Effect of Heterogeneities in Soil on Spatial Variation of Peak Ground Acceleration

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ABSTRACT

In the proximity of an active fault, spatial variation of peak ground motion is significantly affected by the faulting mechanism. It has been observed that near fault ground motions consists of different characteristics compared to the far fault ground motions. Near fault records, in the distance range of less than 100 m from the faults are not available except for few cases. Therefore numerical simulation of ground motions for such near-fault situations is necessary. In addition to the understanding of the phenomenon of near fault ground motion there is a need to enhance our understanding of the possible potential hazard that can be caused due to the future rupture activity by understanding the phenomenon of surface faulting. In this paper we propose numerical simulation based on discrete modeling to investigate the fault rupture propagation and its effect on the surface peak ground acceleration. In the present two dimensional study rupture propagation due to bedrock motion has been observed for different shear wave velocity. A model of size 1000 X 150 m is selected for this purpose. It has been observed that as the stiffness of the media is decreasing, the affected surface is decreasing and also width of the shear crack zone is decreasing. Secondly, we attempted to study the ground motion on the surface due to the bedrock motion in presence of boulders in the soil media. Surface faulting has been examined by keeping the boulder at different positions. We find that there is an increase in the shear zone as well as the PGA on the surface when the boulder is present on the foot wall and in the vicinity of the rupture zone. Finally, we performed the analysis using layered media and studied the affect of crack propagation and also the variation of peak accelerations. Findings from the study can be utilized to assess the damage potential of the near fault areas.

INTRODUCTION

In the past decade several earthquakes near large urban areas have caused considerable damage, including the 1994 Northridge, California, the 1995 Hyogo-Ken Nanbu (Kobe), Japan, the 1999 Izmit and Duzce, Turkey, and the 1999 Chi-Chi, Taiwan, earthquakes as
referred in JSCE (1999a&b). These earthquakes and their associated ground motion records have increased the awareness of the destructive capability and characteristics of near-fault ground motions in the vicinity of faults. The primary factor controlling the size of near-fault ground motions is not simply the distance the rupture propagates, but the distance the rupture propagates in the direction of slip. The ability to capture pulse-type ground motions in the near-fault region is of recent development and records of this type are few. In addition to the near fault ground motion it is necessary to understand the possible location of the fault appearing on the surface due to future rupture activity. The study of fault rupture propagation is necessary because engineers are more concerned about the damage that will be caused when structures are located on the vulnerable area.

Many researchers have studied the phenomenon of fault rupture propagation by experimental models, but however, replicating the actual field conditions using experiments is very difficult, especially, controlling the material properties and modeling the boundary conditions. Numerical modelling allow us to investigate a number of aspects of the fault rupture propagation, which is difficult to study from the examination of case histories or the conduct of physical model test. The uncertainty in the behavior of how faults rupture has led researchers to create simple, ad hoc models that produce reasonable behavior. Most of the studies that are documented till now in the literature for studying the fault rupture phenomenon are either finite element method or finite difference method of analysis. Oglesby et al. (1998) used the finite-element method to study the difference between ruptures on two-dimensional normal faults and thrust faults in a homogeneous medium. They found that thrust/reverse faults produce higher ground motion than normal faults and larger ground motions on the hanging wall compared to the footwall that are consistent with recorded ground motions. Aagaard el al. (2000) simulated the earthquake ground motions with prescribed ruptures and dynamic failure using finite element technique. They have found that for blind thrust faults the peak displacement and velocities occur in the hanging wall region. Shi et al. (1998) carried out dynamic simulation using a 2D lattice numerical model to study thrusting rupture behavior and the associated near-fault strong ground motions. It has been seen that when rupture reaches the toe of the fault outercrop, the hanging wall breaks away from the foot wall and creates a large opening vibration at the hanging wall toe. The increase in peak acceleration at the toe is caused mainly by multiply reflecting stress waves trapped in the wedge-shaped hanging wall of the fault. Using same 2D lattice particle model Shi et al. (2003) have simulated the dynamic rupture process of a normal fault. In the vicinity of the fault outercrop, the particle velocity and acceleration increase rapidly, both on the hanging wall and the footwall. These motions are amplified as the fault scarp develops (rupture breaks out at the surface), with strong asymmetry between the hanging wall and the footwall. O’Connell el al. (2007) investigated the influence of fault dip (35-60°) rupture dynamics and near-fault ground motions from normal and reverse faulting using finite element technique.

Many researchers have studied the fault rupture problem using finite element method to study the response on the surface. FEM can be applied to study this problem provided that the soil’s nonlinear stress-dependant stress strain relation is properly modeled. Nonlinear stress-deformation behavioral models provided significantly better predictions
of observed behavior of shear and tension zones. However once a shear tension crack i.e. a discontinuity develops within the soil mass it typically becomes difficult to reliably apply the numerical approach based on the continuum mechanics. Scott (1987) identified a number of limitations of FEM in the analysis of failure. Hence a suitable numerical approach must be chosen to study this problem. Pradeep et al, (2000) have used 2D Applied element method based on discrete modeling to investigate response on the ground surface due to seismic base fault movement. The main advantage of this method of modeling is it has the ability of crack initiation based on the material failure and propagation of crack till the collapse. They have found that the ground acceleration very near to the fault is not maximum instead the peak value is little away from the fault trace due the high nonlinearity of the soil. Both the vertical and normal peak ground motion has been seen to occur on the hanging wall side due to multiple reflections in the wedged shape hanging wall. In the present study the effect of the presence of hard rock material in the soil media is being studied using Applied element method.

SIMULATION METHOD

The method used here is the Applied Element Method which was developed by Hatem et al. (1998). With the AEM, the system is modeled as an assembly of small elements that are made by dividing of the structure virtually, as shown in Fig.1 and Fig 2. The two elements shown in Fig. 1 are assumed to be connected by pairs of normal and shear springs located at contact locations that are distributed around the element edges. Each pair of springs totally represents stresses and deformations of a certain area of the studied elements.

\[ k_n = \frac{ExdxT}{a} \quad k_s = \frac{GxdxT}{a} \] (1)

The normal and shear stiffness of the spring is determined as shown in Eq. (1). The above equation indicates that each spring represents the stiffness of an area \((a \times T)\) with length \(a\) of the studied material where, \(d\) is the distance between springs, \(T\) is the thickness of the element and \(a\) is the length of the representative area. E and G are the Young’s and shear modulus of the material, respectively.

![Fig.1 Element formulation](image-url)
MODEL PARAMETERS

The mechanism shown in Fig. 3 is called Reverse Dip-Slip Faulting. This is one of the types of fault where the hanging wall moves upward relative to the footwall. If the direction of the movement of the hanging wall is downward then it is called normal faulting. To analyze the mechanism of fault rupture zone near dip-slip faults, 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.
Generally, soil strata and bedrock extend up to tens of kilometers in horizontal direction. Numerical modeling of such a large media is a difficult task and moreover, for studying the surface behavior near the active fault region, it is necessary to model the small portion of the region that includes all the effects when the bedrock moves. For studying the selected region numerically, we assumed the boundary on left side as an absorbing boundary. These absorbing boundaries prevent waves from reflecting and contaminating the solution. In order to avoid the interference of boundary condition on numerical results, boundary is kept at sufficient distance from the fault zone.

**SLIP FUNCTION**

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 as shown in Fig. 5 referring to Mladen (2000). As an approximation, the corresponding displacement pulse can be assumed as Gaussian-type function given by Eq. 2.

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

(2)

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, \( n \) is a constant equal to 6 and \( t \) is the time. The term \( T_p/n \) has the meaning of standard deviation and controls the actual spread of the pulse with respect to the given pulse duration and \( \Phi \) is the normal probability function.

![Fig.5 Assumed input displacement at the bedrock](image)

**CASE STUDY**

To analyze the surface fault rupture zone materials having shear wave velocity \( V_s = 527 \text{m/s} \) and \( V_s = 265 \text{m/s} \) have been taken respectively. Figure 6 shows the propagation of shear and tension cracks in the material. 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 shear cracks gets localized.
In order to find the attenuation of the of the peak ground acceleration along the surface due to the input displacement at the bed rock as shown in fig 5, only soil mass has been considered. Young’s modulus of elasticity of the soil has been considered as 10x10^5 kN/m^2, and the shear wave velocity considered as 527 m/s. Attenuation of the peak ground acceleration on the surface has been plotted in fig 7. From the figure it is seen that ground acceleration (PGA) attains a maximum value in the hanging wall side and then decreases with distance. Pradeep (2001) suggested the reason as, near the surface fault rupture, the material becomes highly nonlinear and the response of this region becomes low compared to the adjacent areas of response. Response time history of the element at which peak response is observed has been plotted in fig 8(a) & 8(b). From the response history it can be seen that the peak value attained is only for a small instant of time and then it is reduced because of high nonlinearity of soil.
Fig 7. Attenuation of PGA on the surface

Fig 8. Acceleration Time history at maximum ground motion

Table 1. Material Properties
It is well known that the soil is not a homogenous strata. It is filled with heterogeneities. Case study has been done to study the effect of the presence of boulders in the soil on the ground surface. The analysis is carried for four cases to study the response on the surface in presence of boulders in the soil medium. In Case.1 the boulder is placed in foot wall and nearer to the rupture zone and in Case.2 the boulder is placed in the footwall and away from the rupture zone. In Case.1 the boulder with young’s modulus 66x10^6 kN/m^2 and the shear wave velocity considered as 3496 m/s has been placed in the footwall and the analysis has been performed to find the the response on the surface. Material properties of the rock and the soil deposit have been shown in Table 1. Figure 9 shows the attenuation of peak ground acceleration on the surface and the crack propagation in presence of a boulder in the foot wall. Large variation in the ground motion has been observed when compared to results of without boulder condition(Fig 7). The reason for this is in the beginning of the analysis i.e before the occurence of the rupture the energy gets concentrated around the boulder as shown in the Fig. 10 and this energy is suddenly released during the process of rupture. Multiple reflections of the body waves after interacting with the hard rock medium are reflected back on to the hanging wall side with greater intensity. Peak acceleration response on the surface is increasing from 2 to 6 g when compared with the case of without boulder. Though this much value is not actually seen in the real field situations but since, this is an hypothetical model there is that much variation.

![Fig 9. Attenuation of PGA on the surface in presence of boulder in foot wall.](image)

![Fig 10. Energy distribution in the system before fault rupture](image)
In Case.2 the boulder is placed in foot wall but some distance away from the rupture zone. From the plot of peak ground acceleration on the surface as shown in Fig. 11 it can be seen that there is not much increase in PGA value compared to without boulder condition except at place just besides the boulder. In Case.3 the boulder is placed in hanging wall and nearer to the rupture zone and the analysis has been performed to find the the response on the surface. The attenuation of peak ground acceleration on the surface in presence of a boulder in the hanging wall can be seen in the Fig 12. Not much effect of the presence of boulders in hanging wall has been seen except, there is an increase in the ground motion just beside the boulder. The reason for this amplification is that the energy which is being released during the process of rupture interacts with the boulder present in the hanging wall and reflects back on to the surface.

In Case.4 the boulder is placed in hanging wall and away from the rupture zone and the analysis has been performed to find the the response on the surface. Figure 13 shows the
attenuation of peak ground acceleration on the surface in presence of the boulder in the hanging wall. It has been seen that there no change in the ground response on the surface due to the presence of boulder in hanging wall away from the rupture zone when compared to the case of without boulder.

![PGA attenuation graph](image1)

*Fig. 13 Attenuation of PGA on the surface in presence of boulder in hanging wall away from rupture zone.*

Finally rupture propagation in the soil has been studied in the layered media. A layered media consisting of 5 layers with shear wave velocity from bottom to the surface are 527, 471, 408, 333 and 235 m/s respectively (Fig 14) have been taken. From fig. 17 & 18 it can be seen that the vertical surface deformation is less and the horizontal surface deformation is more in the layered media when compared to the homogeneous media. The reason for this is that in the layered media waves get reflected and the bad rock deformation is absorbed by the soil deposit due to the dispersion of the waves.

![Rupture propagation in layered media](image2)

*Fig. 14 Rupture propagation in layered media*

![Comparison of vertical surface deformation](image3)

*Fig. 15 Comparison of vertical surface deformation*
Over the past few decades, significant efforts have been made to understand the problem of ground-shaking. Accordingly, numerous design and construction procedures have been developed to minimize damage due to strong ground motion. Hence, it is proposed here to study the response of soil deposits to underlying bedrock fault displacement. Although the complete understanding of the fault rupture phenomenon in soil is not so easy, since the factors governing the phenomenon is highly variable. Soil is consisting of different geological and geotechnical properties. Existing planes of weakness or rigid inclusions within a weaker soil mass will certainly cause the fault rupture pattern observed in the field to deviate from any fault rupture pattern predicted by the theories based on the assumptions of homogeneous soil masses. Earthquake shaking, in conjunction with the movement across the fault, may alter the response of the overlying soil deposit. The repetitive nature of faulting gives us an important basis for predicting future activity of faults by using geological 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. The hazard of surface faulting is an important problem because of the potentially adverse consequences of ground breakage. From a seismological point of view, some difference between the real fault and the expected fault line is acceptable; but for engineers this difference sometimes might be a major concern. This understanding would also assist engineers in siting and designing critical buildings, utility and transportation systems, and other types of facilities constructed in regions where soils overlie potentially active faults.

CONCLUSIONS

Numerical modeling of fault rupture propagation in dynamic condition is done using 2D AEM. Rupture phenomenon and the response on the surface in presence of heterogeneities like rock boulders in the soil medium has been studied using hypothetical model. Presence of boulders in the footwall and in proximity of the rupture zone increases the PGA value in the hanging wall to a large extent, whereas the presence of boulder in hanging wall does not affect much on the surface ground motion. It has been seen that there is a considerable change in the rupture pattern between layered media and homogenous media. Findings from the study can be utilized to assess the damage potential of the near fault areas when we to the analysis considering the actual field conditions.
REFERENCES


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