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Fault Induced Ground Deformations and Their Effect on Structures

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SYNOPSIS: In the United States and in many other regions of the world, structures such as earth dams are built in areas very close to strike-slip faults. For the safe design of these and other types of structures, geotechnical engineers need a reliable estimate of the ground deformations that fault movement will induce at the site of the proposed structures. In this study, the vertical ground deformations induced by the movement of one strike-slip fault segment is estimated with the use of Linear Elastic Fracture Mechanics (LEFM) theory. The ground deformations estimated using this theory and the deformations experienced by the ground surrounding one strike-slip fault segment in Japan compared well. The effect of the ground displacements on structures near strike-slip fault segments is also examined.

INTRODUCTION

In the United States and in many other regions of the world, structures are often built in areas very close to faults (Seed et al., 1978; Seed, 1979). According to Billings (1985), by 1985 the number of earth dams located within 5 miles of major faults in the state of California reached 60. For the safe design of these and other types of structures, earthquake and geotechnical engineers need a reliable estimate of the ground deformations that fault movement will induce at the sites of the proposed structures. In the present study Linear Elastic Fracture Mechanics (LEFM) theory will be used to estimate the vertical ground deformations induced by the movement of strike-slip fault segments.

FAULT SEGMENTATION

Recent field studies have demonstrated that strike-slip fault zones, especially long ones, do not rupture along their entire length during a single earthquake but along individual fault segments that appear to have continuity, character, and orientation; this suggests that a segment mobilizes as a unit (Segall and Pollard, 1980; Schwartz, 1988). This discontinuous feature of strike-slip faults allows them to be treated as large cracks in brittle materials. Thus, Linear Elastic Fracture Mechanics (LEFM) theory can be used to evaluate vertical ground deformations induced by fault movements.

GROUND DISPLACEMENTS

When a strike-slip fault segment slips, the ground surrounding the segment is subjected to two very different types of displacements. The first type of displacement is the one associated with the seismic slip of the segment (ground shaking) (Housner, 1970). The second type of ground displacement is the one associated with the fault-ends induced stresses (Lawn and Wilshaw, 1975; Vallejo, 1987).

This study is concerned with the ground displacements associated with the fault-ends induced stresses. When cracks or fault segments mobilize, the ends of the fault segments concentrate stresses in the surrounding material (Vallejo, 1986, 1987, 1988, 1989). These concentrated stresses are a function of the tectonic stresses that cause the mobilization of the fault segments. According to Chinnery (1964), the tectonic shear stress that causes the mobilization of the strike-slip fault segments forming part of the San Andreas fault system is of the order of 10^7 dynes/cm^2. Thus, the stresses concentrated by the ends of strike-slip fault segments are in fact extremely large. These concentrated stresses will in turn cause large deformations of the ground surrounding the strike-slip fault segments. Thus, fault-ends induced deformations need to be taken into consideration when designing structures in areas close to strike-slip fault systems.

THEORETICAL STRESSES AND DISPLACEMENTS

Stresses

The stresses and displacements associated with the movement of one strike-slip fault segment are calculated using the principles of Linear Elastic Fracture Mechanics (LEFM) theory (Lawn and Wilshaw, 1975). The strike-slip fault segment is analyzed as a discrete planar crack of fixed epth, length and orientation in a homogeneous, linear elastic material. The fault segment will be assumed closed. Ehen the fault segment is subjected to a far-field shear stress, τ_∞ , (Fig. 1(a)), the strike-slip fault segment is activated and a frictional shear resistance,

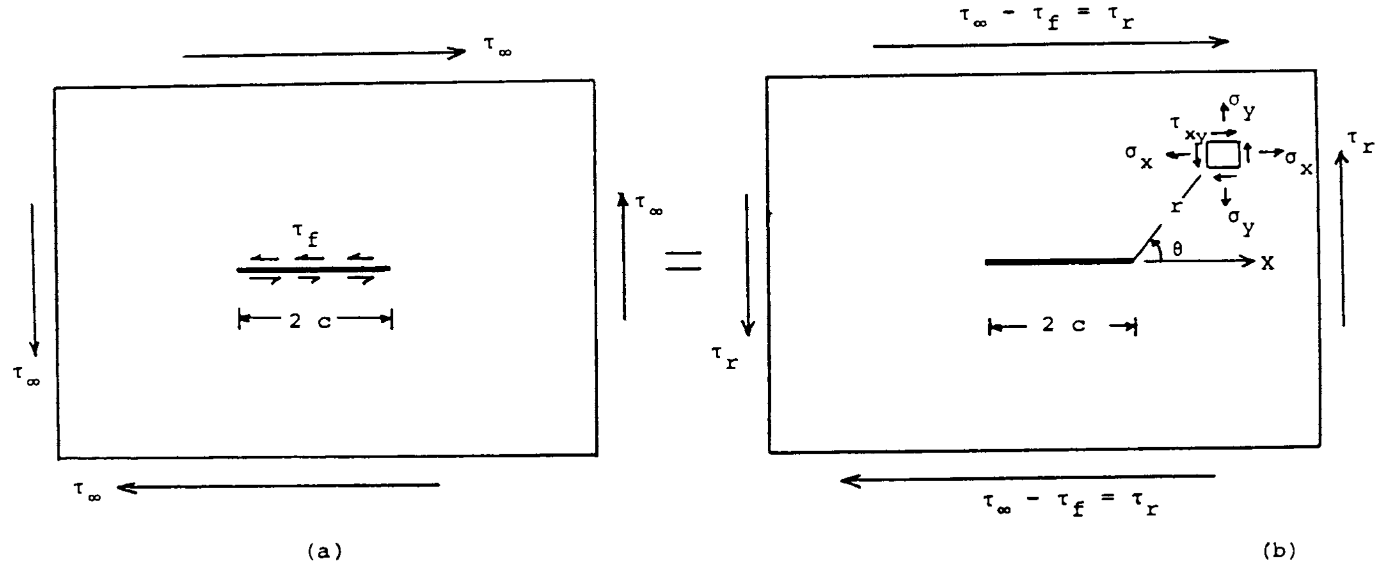

Fig. 1 System Of Stresses Associated With A Strike-Slip Fault Segment Idealized As A Shear Mode II Fault.

τ_f , mobilizes in the plane of the fault segment (Fig. 1(a)). According to Rudnicki (1980), the system of shear stresses acting outside and in the plane of the strike-slip fault segment (Fig. 1(a)) can be replaced by a single far-field shear stress, τ_r , (Fig. 1(b)), in order to calculate the stresses and vertical deformations around the tip of the fault segment. The far field shear stress, τ_r , for fault segments in the San Andreas fault system can have values of the order of 10^7 dynes/cm^2 (Chinnery, 1964).

The normal and shear stresses, σ_x , σ_y and τ_{xy} (Fig. 1(b)) in areas close to the tips of one strike-slip fault segment can be obtained from the following relationships (Lawn and Wilshaw, 1975)

$$\sigma_x = \frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\left[- \sin\frac{\theta}{2}\left(2 + \cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right)\right] \qquad (1)$$

$$\sigma_y = \frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\left(\sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2}\right) \qquad (2)$$

$$\tau_{xy} = \frac{K_{II}}{(2\pi r)^{\frac{1}{2}}}\left[\cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)\right] \qquad (3)$$

where r is the distance from the tip of the fault segment at which the stresses and vertical ground deformations are being calculated (Fig. 1(b)), θ is the angle that the radius r makes with the plane of the fault segment, and K_{II} is the stress intensity factor that can be obtained from the following relationship (Rudnicki, 1980)

$$K_{II} = \tau_r\,(\pi c)^{\frac{1}{2}} \qquad (4)$$

where c is half the length of the fault segment, and τ_r is the shear stress that cause the mobilization of the fault segment.

Using Equations (1) through (4), the value of the principal stresses, σ_1 and σ_3 can be obtained from (Vallejo, 1987)

$$\sigma_{1,3} = \frac{\sigma_x + \sigma_y}{2} \pm \left[\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}\right]^{\frac{1}{2}} \qquad (5)$$

For a hypothetical strike-slip fault segment, mobilized by a tectonic shear stress (τ_r) equal to 1000 units of stress, the value of the principal stresses developed by the ground surface surrounding the segment were calculated using Eqs. (1) through (5). Fig. 2 shows the magnitude and direction of the principal stresses around the tips of the strike-slip fault segment. This figure indicates that the segment concentrated large compressive stresses on the upper right and lower left sections of the segment and concentrated large tensile stresses in the upper left and lower right sections of the fault segment. The compressive stresses will be associated with uplift zones in the ground surrounding the fault, and the tensile stresses will be associated with zones of subsidence in the ground surrounding the fault segment.

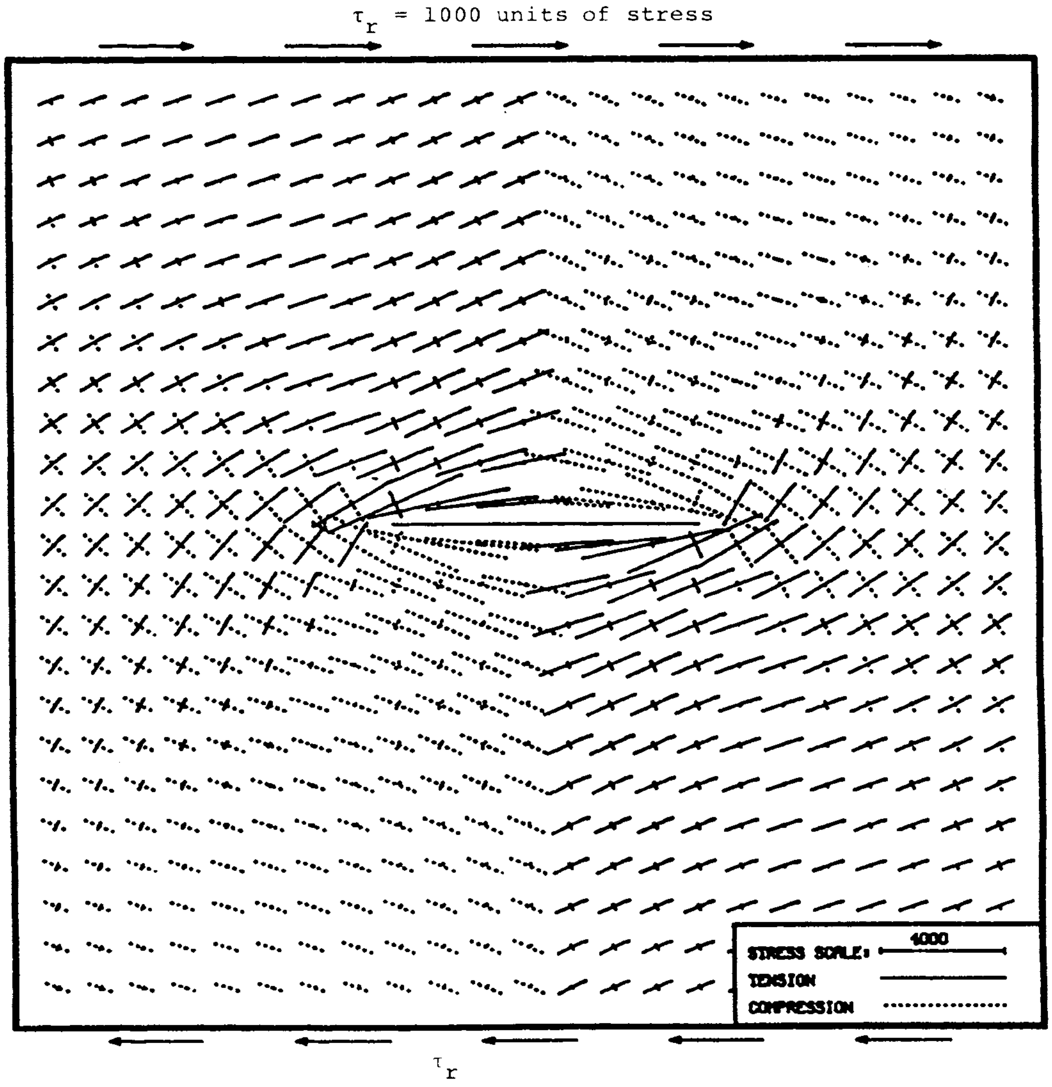

Fig. 2 Principal Stresses Around A Strike-Slip Fault Segment Subjected To A Tectonic Shear Stress Equal To 1000 Units of Stress. Solid Lines Show Tension. Dotted Lines Indicates Compression.

Displacements

The vertical (normal to the ground surface) displacement, u_z, in areas close to the tips of the strike-slip fault segment (Fig. 2) can be obtained from the following relationship (Lawn and Wilshaw, 1975)

$$u_z = \left(- \frac{\nu z}{E} \right) (\sigma_x + \sigma_y) \qquad (6)$$

where ν and E are the Poisson's ratio and the Young's modulus of elasticity of the material surrounding the strike-slip fault segment, z is the depth (normal to the ground surface) of the strike-slip fault segment, and σ_x and σ_y are the stresses near the tip of the fault segment that can be obtained from Eqs. (1) and (2).

Using Eq. (6) the value of the vertical displacement of the ground close to the right tip of the strike-slip fault segment depicted in Fig. 2 was calculated and plotted in Fig. 3. Fig. 3 shows that the right end of the fault segment developed two different displacement zones. One was a zone of subsidence associated with the tensile stresses in Fig. 2, and the other was a zone of uplift associated with the compressive stresses in Fig. 2. Fig. 3 also shows that the intensity of vertical ground deformations associated with the stresses concentrated by the ends of the segment were very large near the tip of the segment and progressively decreased as one moves away from the fault segment. In Fig. 3 the amount of vertical

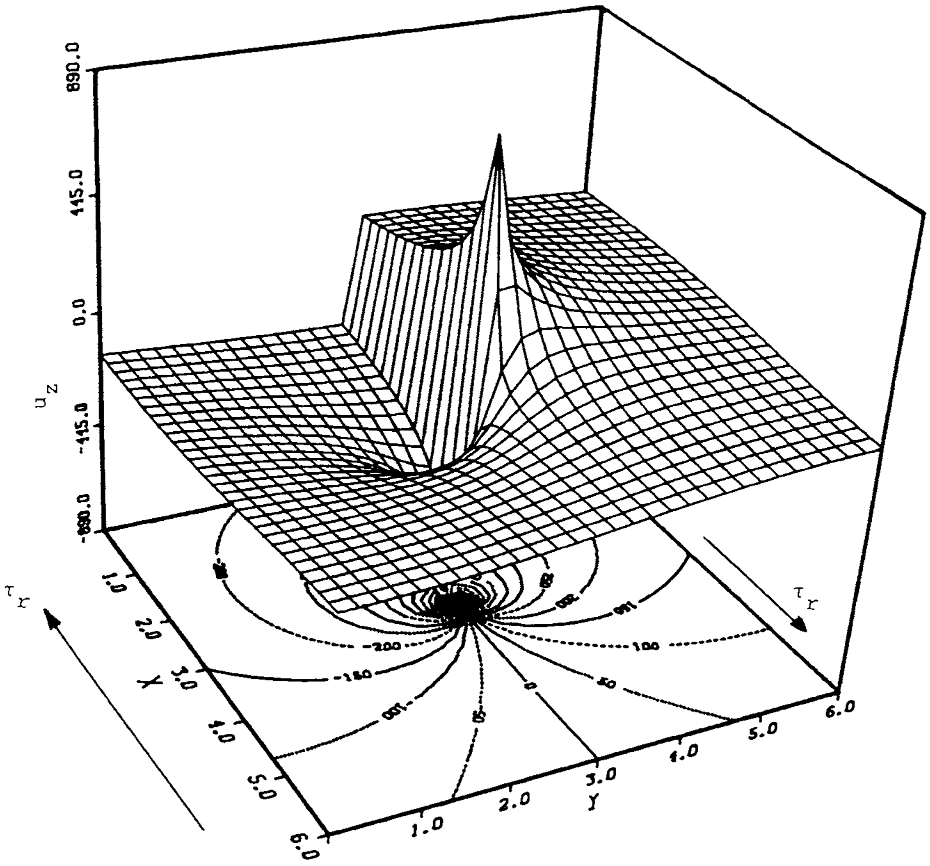

Fig. 3 Vertical Displacements Around The Right-End Of The Strike-Slip Fault Segment Subjected To A Far Filed Shear Stress τ_r = 1000 psi, E = 1 psi, ν = 0.3 and z = 1 in . This Plot Was Obtained Using Eq. (6).

deformation is also plotted in a contour form on a plane normal to the vertical direction.

SUBSTANTIATION OF THE THEORETICAL METHOD

Examples of subsidence and uplift zones associated with the fault-ends induced stresses and the resulting vertical ground deformations have been reported to occur in northern California and Japan (Bonilla, 1970; Ando, 1974). In California, Bonilla (1970) reports subsidence zones measuring as much as 2 feet in depth that developed at the ends of strike-slip fault segments forming part of the San Andreas fault system. A more dramatic example of the ground deformations induced fy the fault-ends induced stresses can be seen in Fig. 4. This figure shows the zones of subsidence (dotted lines) and uplift (full contours) generated by the Kozu-Matzuda sltrike-slip fault segment when it became mobilized in 1923. The right-lateral tectonic shear stress induced stress concentrations at the ends of the fault which in turn produced large zones of subsidence and uplift at the end of the fault segment. These zones of subsidenc and uplift are predicted well by the theoretica method presented in this paper (compare Fig.3 with Fig. 4). The zones of subsidence (dashed contours in Fig. 4) extended up to a distance of 40 km from the left end of the Kozu-Matzuda fault in Japan. The zone of uplift (solid contours in Fig. 4) in turn extended to a distance in excess of 50 km from the right end of the fault.

Thus, by comparing Figs. 3 and 4 it can be concluded that the vertical ground displacement obtained from Linear Elastic Fracture Mechanics theory (Eq. (6)) predicts well the pattern of displacements in the field for the case of one strike-slip fault segment. This finding suggests that with proper calibration, the theoretical method presented in this study can be used to obtain a good estimate of the deformations that a given movement of strike-slip fault segments will induce in the surrounding area.

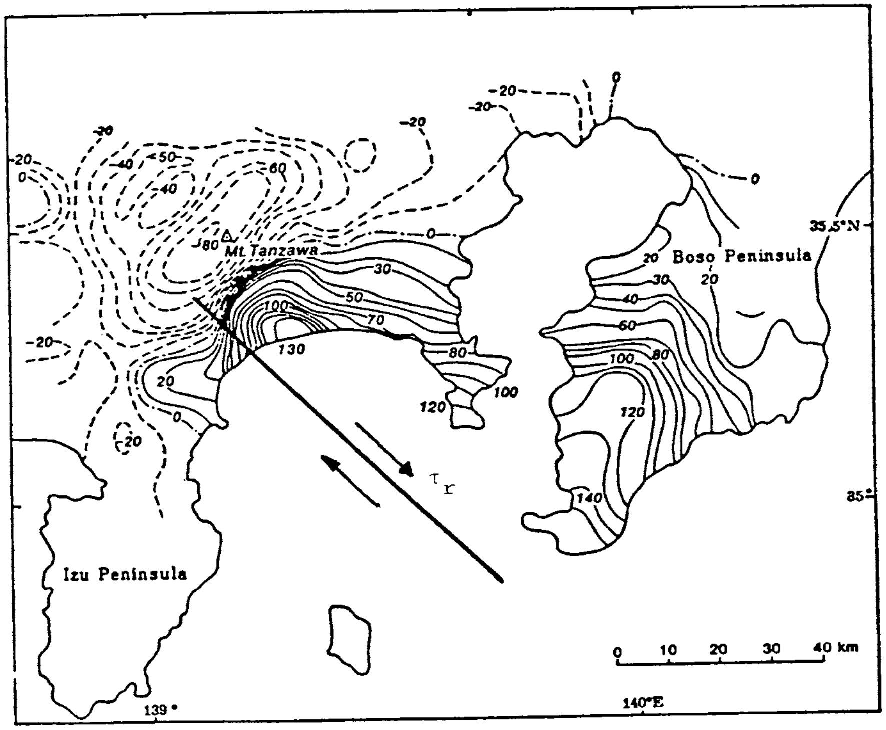

Fig. 4 The Kozu-Matsuda Strike-Slip Fault Segment In Japan (Ando, 1974). Dotted Lines Show Zones of Subsidence. Full Contours Show Zones of Uplift.

EFFECT ON STRUCTURES

Fig. 2 shows that when a strike-slip fault segment becomes activated, distinctive zones of tensile and compressive stresses are induced around the tips of the fault segment. The tensile and compressive stresses will induce tensile and compressive strains in the ground surrounding the fault (Fig. 3). If a structure is located in areas surrounding a strike-slip fault segment, such as the one shown in Fig. 4, the tensile and compressive strains developed by the ground surface could cause the distortion, cracking and failure of buildings, dams, walls, bridges, pipelines, highways, railroads and electric cable systems (O'Rourke and Trautmann, 1981).

Slope changes in the ground surface (Figs. 3 and 4), also referred to as differential settlement or tilt, could affect gradients of roads, rail tracks, gas and water mains and the overall drainage patterns of the area surrounding strike-slip fault segments. Tilting can be detrimental to buildings, machines and water tanks. In addition, an increase in the ground slope may increase the erosion potential of soils in agricultural areas (Wahls, 1981).

CONCLUSIONS

In this study, a theoretical method based on Linear Elastic Fracture Mechanics (LEFM) theory has been presented to estimate the vertical ground deformations produced when a strike-slip fault segment is mobilized by a tectonic shear stress.

The pattern of vertical displacements experienced by the ground surrounding a strike-slip fault segment in Japan and those calculated by the theoretical method compared well.

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