RECURRENT OF LIQUEFACTION AT THE SAME SITE

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SUMMARY

Liquefaction is known to occur at the same site during more than one earthquake as shown by examples from Japan and the United States. Earthquakes compact liquefiable layers slowly from the bottom up, generally leaving them susceptible to liquefaction until the process is complete; and large shear deformations generally dilate soils in the shear zone perpetuating their susceptibility to liquefaction. Thus, maps and records of sites of past liquefaction provide key information for hazard assessments.

INTRODUCTION

Liquefaction is not a once-only phenomenon: it can occur at the same site during successive earthquakes. This paper reports several examples of recurrence of liquefaction at the same site and examines the mechanisms that cause recurrence. Because areas that have undergone liquefaction are very likely to reliquefy during future earthquakes, maps and descriptions of past occurrences of liquefaction provide important data for earthquake hazards assessments.

The list of reported instances of recurring liquefaction is short, largely because very few large earthquakes have recurred in the same region since scientific investigations of earthquakes began. As more earthquakes recur in areas of earlier studies, this list will surely grow.

Kuribayashi and Tatsuoka (Ref. 1) identified seven areas in Japan where surface effects of liquefaction have occurred more than once at the same site in the past 100 years. Along the former course of the Tone river northeast of Tokyo, sand boils erupted during four successive earthquakes, in 1894 (M 7.5), 1895 (M 7.3), 1923 (M 7.5), and 1931 (M 7.0). Sand boils recurred in two parts of the Nobi plain northwest of Nagoya during successive earthquakes; in the northwest part of the plain in 1891 (M 8.4) and 1909 (M 6.9), and in the southern part in 1891 and 1935 (M 6.3). Earthquakes in Nagoya in 1944 (M 8.0) and 1945 (M 7.1) generated sand boils near airplane factories that sustained damage; and shocks in 1894 (M 7.3) and 1964 (M 7.5) generated large and rather violent sand boils on the left bank of the Mogami river near the Sea of Japan.

Liquefaction effects have recurred at several localities in California. During the 1868 Hayward (M 6.5-7) and 1906 (M 8.3) San Francisco events, sand boils, ground fissures, and spreading and slumping of river banks occurred at the same localities along Coyote and Alameda creeks (Ref. 2), within a few kilometers of San Francisco Bay. Fissures caused by liquefaction recurred in San Francisco during earthquakes in 1865, 1868, and 1906 (Ref. 2).

In southernmost California, several sand boils with deposits about 2 m in diameter erupted on the floodplain of the New River north of Brawley during the 1979 Imperial Valley earthquake (M 6.6) (Ref. 3). These same sand boils

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reactivated slightly during the 1981 Westmorland earthquake (M_s 6.0), producing 15-cm diameter spots on the tops of the previous deposits (Fig. 1). These rejuvenated sand boils were at the fringe of the zone within which liquefaction effects occurred during the 1981 event (Ref. 4).

Excavation of liquefaction sites has revealed evidence of prehistoric liquefaction. A trench across a fissure on which several sand boils erupted during the 1971 San Fernando, California earthquake (M_s 6.5) exposed a sand-filled fissure and thin foliated layers of sand in the shallow subsurface. The sand beyond the area of 1971 sand boils was not injected during the 1971 event, indicating that liquefaction and opening of fissures had occurred previously. The fissure and sand boils were in a field south of the San Fernando Valley Juvenile Hall, a facility that was heavily damaged by a liquefaction-caused lateral spread during the 1971 event (Ref. 5).

**PROCESSES PRODUCING RELIQUEFACTION**

Two processes that directly affect the initial development and recurrence of liquefaction are compaction and shear. Although earthquake vibrations generally compact granular soils, including those that liquefy, the compaction process takes time, and several recurrences of liquefaction may occur before compaction is complete. On the other hand, dilation of granular layers during shear loosens soils, which may offset compaction caused by vibratation and perpetuate a susceptible condition during many earthquakes.

**Compaction**

Increase of excess pore pressure that causes liquefaction during an earthquake is caused by the tendency of the soil to compact during vibration. The more easily the soil compacts, the faster pore pressures rise and the more susceptible the soil is to liquefaction. Thus, the state of compaction left by a previous episode of liquefaction directly affects the susceptibility of the soil. Three aspects of liquefaction-compaction behavior are important in this connection:

1. Liquefaction of a uniform layer of sand generally begins at the top of the layer and propagates downward. This behavior is illustrated in tests by Florin and Ivanov (Ref. 6) in which they vibrated a saturated layer of sand in a rigid-walled tank. Initially, excess pore pressures increased uniformly with depth leading to a zero effective stress state and liquefied condition near the top of the layer where overburden pressures were least. With time, excess pore pressures continued to increase uniformly below the level of zero effective stress causing that level, and the liquefied condition, to propagate downward through the layer (Fig. 2a). Similarly, liquefaction of a uniform granular layer in the field should begin at the top, where overburden pressures are least, and then propagate downward through the layer if the duration of shaking is long enough.

2. If an liquefied granular layer lies immediately above a liquefied layer with generally similar grain-size characteristics, the liquefied condition can propagate upward with time into the overlying layer. This behavior is predicted by mathematical models (Refs. 7 and 8) and confirmed by field observations. For example, the eruption of sand boils and tipping of buildings in Niigata, Japan in 1964 began several minutes after strong ground
Fig. 1. Sand boils on floodplain of the New River, California which erupted during the 1979 Imperial Valley, California earthquake (a) and slightly rejuvenated during the 1981 Westmorland, California earthquake (b).
Fig. 2. Data from tests by Florin and Ivanov (Ref. 6) showing (a) that liquefaction of a granular layer begins at the top of the layer and propagates downward, and (b) that reconsolidation begins at the bottom of the layer and propagates upward.

shaking ceased, indicating that liquefaction began in a layer several meters deep and then propagated upward through initially unliquefied layers to the ground surface (Ref. 8). Such action can leave the layers through which liquefaction propagated in a looser, more susceptible condition than they were before the earthquake.

3. Reconsolidation of a liquefied layer begins at the bottom and propagates upward through the layer. This behavior was documented in the laboratory experiments by Florin and Ivanov (Ref. 6) who found that decrease in excess pore pressures and reconsolidation of liquefied layers began at the bottom of the layer and propagated upward. The data in Fig. 2b documents this behavior for one test; in this instance, however, vibration continued during the reconsolidation process and the layer was compacted in the process. In tests where vibration was stopped during reconsolidation, those parts of the liquefied layer that reconsolidated after shaking stopped reconsolidated into a loose condition possibly even looser than the original material. Similarly, layers of granular material that liquefy in the field would also reconsolidate and compact from the bottom upward and if earthquake shaking stops before reconsolidation is complete, the material could be left vulnerable to reliquefaction.

Where drainage from the top of a layer is restricted, compaction from the bottom up can cause a loose, readily liquefiable zone to form at the top of the layer which may persist through many earthquakes until compaction is complete. A site where field evidence indicates that such a loosened layer has developed is River Park in Brawley, California. Cone penetration data from that site reveal a loose zone at the top of a buried layer of sand several meters thick (Fig. 3). The sand layer is overlain by 0.9 to 1.5 m of clay which in turn is overlain by 1.8 to 2.5 m of silt and sandy silt. Cone penetration resistance in the loose zone is as low as 10 kg/cm² but within a meter below it exceeded 100 kg/cm² indicating dense sand at that depth. The upper part of the sand layer liquefied during the 1979 Imperial Valley earthquake, producing hundreds of sand boils and a slump near a river at the west margin of the site (Ref. 9). The loose zone most likely developed as a consequence of liquefaction and reconsolidation of the sand layer during past
Fig. 3. Cone penetration data from River Park in Brawley, California, revealing a loose zone at the top of a thick granular layer. The loose zone liquefied during the 1979 Imperial Valley earthquake, is susceptible to reliquefaction during the next major earthquake, and probably formed as a consequence of liquefaction and reconsolidation of the layer during past earthquakes.

Earthquakes with compaction beginning at the bottom of the layer and the expelled water collecting at the top of the layer beneath the impermeable clay. The loosened condition was maintained during the 1979 earthquake, and the penetration data indicate that the zone remains highly susceptible to reliquefaction. The compaction behavior of this layer is probably typical of many granular layers in seismic zones.

Shear

During shear, granular soils may compact or dilate depending on the compactness of the soil, the confining pressure, and the amount of shear deformation applied. Drained tests by Roscoe and others (Ref. 10) show that except for very dense packings, sands initially compact as shear strain is applied. At larger strains, all but very loose sands or sands under high confining pressure dilate toward a critical void ratio condition (Fig. 4). For undrained or partially drained conditions these compaction and dilation tendencies generate an increase or decrease of pore pressure, respectively.
An increase of pore pressure induces drainage out of the shear zone and compaction of the soil. A decrease in pore pressure generally leads to sucking of water into the shear zone and loosening of the soil. Thus, in granular layers where ground failure produces large shear strains, such as in the shear zone beneath a lateral spread, shear deformation and dilation can loosen the layer. Over a series of earthquakes, soils in such shear zones can be loosened to a void ratio near critical, and reach a state of perpetual susceptibility to liquefaction.

An example of these conditions is the lateral spread that crossed Heber Road during the 1979 Imperial Valley earthquake (Ref. 9). That spread disrupted and shifted Heber Road and a parallel unlined canal as much as 2 m southward. Post-earthquake soundings revealed a 3-m thick layer of loose, saturated, very fine sand and silty sand beneath the site (Fig. 5); liquefaction of that layer generated the lateral spread. If shear deformations were uniformly distributed across the liquefied layer, they were as great as 70 percent. The penetration data indicate that this layer remains in a loose condition that is susceptible to liquefaction.

Dilatancy caused by shear of granular soils can create small voids near particles rolling or sliding over one another; these voids readily collapse when shear stresses reverse, which frequently occurs during earthquake shaking (Ref. 11). If many of these small voids are left in the soil structure at the conclusion of shaking and associated shear deformation, a soil fabric remains that makes the soil highly susceptible to liquefaction during subsequent earthquakes. For example, laboratory tests by Finn and others (Ref. 12) showed that only a few loading cycles were required to cause liquefaction of samples that had required tens to hundreds of cycles to liquefy initially. Thus, the first occurrence of liquefaction can leave a soil more vulnerable to liquefaction than it was to initial liquefaction.
Fig. 5. Geotechnical section revealing a 3-m-thick layer of loose fine sand and silty sand (unit A₂) which liquefied during the 1979 Imperial Valley, California earthquake and across which up to 2 m of horizontal displacement occurred. Post-earthquake penetration data indicate that this layer is susceptible to reliquefaction during the next major earthquake.

CONCLUSIONS

1. Historical evidence indicates that sites of past liquefaction are likely sites of future liquefaction if soil and groundwater conditions remain unchanged.

2. Earthquakes generally liquefy soil layers from the top downward and compact them from the bottom upward, a process that takes considerable time and may create a loose zone at the top of the layer, which is repeatedly liquefiable and which persists until compaction is complete.

3. Shear deformation produced by ground failure displacement can dilate and loosen granular soils in the shear zone, leaving them as susceptible or more susceptible to liquefaction than they were before.
REFERENCES


