

# A RATIONAL ANALOGY FOR SURFACE DEPOSIT RUPTURING PROBLEM

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The 1999 ChiChi-Taiwan and Kocaeli -Turkey earthquakes, did great damage to a number of bridges along the trace of the surface rupture. With fault motion and induced deformation on surface deposit, consequently an embedded foundation will be shifted from its original location, and deformed even though it is located off the major rupture zone. Understanding the important factors of soft surface deposit shearing is an essential step for investigating its effect on the adjacent structure. In this paper with considering nonlinearity nature of problem, a simple conceptual model is introduced, then essential dimensionless groups are extracted. Using Material Point Method (MPM) together with plasticity, the validity of derived groups are checked by 2D numerical case studies. The derived similarity law is useful for understanding the effect of factors like elastic, strength distribution among depth and deposit thickness. Then the effects of horizontal and vertical fault motion are separately studied and later with proposed framework the effect of material dilatancy, initial stress, Normal-Reverse type and dip fault motions are explained.

Key words: Characteristic Length, Dilatancy, MPM, Rigid block kinematics, Soft Deposit rupturing

# **INTRODUCTION**

Surface faulting is displacement (Shear strain) that reaches the earth's surface during slip along a fault. Commonly occurs with shallow earthquakes, those with an epicenter less than 20 km. Surface faulting also may accompany aseismic creep or natural or man-induced subsidence.

A sample of catastrophe due to surface faulting is 1999 Taiwan ChiChi earthquake.

The trace of the surface rupture that appeared in the earthquake, closely followed the frontal slope of the local mountain range where the range trends north south. Some major rivers cut this range, and bridges crossing these rivers were seriously damaged by large deformations of soils caused by the fault rupture Chen<sup>1</sup>, Kosa<sup>2</sup>) .A discussion on this issue must be based on a quite different scenario from those for ordinary designs, in which ground accelerations and/or velocities are crucial factors. Many foundations supporting the damaged bridges were embedded in soft deposits of sands, gravel and other suspended matters that rivers have carried over centuries. Therefore due attention should be directed to deformation buildup in soil deposits that cover hidden faults. When a base rock comes steadily up into a soft soil deposit, strains will be distributed over some wide zones, which extent depends largely on the material properties, dip angle, etc. Some researches have been conducted both for soil deformations caused by dip-slip and strike-slip fault dislocations. Most of them were experimental works with numerical verifications (see e.g.  $Bray^{3}$ ,  $Stone^{4}$ ).

In this paper it is tried to make a clear explanation for phenomena. Analyzing deposit rupturing as "it exists" is a nearly impossible task and more over because of including many parameters, interpreting and understanding the result is cumbersome and not easier of such analysis.

To make a clear view, by using various simplified models, the effect of important factors is highlighted separately. Simplifications are done on the many features of a problem including geometric, material, loading history, etc. and accuracy (validity) of a simplification can be evaluated by either scientific judgment or more complex analysis.

# NUMERICAL MODELING

## Geometry simplification

Geometric simplification is the first step for simplifying. The scale of Analysis is much smaller than geological scale (tens of Km). Regarding this scale, which is around hundreds meter it is assumed that fault dip angle and motion is constant along the fault line. Also it is assumed that the fault motion is one directional.

The basement is the layer where the rupture is continuing as major line and is different than bed rock definition for soil structure interaction analysis. Due to deformability of basement layer the dislocation on the basement is different (less) than original fault slippage.

## Numerical Scheme

A material point method (MPM) is used herein for numerical modeling of surface deposit rupturing (shearing). The MPM is categorized as one of the finite element methods formulated in an updated Lagrangian description of motion. In MPM, a body to be analyzed is described as a cluster of material points. The material points, which carry all Lagrangian parameters, can move freely across cell boundaries of a mesh.

This mesh, called a computational mesh, should cover the virtual position of the analyzed body.

The computational mesh can remain constant for the entire computation, thus the main disadvantage of the conventional finite element method related to the problem of mesh distortion is eliminated. Its main drawback, however, is that any localization, heterogeneity and boundaries that can exist within one cell are not sharply outlined (see **Figure 2**). In other word, a cell size determines the resolution of MPM.

# Soil

It is assumed that Energy dissipation is done by shearing and terms regarding energy release by fracturing is not considered.(However there is equity between these two), the main focus is on the upper formed wedge near surface and upper soft layer. The soil discussed herein is assumed to be a homogenous and isotropic material with constant elasticity properties.

Soils in nature are often rich-graded granular assemblages. When a soil is sheared, it keeps dilating without showing any clear sign of contraction (**Figure 1**), and reaches its maximum volume when the shearing displacement reaches two to three times of its shear band thickness.

Two type of plasticity model is used for analysis on this paper.

For simulation of dilatation feature, Mohr Coulomb criterion with different dilatancy angle is used. To check the effect of contraction, Generalized plasticity is utilized which is a cap plasticity-Critical state model.



Dense Sand Loose Sand Figure 1- Dilating and contracting behavior of granular assemblage



D = ?

Figure 2- Idealized model for deposit rupturing by MPM method



Figure 3- The illustration of Conceptual 1D Model

## **CONCEPTUAL MODEL**

Assuming that the rupture propagates in the deposit as a single straight line and Strips (blocks) alongside this rupture line are slipping over each other, a 1D model can be derived as shown on **Figure 3**.

The effective area of sliding strips **A** is assumed to be constant. In reality **A** is variable on depth and increasing with the rupture propagation; so it is not easy to determine **A**. However the derived relations will be independent of **A**.

To represent plasticity (friction), these two strips are connected by bilinear springs. These springs are combination of an elastic spring and a sliding joint with slipping limit  $\boldsymbol{\tau}_{slip}$ .

Along depth, due to various geological situation on different ages, the increase in elasticity and strength of deposit can be linear, quadrate, etc. function. To generalize the model, it is assumed that strength and stiffness are varying by power  $\gamma$  and  $\beta$  with depth.

For a given base dislocation  $\delta$ , for calculating slip length ( $\mathbf{L}_{slip}$ ) a characteristic equation can be derived by considering compability and equilibrium between these strips. The solution of this characteristic equation is not straight forward as it includes highly nonlinear terms like Bessel function. However with rearranging terms, two dimensionless groups with two important terms are recognizable.

These two major terms with length dimension are:

$$L_{e} = \sqrt{\frac{E_{0}A}{2k_{0}}}$$
(1)  
$$\delta_{ultimate} = \frac{\alpha_{0}L^{2+\gamma-\beta}}{(1+\alpha)(2+\gamma-\beta)E_{0}A}$$

The  $L_e$  has meaning similar to buckling or wave length, it is a measure for problem dimension, i.e. assume system is completely elastic, L=6L<sub>e</sub> is the length that induced dislocation on the bottom is damped inside system and doesn't reach surface. On the other words if springs be elastic, it is the length which strips can be considered infinitely long thus never deformation appears on the head of strips. The meaning of second term  $\delta_{\text{ultimate}}$  is straight. It is related to dislocation at the bottom which make whole strips to slide or ultimate dislocation that yield all springs.

This parameter has a key role for similarity analysis. Consider two 2D geometric configuration with geometric proportional ratio  $\kappa$  and same material properties, assuming original model has dislocation  $\delta_1$  at base and the slipped length is  $L_{1slip}$ . The corresponding dislocation  $\delta_2$ which makes plastic zones to be geometrically proportional with ratio  $\kappa$  ( $L_{2slip} = L_{1slip} .\kappa$ ) can be calculated using this dimensionless group and consequently following relations can be derived between these two configurations:

**KEY DIMENSION LESS GROUPS** 
$$\frac{E_0 A. \delta}{\alpha_0 L^{2+\gamma-\beta}}$$
$$\delta_2 = \kappa^{1+\gamma-\beta} \delta_1 \qquad (2)$$
$$\varepsilon_2(\delta) = \kappa^{\gamma-\beta} \varepsilon_1 \left(\frac{\delta}{\kappa^{1+\gamma-\beta}}\right)$$
$$\sigma_2 = \kappa^{\gamma} \sigma_1$$

The validity of derived similarity law is checked by 2D MPM-FEM simulation in the case of geometrical proportionality.

On **Figure 4** the analysis result of two deposits rupturing under reverse fault are presented. First case has 50 m and second case has 150 m thickness; Mohr-Coulomb Associate Plasticity with Constant Elasticity with same parameters is assumed as material model for both cases. The similarity law for these assumptions can be written as:

$$\gamma = 1, \beta = 0 \quad \kappa = \frac{150}{50} = 3$$
$$\delta_2 = \kappa^{1+\gamma-\beta} \delta_1 = 9.\delta_1$$
$$\varepsilon_2(\delta) = \kappa^{\gamma-\beta} \varepsilon_1(\frac{\delta}{\kappa^{1+\gamma-\beta}}) = 3.\varepsilon_1(\frac{\delta}{9})$$
$$\sigma_2 = \kappa^{\gamma} \sigma_1 = 3.\sigma_1 \text{ (Total and increment)}$$

It can be seen that on **Figure 4** that based on these similarity law, the shear strain distribution of these two cases are identical and derived dimensionless group is valid for reverse fault.

The validity of this dimensionless group has been proven for many cases and complex material  $\overline{r}$ ) models. Sadr<sup>5)</sup>

Also  $\delta/\delta_{\text{ultimate}}$  can be considered as an index for expressing damages due to the surface faulting occasion.

By rule of thumb for many practical cases this  $\delta_{\text{ultimate}}$  is about %3~%10 of soft deposit Height.



Figure 4-Similarity Analysis for Reverse Fault and associate flow rule(H=50m& 150m)

## **DEPOSIT SHEARING CRITERIA**

#### **Kinematics** Criterion

One approach for analysis of soil deposit dislocation problem is to consider it as a sliding rigid blocks problem.

In this approach shear zones are assumed to be in the form of slip lines, which divide media to multiple parts. To keep system cinematically possible there are geometrical requirements for these rupture lines otherwise system will be locked and another rupture lines pattern must be considered.

Due to Dilative feature of soil which accompanying frictional sliding, there is secondary motion perpendicular to slip line. This vertical motion can be in the form of either contraction or dilation and is varying during slipping.

Here for simplicity dilatancy angle  $(\psi)$  is considered to be constant.

On **Figure 5** the kinematics requirements for dilative sliding are illustrated for single and double rupture line configuration

For single line rupture system the orientation of shear band is determined only by kinematics requirements. Its orientation is in such away that by adding dilatancy angle ( $\psi$ ) the direction of motion on the rupture line becomes in the attitude of input motion. In this case the orientation of rupture becomes independent of stress conditions (like determined structure).

For the case of double shear bands system the kinematics condition doesn't pose any restrictions on shear band orientation and just give an equation relating input motion and slip on rupture lines. Therefore from kinematics point of view in this case, rupture pattern can be arbitrary and is determined mostly by stress criterion.

#### Strength (Stress) criterion

For a material nonlinear problem, Elastic analysis gives useful hints for predicting and understanding the possible failure modes. For a dip slip fault, the motion has two components: horizontal and vertical. First in this part the effects of these motions are considered separately; and by using the result of these analysis the effects of other factors like dip angle, material dilatancy on failure modes are interpreted.

On **Figure 6** the result of elastic analysis for pure vertical and horizontal are depicted.

By the elastic analysis and superposition of vertical and horizontal motion the effect of horizontal and vertical motion almost neutralize increment of  $\sigma_{xx}$ ,  $\sigma_{yy}$  on the left side of (Dislocation point)DP while it amplifies the increase and decrease of  $\sigma_{xx}$ ,  $\sigma_{yy}$  on the other side. So with this view, surely on the right side of DP, a passive shear band will be created and on the left side based on dip angle and material dilatancy may be the second sheared passive zone will be formed.



Figure 5- Kinematics of rigid sliding for single and double rupture line patterns



Figure 6- strain distribution due to 1%(0.04) strain horizontal & Vertical dislocation input

The nonlinear analysis of pure horizontal base motion is equal to famous retaining wall Analysis. Due to symmetric geometry and boundary condition, horizontal displacement and shear strain on the centerline is zero; so the retaining wall is rigid with zero rotation and the friction angle between retaining wall and backfill is zero (frictionless).For this dual rupture line system, from kinematics point of view, to make possible middle wedge to be pushed up rigidly, shear band angle with horizontal axis should be less than  $90-\Psi$ .



Figure 7- Interpreting pure horizontal dislocation as two symmetric retaining walls

#### **Dilatancy** Effect

As explained on the kinematics criterion, the volumetric feature of soil deposit is the main parameter of system kinematics character. From kinematics point of view for deposit rupturing problem at least one shear band should be created so left and right side blocks can slide over each other freely. The orientation of shear band is

## mainly determined by **dilatancy**.

Consider a 50 m deposit under rupturing by a reverse fault with  $45^{\circ}$  dip angle. As said before, surely on the right side of DP, a passive shear band will be created and on the left side based on material dilatancy may be the second sheared passive zone will be formed.



Figure 8- Effect of Dilatancy on Sheared Area Orientation under 45° reverse fault

For this case with different dilatancy assumptions analysis have been done and shear strain are plotted on **Figure 8**.

On case **A** with associate plasticity and dilatacny two conjugate shear bands are formed. From stress analysis point of view on the right side by decrease in  $\sigma_{yy}$  and increase on  $\sigma_{xx}$  passive failure mode happens. While on the left side due to neutralizing horizontal dislocation effect by vertical ones, left side shear band shear band is narrower from right hand side.

If shear zone centerline is considered to represent shear band, from compability point of view, for a wedge sliding system with  $\alpha$ =45 ° and  $\psi$ =30 ° to make possible rigid slipping orientation should be greater than 10 ° ( $\beta$ >10 °) (see **Figure 5**), which here is  $\beta$ =35 °. And rationally regarding existence of dilatancy, the first shear band should be below fault motion attitude.

Case **B**, represents zero dilatancy plasticity model. Regarding numerical problem of zero dilatancy, in this Analysis an initial dilatancy is set for whole domain, the shear zones lose their dilatancy by small shearing (Variable dilatancy). The system is almost single band therefore shear zone orientation is determined from dilatancy solely. Around DP(dislocation point) with nearly zero dilatancy the shear zone is along the input motion orientation.

Case **C**, using cap plasticity model, there is contraction. The system has only single shear zone which is wider than other cases. With shear contraction or negative dilatancy angle, the centerline of shear zone is rotated toward vertical axis to keep compability.

For the previous cases on **Figure 9** the pofile of deformation on the deposit surface is displayed. For associate plasticity from displacement contour it can be said that a rigid block is pushed up and shape of sheared zone is constant during loading.

With zero(nearly zero) dilatancy near surface a smaller variable wedge is formed and with base motion the orientation of shear zone is changed.

On Generalized plasticity case due to contraction Ux is more than base motion on the sheared area.



**Figure 9-** Surface deformation profiles for 45<sup>0</sup> reverse fault analysis (**HRMC:** Associate Mohr Coulomb **VD:** Variable dilatancy(nearly zero) **GP:** Generalized(Cap) plasticity-Contractive model

To check derived Kinematics relations, for Mohr Coulomb (HRMC) model, by using orientation of shear bands on **Figure 8**, the motion of wedge can be calculated as :

$$\alpha = 45^{\circ} \ \beta = 35^{\circ} \ \gamma = 32^{\circ} \ \psi = 30^{\circ} \ \delta_{input} = 2m$$
$$\delta_{y} = \sin(\psi + \beta) \times \frac{\sin(\alpha + \gamma + \psi)}{\sin(2\psi + \beta + \gamma)} \times \delta_{input} = 2.17m$$

$$\delta_x = \cos(\psi + \beta) \times \frac{\sin(\alpha + \gamma + \psi)}{\sin(2\psi + \beta + \gamma)} \times \delta_{input} = 1.01m$$

The calculated wedge displacement is near to surface deformation profile on **Figure 9**.

## Dip Angle & Fault type effect

With changing Dip angle the ratio of Vertical to horizontal motion is changed. As mentioned, the effect of horizontal and vertical motion, neutralize each other one side and amplifies their effects on the other side of dislocation point. So changing Dip angle will affect the formation of shear band on the neutralized side.

For a specific site and fault slip, with reducing

Dip angle and increasing lateral pressure; there is a threshold dip angle which pattern of shear band changes from single to dual system.

For the associate plasticity which dilatancy pressurizes the deposit and helps to create conjugate sheared zone, this threshold is higher from zero dilatancy case. For contractive material the formation of second shear zone will be delayed more and with high contraction the formation of dual shear zones system becomes impossible for reverse fault.

By passing this dip angle threshold and creation of dual shear zones system the sheared zone shape is independent of dip angle and it is possible to calculate the deformation from kinematics.

The other note is about surface fissure brushing direction. For nearly vertical dip angle and with  $\sigma_{xx}$  concentration near surface in tension form (**Figure 6**) a small active zone is created behind main shear band. Due tension nature of active zone, this zone is visible near surface as fissures.

By reducing dip angle and increasing  $\sigma_{xx}$  this active zone will be diminished and replace a passive zone will be created on the front of main shear band. Usually passive zones can not be

recognized unless excessive deformation take place.

failure mode is formed and the possibility of formation of conjugate shear band is higher than thrust fault motion.

In normal faulting the motion direction is opposite to reverse fault and horizontal motion component impose extension on the media. Due to this extensional horizontal motion, active

The formed wedge over dislocation point is active type wedge and is narrower than reverse fault passive wedge.



Figure 10- Cross section of an excavated trench (After Tani 1998 CRIEPI) Formed wedge and upheaval motion is clear

# CONCLUSIONS

In this paper, Deposit rupturing phenomenon was clearly described by simplification of the problem's geometry, material model. The main concern was about sheared zone shapes, orientation, formation sequence and deposit profile deformations; Effects of the important parameters such as Deposit Dilatancy, Mechanical properties distribution, Fault type and dip angle were described.

From kinematics point of view, deposit rupturing can be debated as sliding of rigid blocks (similar to Upper bound solution). The key factor for this type of analysis is "dilatancy".

To keep the system cinematically moving, the geometrical requirements for the orientation of these rupture lines were considered and a method. Assuming single or double rupture lines patterns, a useful relations were derived in order to express the relation between rupture orientation, dilatancy and blocks motion.

To determine the conditions of either single or dual band system formation, the system statics should be considered. For a dip slip thrust fault, the motion has two components: horizontal and vertical. Elastic analysis and superposition of the vertical and horizontal motions showed that on the hanging wall side, the effect of horizontal and vertical motions almost neutralizes the effect of each other while the on the footwall side, their effects are amplified. Considering this, on the footwall side, a passive shear band will definitely be created and on the hanging wall side, based on dip angle and material dilatancy, a second sheared passive zone may form.

There is a threshold dip angle, at which the shear band pattern changes from single to dual. This threshold dip angle is dependent on dilatancy feature. This threshold is lower (less inclined dip motion) in case of zero dilatancy; while in case of the associate plasticity, dilatancy pressurizes the deposit and helps to create the conjugate sheared zones. For contractive materials, the formation of second shear zone will be delayed. For dual shear zones system sheared zone shape is independent on the input motion dip angle and it is possible to calculate the deformation by using kinematics compatibility. From limit equilibrium point of view, a pure horizontal base motion is equal to symmetric rough retaining wall (Rankine) problem. So horizontal component of reverse fault motion will cause passive type failure in deposit; Similarly, active type failure will be developed for normal fault. Rationally, for a thrust fault, failure zone is wider than normal fault; Due to the tensional nature of active zone, rupture lines are more visible for normal faulting.

Also for expressing the sequence of shear band formation and deriving the dimensionless groups a conceptual model is made regarding the nature of problem. This model consists of parallel elastic strips connected by bilinear springs. The important terms of the model were  $L_e$  and  $\delta_{ultimate}$ . The  $L_e$  is a measure for problem size, from elasticity point of view.  $\delta_{ultimate}$  is the displacement that occurs at the base (bottom) and causes a failure (slip) to reach the surface.  $\delta_{input}/\delta_{ultimate}$  is an important dimensionless group for similarity analysis and scale prototype test.

The validity of this dimensionless group is proved by 2D FEM simulation using Mohr Coulomb for Geometric proportional configurations.

 $\delta_{\text{input}}/\delta_{\text{ultimate}}$  can be considered as a suitable index for hazard assessment at a specific site. In this regard, as  $\delta_{\text{input}}$  can be determined from

seismic-geology data, an estimation of  $\delta_{\text{ultimate}}$  will give useful hints about the developed degree of rupture propagation on the deposit.

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