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Liquefaction zones predicted by the type of stresses induced by the ends of fault segments

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ABSTRACT: Faults are discontinuous geologic features consisting of discrete segments, allowing them to be treated as cracks. When a fault segment is mobilized by a tectonic shear stress, one end (dip-slip fault) or both ends (strike-slip) of the segment concentrate stresses. The large stresses that one or both ends of the fault segment concentrate are of two kinds. One side of the fault-end concentrates tensile stresses while the other side concentrate compressive stresses. If the zones surrounding the segment contain soils susceptible to liquefaction, the zones around the fault-end that develop compressive stresses can liquefy because the compressive stresses can cause the pore water pressure to increase to the levels of the intergranular stresses. Liquefaction may not occur in areas of tensile stresses because there the soil expands. Thus, fault-end induced stresses have a marked influence in dictating where soils liquefy. Evidence supporting this hypothesis was found in areas around four faults in Idaho, California and Missouri.

1 INTRODUCTION

Current predictive models for earthquake induced liquefaction of saturated loose sands assume that their liquefaction is a function of the cyclic shear stresses induced in the sediments by seismic shear waves (Seed and Lee, 1966). The cyclic shear stresses cause excess pore water pressures in the sands. These pore water pressures can become equal to the intergranular stresses and thus liquefaction is the end result. Current earthquake induced liquefaction analysis, however, does not take into consideration the influence of the large stresses induced in the ground by the ends of fault segments.

Recent field studies have demonstrated that faults are discontinuous geologic features consisting of one or a multiple number of discrete segments (Segall and Pollard, 1980). This discontinuous nature of faults allows them to be treated as large cracks in brittle materials. Thus, Linear Elastic Fracture Mechanics (LEFM) theory can be used to evaluate the stresses in the ground induced by fault movements.

Vallejo (1987), Vallejo and Shettima (1991) (Figs. 1 and 2) and Segall and Pollard (1980) have found using LEFM theory that when strike-slip fault segments are mobilized by a tectonic shear stress, τ , the ends of the segments concentrate large stresses. The stresses that the ends of the segment concentrate are of two kinds. One kind of stress is of the compressive type (C) and the other is of the tensile type (T). The type of stress that the ends of the strike-slip segments develop depends upon the direction of the tectonic shear stress, τ , and the arrangement of the strike-slip fault segments.

If the zones surrounding the strike-slip fault segments shown in Figs. 1 and 2 are filled by soils susceptible to liquefaction, the zones around the fault with high compressive stresses (C) may liquefy. The reason for this is that the compressive stresses can cause the pore water in the soils to develop high pressures that can reach the levels of the existing intergranular stresses. Liquefaction may not occur in zones of tensile stresses (T) surrounding the faults because the soils there will expand, causing a decrease in pore water pressures. Thus, fault-ends induced stresses may have a marked influence not only in causing liquefaction of soils but also in dictating where soils may liquefy in the field. Therefore, any seismic zonation with respect to earthquake induced liquefaction should consider the fault-ends induced stresses.

The purpose of this study was to determine if fault-end induced stresses influence the location of liquefaction near active faults. To check the validity of this hypothesis, the liquefaction data of zones around four active faults were compared with the type of stresses induced by the ends of these faults. The active faults selected are located in Idaho, California and Missouri.

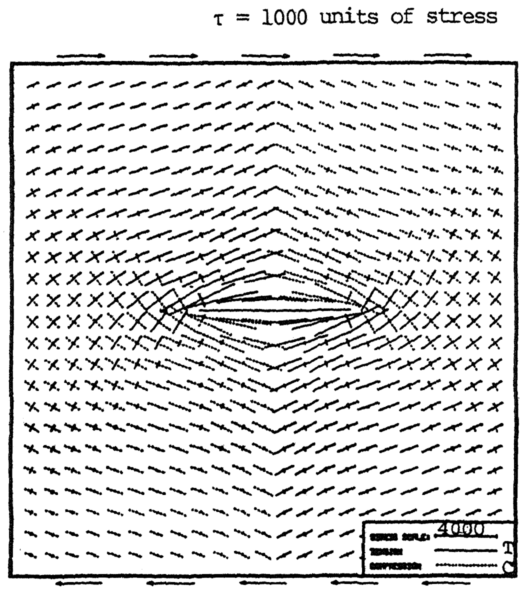

Fig. 1 Principal stresses around a strike-slip fault segment subjected to a tectonic shear stress (solid lines are tension, dotted lines represent compression).

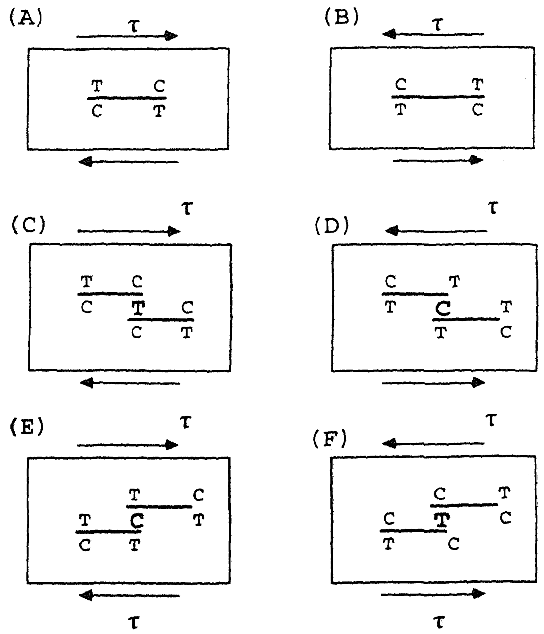

Fig. 2 Zones of compression and tension around a single strike-slip fault (A and B), and around two left-stepping strike-slip fault segments (E and F) or two right-stepping strike-slip fault segments (C and D).

2 LIQUEFACTION ZONES AND STRESSES ASSOCIATED WITH THE LOST RIVER FAULT, IDAHO

On october 28, 1983, an earthquake with a magnitude 7.3 struck east-central Idaho. The earthquake known as the Borah Peak earthquake was the result of the mobilization of the Lost River fault. The Lost River fault is a dip-slip fault segment with a dip angle of 47 degrees and a depth of about 13.3 km (Stein and Barrientos, 1985) (Fig. 3A). According to Youd et al. (1985), the region where the fault is located, known as the Lost River Range, is filled with Quaternary alluvial, and fluvial sediments that are susceptible to liquefaction.

Liquefaction effects generated by the movement of the fault were concentrated to the left of the fault at the locations known as Chilly Buttes and Thousands Springs Valley (Fig. 3B). At the Chilly Buttes area some of the most spectacular effects of the earthquake were the violent eruptions of huge sand boils and springs in a 1 mile long zone to the left of the fault. According to Youd et al. (1985), 66 liquefaction craters developed in the Chilly Buttes area. The liquefaction that produced these craters seem to have taken place as a result of the compaction of saturated sediment layers at depths greater than 5 feet and located to the left of the fault segment (Fig. 3B).

2.1 Stresses associated with the Lost River fault

The stresses associated with the movement of the Lost River fault can be obtained using Linear Elastic Fracture Mechanics (LEFM) theory. In previous papers (Vallejo and Pramono, 1984; Vallejo, 1985; 1986; 1987; 1988a; 1988b; 1989; Vallejo and Shettima, 1991), the Author has presented in detail the method for obtaining the stresses associated with the movement of faults (Figs. 1 and 2). Thus, in the present study the methodology for obtaining these stresses will not be presented. Only the final plots of the magnitude and direction of the principal stresses induced around the Lost River fault are presented.

Fig. 3A shows the Lost River fault dipping at an angle of 47 degrees and subjected to a combination of gravity-tectonic induced normal and shear stresses. Fig. 4 simulates the Lost River fault. The simulated fault segment is subjected to a normal stress, σ equal to 500 units of stress, and a shear stress, τ , equal to 1000 units of stress. These stresses follow similar directions as those acting on the actual fault. Using

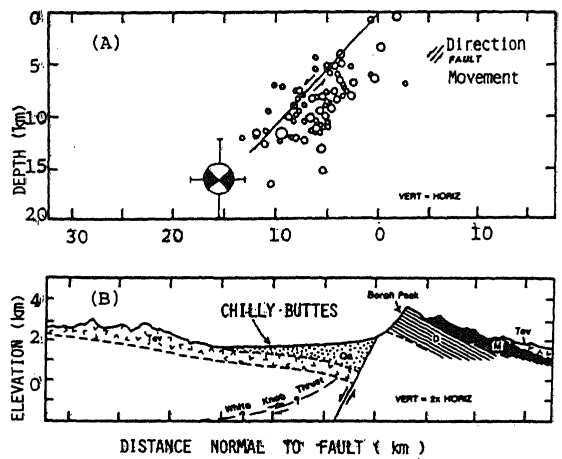

Fig. 3 Profile of the Lost River fault that cause the Borah Peak earthquake (after Stein and Barrientos, 1985)

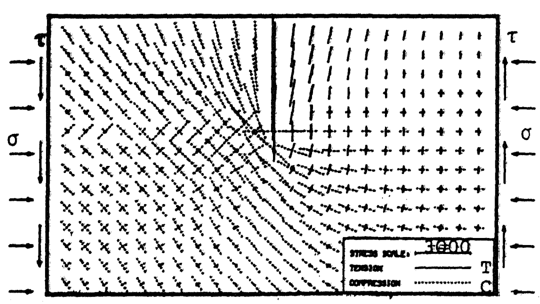

Fig. 4 Principal stresses around dip-slip segment that simulates the Lost River fault (solid lines are tension, dotted lines represent compression).

the principles of LEFM theory, the magnitude and direction of the principal stresses around the fault segment are shown in Fig. 4. These principal stresses are the result of the tectonic-gravity induced normal and shear stresses that act normal and parallel to the plane of the fault.

Fig. 4 indicates that the left section of the fault developed large compressive stresses. These compressive stresses will compact the saturated sediments located at the left of the fault segment. The compaction of these saturated sediments will induce in them excess pore water pressures that in turn will cause sand boils and springs. Thus, the compressive stresses induced by the ends of the Lost River fault influence the location of liquefaction zones around the fault.

3 LIQUEFACTION ZONES AND STRESSES ASSOCIATED WITH THE IMPERIAL AND BRAWLEY FAULTS, CALIFORNIA

On October 15, 1979 the Imperial and Brawley faults in southern California were mobilized causing what is known as the Imperial Valley earthquake (Youd and Wieczorek, 1982). The Imperial fault ruptured along segments that measured 30.5 km. The Brawley fault ruptured along a segment that measured 13.1 km. The Imperial fault is of the strike-slip type, while the Brawley fault is a dip-slip type. A right-lateral slip type of movement took place on the Imperial fault. Vertical displacement in the Brawley fault was downward on the west (left) side of the fault (Fig. 5).

The areas around the fault segments that broke during the 1979 earthquake are filled with channel, flood-plain, and artificial-fill deposits. All these deposits are composed primarly of sand. The water table was located at 1.5 meters from the ground (Youd and Wieczorek, 1982). Liquefaction in the form of sand boils were recorded to occur within 4 km of the fault segments. The locations of the sand boils (the number of which were recorded to be 13)are shown in Fig. 5.

The type of stresses induced in the ground by the ends of the strike-slip fault segments forming part of the Imperial fault are similar to those shown by Figs. 1 and 2(A). The type of stresses induced in the ground by the end of the Brawley fault (dip-slip fault) are similar to those shown by Fig. 4. Fig. 5 shows that 9 of the recorded 13 sand boils took place in the areas of compressive stresses. Thus, the compressive stresses induced by the ends of the Imperial fault segments and the end of the Brawley fault segment seem to have a marked influence on the location of liquefaction zones around these faults.

4 LIQUEFACTION ZONES AND STRESSES ASSOCIATED WITH FAULTS IN THE NEW MADRID AREA, MISSOURI

During the years 1811 and 1812, the New Madrid area of Missouri experienced earthquakes of magnitudes equal to or greater than 6.2. Among the many tectonic surface deformations produced during the earthquakes, the Lake County uplift near New Madrid is worth mentioning. According to Russ (1982), the uplift is about 10 meters high, 50 kilometers long, and 23 kilometers wide. The uplift was produced by the interaction of two strike-slip fault segments as shown in Fig. 6. The type of movement on the segment is right-lateral like the one shown in Fig. 2(E). Fig. 2(E) shows that when

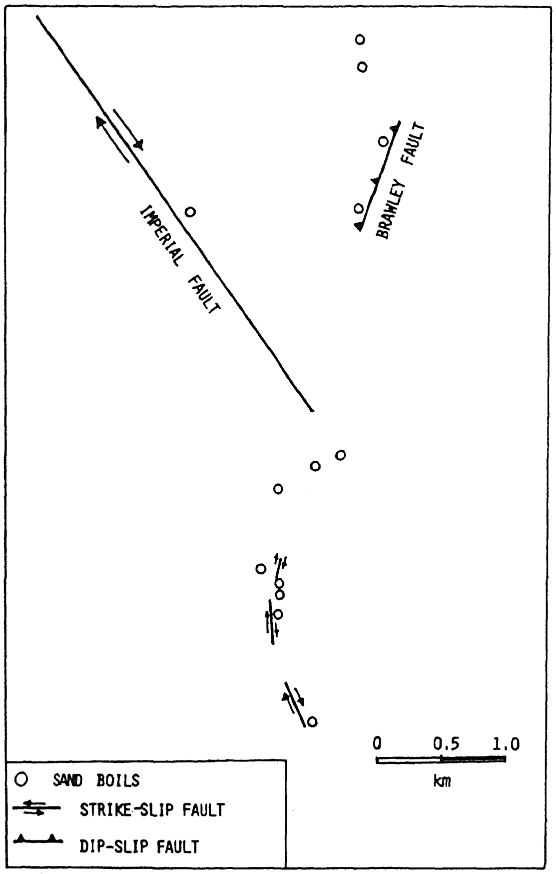

Fig. 5 Liquefaction zones around the Imperial and Brawley faults, California (after Youd and Wieczorek, 1982)

two left-stepping strike-slip fault segments are subjected to a right-lateral shear stress, the overlapping zone develops large compressive stresses. These compressive stresses seem to be the cause of the Lake County uplift.

In addition, McKeown (1982) has reported that a large portion of the Lake County uplift area experienced sand blows during the 1811-12 earthquakes. The Lake County uplift area is filled by fluvial sand deposits resulting from the regular flooding of the area by the Mississippi river. The compression of the saturated sand deposits in the area forming part of the Lake County uplift could explain the formation of the sand blows in this zone. Thus, as in the case of the faults in Idaho and California, the fault-ends induced stresses seem to have a marked influence on the location of liquefaction zones around faults

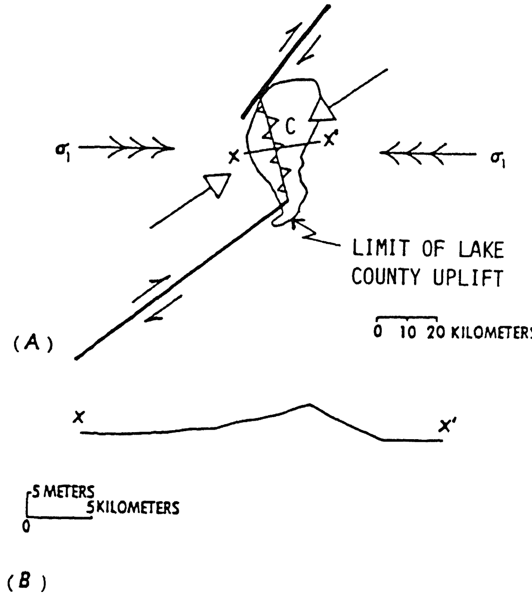

Fig. 6 Lake County uplift formed by the interaction of two left-stepping strike slip fault segments in the New Madrid area, Missouri (after Russ, 1982)

5 CONCLUSIONS

Using the principles of Linear Elastic Fracture Mechanics theory as well as the records of zones of liquefaction associated with four faults located in Idaho, California and Missouri, the following findings have been determined:

1. Depending on the direction of the tectonic shear stresses that mobilize fault segments, and depending on the arrangement of the segments, the ends of these segments concentrate tensile (T) and compressive (C) stresses in different areas of the ground.
2. The location of the compressive and tensile stresses in the ground surrounding the fault segments have a marked influence not only on the liquefaction of the saturated sands surrounding the faults, but on the location of this liquefaction.
3. Any seismic zonation study with respect to earthquake induced liquefaction should consider the effects on liquefaction of the fault-ends induced stresses.

6 ACKNOWLEDGMENTS

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