil deposit (Case 2)



(b) Crack pattern

Fig. 9 Propagation of failure (Case 2)

Figures 8 and 11 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 9 and 12 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 2, the

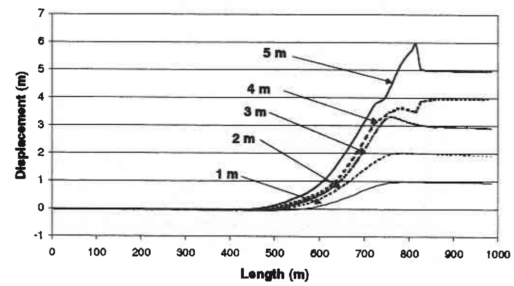


Fig. 10 Surface displacement
(Case 3: non-linear analysis, dip angle = 45°)

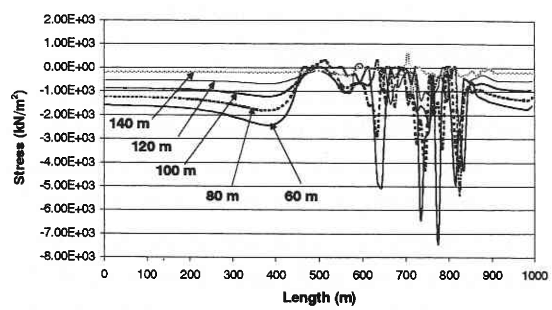
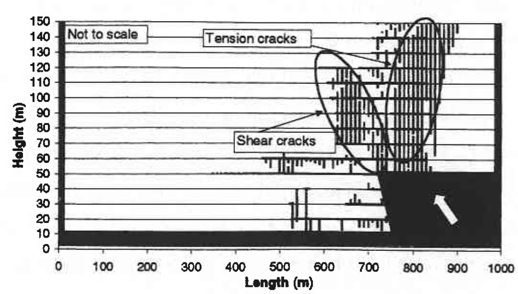


Fig. 11 Stresses in soil deposit (Case 3)



(b) Crack pattern

Fig. 12 Propagation of failure (Case 3)

Table. 1 Material Properties

	Young's modulus E (kN/m²)	Unit weight γ (kN/m³)	Comp. Strength f_c (kN/m²)	Tensile strength f_t (kN/m²)
Bedrock	$66x10^6$	26.5	$2.5x10^3$	$2.5x10^4$
Soil deposit	$20x10^5$	18.0	$1.5x10^4$	$1.5x10^3$

tension failure is almost vertical but where as in Case 3, the tension failure is inclined.

5. Parametric Study

A parametric study has been carried out to show the relationship between the bedrock displacement and influence length using dip angles 90°. In this case, two different thicknesses of soil deposit are studied, one is 100 m thick and the other is 50 m thick. Figure 13 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. 13, 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.

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. 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[4,5]. Hence it is important to study the surface behaviour based on the local soil conditions and fault characteristics.

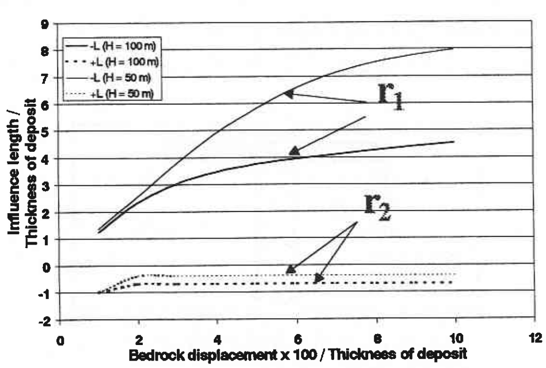


Fig. 13　Influence length (dip angle = 90°)

6. 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.

(Manuscript received, October 30, 2000)

References

1) Meguro, K. and Tagel-Din, H. [2000]. Applied element method for structural analysis: Theory and application for linear materials @, Structural Eng./Earthquake Eng., JSCE, Vol. 17, No. 1, 21s–35s.
2) Meguro, K. and Tagel-Din H. [1997]. A new efficient technique for fracture analysis of structures @, Bulletin of Earthquake Resistant Structure Research Center, Institute of Industrial Science, The University of Tokyo, No. 30.
3) Tagel-Din, H. [1998]. A new efficient method for nonlinear, large deformation and collapse analysis of structures @, Ph.D. thesis, Civil Eng. Dept., The University of Tokyo.
4) Japan Society of Civil Engineers [1999, a], The 1999 Kocaeli earthquake, Turkey, Investigation into damage to civil engineering structures @, Earthquake Engineering Committee, Japan Society of Civil Engineers.
5) Japan Society of Civil Engineers [1999, b], The 1999 Ji-Ji earthquake, Taiwan, Investigation into damage to civil engineering structures @, Earthquake Engineering Committee, Japan Society of Civil Engineers.