研 究 速 報

A Study on the Attenuation Characteristics of Peak Responses in the Near-Fault Region Using Applied Element Method

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1. Introduction

Over the past few decades, significant effort has been devoted to understand the problem of ground shaking. Accordingly, numerous design and construction procedures have been developed to minimize damage due to strong ground motion. However, the efforts towards improving our understanding of the problem of surface faulting have been relatively modest. In the conventional attenuation relationship, peak ground acceleration shows maximum values at the closest distance from the fault. However, in the real observations, sometimes it is found that the damage near to the surface fault is not maximum, instead it is high little away from the surface rupture zone. The common practice with important facilities such as dams, nuclear power plants, and public buildings has been to avoid construction across the recognized trace of an active fault. However, in case of the buried faults, our ability to delineate the possible potential hazard that can be caused due to the future rupture activity is far from complete.

Catastrophic earthquakes in the recent times have posed many new challenges to the engineering profession. Therefore, the engineering profession should develop techniques to mitigate damaging effects of surface faulting. To understand the phenomena of surface failure, many researchers conducted experiments. Cole and Lade[1] 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. They hypothesized that the results may be applicable to cohesive materials. Lade *et al.*[2] studied to determine the multiple failure surfaces by conducting the experiments on sand using fault test box. The results of the sand box model tests concluded that the observed displacement fields were nearly the same in different materials. Onizuka *et al.*[3] have modelled the deformation of ground using aluminium rods. Through experiments, they investigated bedrock stresses induced by reverse dip-slip faults. Bray[4] investigated the pattern of ruptures in clay models under 1-g subjected to dip-slip faulting. Tani *et al.*[5] conducted a 1-g model study of dip-slip faulting using dry Toyoura sand as model material. Results from their tests indicated that the base offset necessary for the rupture to propagate to the ground surface varied with fault orientation. These observations are in agreement with those from the study of Cole and Lade[1].

Using the above experimental methods, we can find the affected length on the surfae. 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. Numerical model allow us to investigate a number of aspects of the fault rupture propagation phenomenon, which are difficult to study from the examination of case histories and the conduct of physical model tests. It allows for the behavior of the soil and the imposed boundary conditions. However, the adopted numerical model should have adequate capacity to study non-linear large deformation analysis. Of course, the accuracy and reliability of any numerical approach depend on the validity of the mathematical conceptualisation of the critical aspects of the problem. If the limitations of the assumptions imposed in the problem definition are understood, then the numerical analyses can assist the engineer in attempting to understand the problem in question.

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2. Applied Element Method (AEM)

Applied Element Method (AEM)[6),7)], 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 medium is modelled as an assembly of small elements that are made by dividing the structure virtually. Two elements shown in Fig. 1 are assumed to be connected by pairs of normal and shear springs set at contact locations that are distributed around the 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 (see Fig. 2). By using the advantage of AEM's simplicity in formulation and accuracy in non-linear range, fault rupture zone that is shown in Fig. 3 is modelled.

3. Model Preparation

To analyse the mechanism of surface fault rupture zone (see Fig. 3), the numerical model shown in Fig. 4 is prepared. Length of the model is assumed as 1 km and depth is 150 m. The location of the base fault is assumed to lie exactly at the centre of the model. Response is measured at some observation points on the left and right sides of the point exactly above the location of the underlying base fault. These points (L1~L6 and R1~R6) are located unevenly (i.e. at 5m, 25m, 65m, 145m, 305m, 485m) on each side. When the model is set with no loading except the self-weight, which is applied as gravity load, the model exhibits free vibrations across the equilibrium position. These vibrations will decay consuming the large amount of CPU time. Hence, the static analysis is performed first and the self-weight is applied in increments. After the total self-weight is applied in static way, the model for performing dynamic fault rupture analysis is ready.

4. Dynamic Analysis

Permanent ground displacements that accompany a seismic event are the consequence of the fault slip and are referred as the static displacement field of that event or as coseismic displacements[8),9)]. This displacement field differs from the ground displacements induced by the seismic waves, which are generated during earthquake rupture propagation and referred as dynamic displacement field. Despite their name, near-fault static displacements are developed rapidly, within short period of the time that is related to the slip rise time. The shortness of this development turns the coseismal displacement into a dynamic phenomenon.

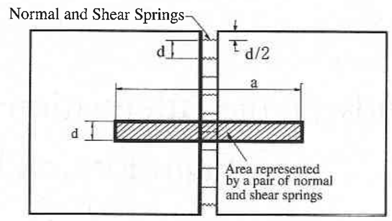


Fig. 1 Element formulation

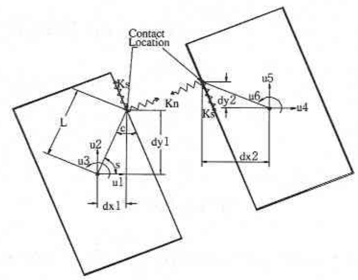


Fig. 2 Spring connectivity

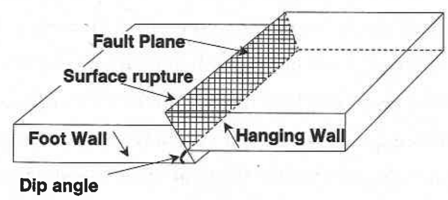


Fig. 3 Terminology

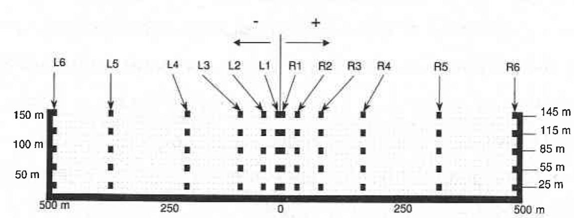


Fig. 4 Numerical model

Since they are likely to be non-reversal and continuous, their time history will appear as a pulse of motion with a ramp-type shape.

For comparing the results with real near field records with large displacement, closed form approximation of static displacement is assumed. Pulse-like displacement time history that represents the base motion is considered (see Fig. 5) referring to Mladen[10)]. As an approximation, the corresponding displacement pulse can be assumed as Gaussian-type function

$$d_{sp}(t) = \frac{\sqrt{2\pi}}{n} V_{sp} T_p \Phi\left[\frac{(t-t_c)}{T_p/n}\right] \quad \cdots\cdots\cdots (1)$$

where V_{sp} is the amplitude of static velocity pulse, T_p velocity pulse duration, t_c time instant, at which the pulse is centered, n constant equal to 6 and t the time. The term T_p/n has the meaning of

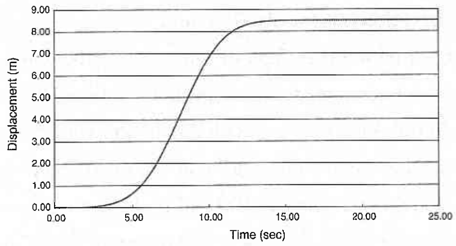


Fig. 5 Input displacement

standard deviation and controls the actual spread of the pulse with respect to the given pulse duration and Φ is the normal probability function. For more details, please refer Mladen[10].

In general, the amplitude of wave attenuates because the material damping absorbs some of the elastic energy of the stress wave; the specific energy (energy per unit volume) decreases as the wave travels through a material. The reduction of specific energy causes the amplitude of the wave to decrease with distance. In purely elastic materials, the energy is conserved (no conversion to other forms of energy takes place), this reduction in amplitude due to spreading of the energy over a greater volume of material is often referred to as radiation damping (or geometric attenuation). It should be distinguished from material damping in which elastic energy is actually dissipated by viscous, hysteretic, or other mechanisms[11]. The above explanation says that the attenuation takes places from the shortest distance from the fault towards the farther distances. This is true when we discuss in large scale but when we look at the places very close to the fault trace, the scenario becomes different. Figure 6 shows the horizontal acceleration time histories of some selected points on the surface. It can be seen from this figure that the acceleration on surface attenuates when we move towards the farther distances due to failure from the fault. Figure 7 shows that the attenuation of peak ground acceleration (PGA) with respect to distance from the surface fault trace. It can be seen from the figure that the PGA increases first and attains the peak value and then attenuates towards hanging wall direction. In general, the amount of destruction exactly on the fault is more because of the large relative permanent displacement. However, little away from the fault, the damage is less because the amplitude of strong ground motion is not so high. And at farther distances, PGA attains greater magnitude and then decreases with distance. This phenomenon is sometimes observed during the past earthquakes. However, due to the sparse distribution of the seismometers, this could not be represented by actual recorded data. But with the help of the newly developed numerical model, we can show this phenomenon. The

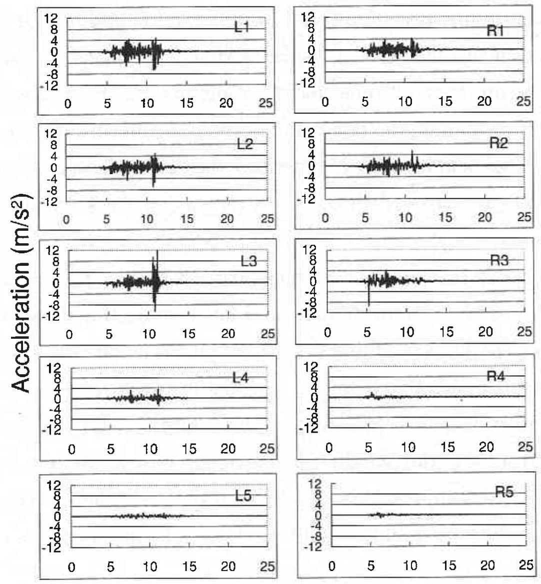


Fig. 6 Horizontal acceleration time histories (L 1~L 5 and R 1~R 5)

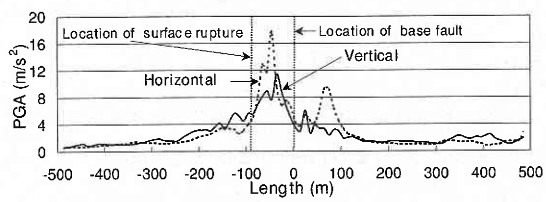


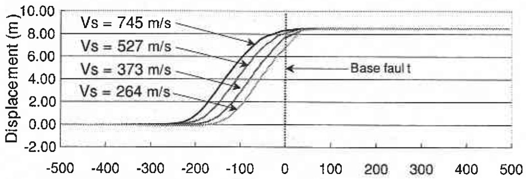
Fig. 7 Attenuation of PGA with distance
(dip angle = 90^0, reverse fault)

reason for this can be, near the surface fault rupture, the material becomes highly non-linear and the response of this region becomes low compared to the adjacent areas response.

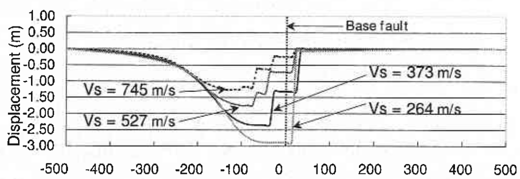
A parametric study is conducted in order to study the influence of soil properties on the attenuation of responses. Figure 8 shows the final surface displacement in vertical and horizontal direction for four cases, whose shear wave velocities are 745, 527. 373 and 265 m/s respectively. From this figure, it can be clearly seen that the length of the influence is more on the left side of the base fault than on the right side. The reason for this is the opening of tension cracks on the hanging wall side. When closely observe the Fig. 8 (b), we can see the gradual decrease in the influence length on the surface and gradual increase in the maximum value in horizontal deformation. This is due to the high deformability of soil when the stiffness reduces. Figure 9 shows the propagation of the shear and tension cracks in materials having shear wave velocities (a)Vs=745 m/s and (b)Vs=264 m/s, respectively. From these figures, it can be said that the thickness of the shear band reduces with the reduction in the shear wave velocity because in the softer material, the shear cracks gets localised. It can also be said from the results that the vertical displacement is more in case of harder soil and horizontal displacement is more in case of softer soil. In case of softer soil, the bedrock deformation gets absorbed in the soil deposit and in case of harder soil, the deformation on the surface will be exposed in the form of tension cracks at distinct locations.

Figure 10 (a) shows the attenuation of peak ground acceleration for Vs=264 m/s. In this figure, solid line is indicating the vertical component and dotted line is showing the horizontal component. From this figure also it can be said that the peak response is not maximum near the place where the rupture is occurring on the ground surface. Instead, they are maximum little away from it and this is because of the reduction in the response of the soil deposit as it has become highly non-linear. Figure 10 (b) also shows the similar observation but for Vs=750 m/s.

In order to find out the effect of thickness of the deposit on the attenuation characteristics of the peak responses, two analyses were carried out. First one was with the thickness of deposit equal to 70 m and the second one was with 50 m. In both cases, the length of model is assumed as 1000 m. In these analyses, element size is fixed as 5 m. Input displacement function shown in Fig. 5 is applied to hanging wall and the PGA is observed at all the element locations on the ground surface. Figure 11 (a) shows the attenuation of PGA. From this figure, it can be said that the trend of the result is same as in case of 140 m thickness soil deposit. Here also peak response is not showing maximum value where the possible surface rupture might take place. Similar trend of result is obtained in case of 50 m soil deposit case (see Fig. 11 (b)). From the above observations, it can be clearly said that the high non-linearity of the soil deposit near the surface rupture zone tends to

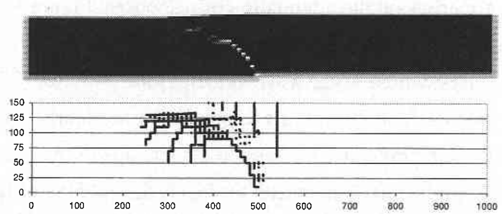


(a) Conparison of vertical srface deforration

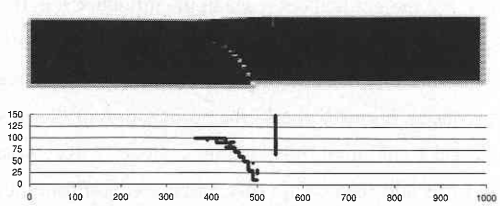


(b) Comparison of vertical surface deformation

Fig. 8 Comparison of surface displacement for different stiffness and same strength (dip angle = 90^0)

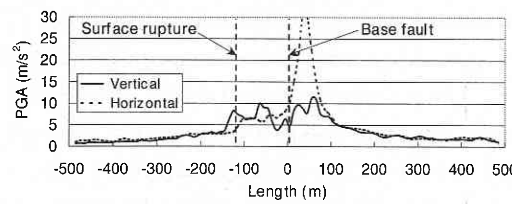


(a) For shear wave velocity, Vs = 745 m/s

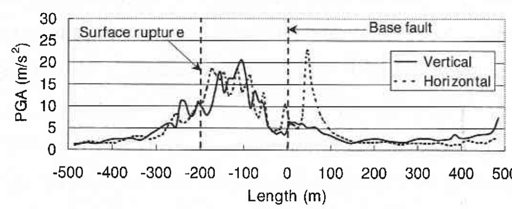


(b) For shear wave velocity, Vs=264m/s

Fig. 9 Propagation of the cracks and the elements location

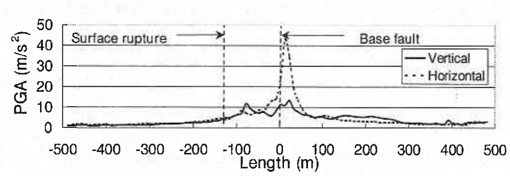


(a) For Vs = 264 m/s

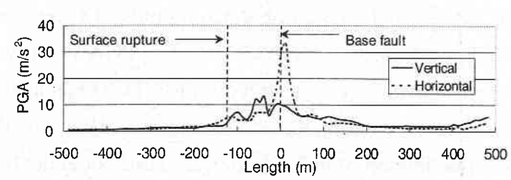


(b) For Vs = 750 m/s

Fig. 10 Attenuation of peak ground acceleration for different shear wave velocities



(a) Thickness of the deposit (H) = 70 m



(b) Thickness of the deposit (H) = 50 m

Fig. 11 Attenuation of peak ground acceleration for different thickness reduce the amplitude of peak responses.

A complete understanding of the phenomena of fault rupture propagation in soil may remain elusive because of the numerous governing factors that are highly variable and not well quantified. Geological observations of surface ruptures associated with historical earthquakes in the world have indicated that surface ruptures occurred, without any definite exceptions, on pre-existing faults. Moreover, there are lines of evidence indicating that moderate to large-scale faults have moved repeatedly in the geologic past. This is because a fault coalesces other faults and fractures near its edge every time it slips, and approaches to the ground surface with time. Conversely, a map-scale fault cannot be formed in a single event. The repetitive nature of faulting gives us an important basis for predicting future activity of faults by using geologic information. And hence, the study on the fault rupture propagation 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 will be caused when the structures are located on the vulnerable area.

6. Conclusions

A new application to Applied Element Method (AEM) is proposed in this paper. Numerical modelling of fault rupture propagation in dynamic condition is done using 2D AEM. It is found from the results that the PGA very near to the fault trace becomes relatively smaller and increases to peak value and then attenuates towards the hanging wall side. This information can give some insights to the actual phenomenon.

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