Module 6
LIQUEFACTION
(Lectures 27 to 32)

Lecture 29

Topics

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6.5 INITIATION OF LIQUEFACTION

The fact that a soil deposit is susceptible to liquefaction does not mean that liquefaction will necessarily occur in a given earthquake. Its occurrence requires a disturbance that is strong enough to initiate, or trigger, it. Evaluation of the nature of that disturbance is one of the most critical parts a liquefaction hazard evaluation. Any discussion of the initiation of liquefaction must specify which liquefaction related phenomena are being considered. Many previous studies of liquefaction initiation have implicitly lumped flow liquefaction and cyclic mobility together, but since they are distinctly different phenomena, it is more appropriate to consider each separately.

Although cyclic mobility is an earthquake related phenomena, flow liquefaction can be initiated in a variety of ways. Flow slides triggered by monotonic loading (static liquefaction) have been observed in natural soil deposits (Koppejan et al., 1948; Anderson and Bjerrum, 1968; Bjerrum, 1971; Kramer, 1988) man-made fills (Middlebrooks, 1942; Cornoirth et al., 1975; Mitchell, 1984) and mine tailings piles (Kleiner, 1976; Jennings, 1979; Eckersley, 1985). Flow liquefaction has also been triggered by nonseismic sources of vibration, such as pile driving (Jakobsen, 1952; Broms and Bennermark, 1967), train traffic (Fellenius, 1953), geophysical exploration (Hryciw et al., 1990) and blasting (Conlon, 1966; Carter and Seed, 1988). Perhaps somewhat ironically, the study of static liquefaction over the past 10 to 15 years has contributed greatly to improved understanding of seismically induced liquefaction by identifying the effective stress conditions at which liquefaction phenomena are initiated.
Understanding the initiation of liquefaction identification of the state of the soil when liquefaction is triggered. In the following sections, these conditions will be presented in a framework that allows the mechanics of both flow liquefaction and cyclic mobility to be clearly understood. Subsequently, practical and commonly, used procedures for determining the nature of the disturbance required to move from initial state to the state at which liquefaction is triggered will be presented.

6.5.1 Flow Liquefaction Surface

The conditions at which flow liquefaction is initiated are most easily illustrated with the aid of the stress path. Hanzawa et al., (1979) first showed that the effective stress conditions, at which strain-softening behavior occurred in loose, saturated sands, could be described very simply in stress path space. As discussed in the following sections, the effective stress conditions at the initiation of flow liquefaction can be described in stress path space by a three-dimensional surface that will be referred to hereafter as the flow liquefaction surface (FLS). While some practical difficulties in the measurement of the FLS for general stress paths remain, it provides (in conjunction with steady-state concept) a very useful framework for conceptual understanding o the relationships between the various liquefaction phenomena. This conceptual understanding is vital for proper evaluation of the behavior of liquefied soils both during and after earthquake shaking.

6.5.2 Monotonic Loading

The conditions at which the initiation of flow liquefaction can be seen most easily when the soil is subjected to monotonically increasing stresses. Consider, for example, the response of an isotropically consolidated specimen of very loose, saturated sand in un-drained, stress-controlled triaxial compression (figure 6.14). Immediately prior to un-drained shearing (point A), the specimen is in drained equilibrium under an initial effective confining pressure, \( \sigma_{3c} \), with zero shear stress (figure 14a, b) and zero excess pore pressure (figure 14c). Since its initial state is well above the SSL the sand will exhibit contractive behavior. When un-drained shearing begins, the contractive specimen generates positive excess pore pressure at it mobilizes shearing resistance up to peak value (point B) that occurs at a relatively small strain. The excess pore pressure at point B is also relatively small; the pore pressure ratio, \( n_u = u_{\text{excess}}/\sigma_{3c} \), is well below 1.00. At point B, however, the specimen become unstable, and because it is loaded under stress-controlled conditions, collapse (the axial strain may increase from less than 1% to more than 20% in a fraction o a second). As the specimen strains from point B to point C, the excess pore pressure increases dramatically. At and beyond point C, the specimen is in the steady state of deformation and the effective confining pressure is only a small fraction of the initial effective confining pressure. This specimen has exhibited flow liquefaction behavior; the static shear stresses required for equilibrium (at point B) were greater than the available shear strength (at point C) of the liquefied soil. Flow liquefaction was initiated at the instant it become irreversibly unstable (i.e., at point B).
Figure 6.14: Response of isotropically consolidated specimen of loose, saturated sand; (a) stress-strain curve; (b) effective stress path; (c) excess pore pressure; (d) effective confining pressure

Now consider the response of a series of triaxial specimens initially consolidated to the same void ratio at different effective confining pressures. Since all of the specimens have the same void ratio, they will all reach the same effective stress conditions at the steady state, but they will get there by different stress paths. (Figure 6.15) illustrates the response of each specimen under monotonic loading. The initial states of specimens A and B are below the SSL so they exhibit dilative behavior upon shearing. Specimens, C, D, and E all exhibit contractive behavior, each reaches a peak un-drained strength after which they strain rapidly toward the steady state. For specimen C, D, and E flow liquefaction is initiated at the peak of each stress path (at the points marked with an x). Hanzawa et al., (1979), Vaid and Chern (1983) and a number of more recent investigations have shown that the locus of points describing the effective stress conditions at the initiation of flow liquefaction is a straight line (the dotted line in figure 6.15) that projects through the origin of the stress path. Graphically, these points may be used to define the flow liquefaction surface (FLS) in stress path space; since flow liquefaction cannot occur if the stress path is below the steady-state point, the FLS is truncated at that level (figure 6.16). This form of the FLS was first proposed (with a different name) by Vaid and Chern (1985). It should be noted that Sladen et al., (1985) proposed an analogous surface (called the collapse surface) that was assumed to project linearly through the steady-state point. For very loose samples, the steady-state point may be so close to the origin that the practical difference between the FLS and the collapse surface is negligible.
Figure 6.15: Response of five specimens isotropically consolidated to the same initial void ratio at different initial effective confining pressures. Flow liquefaction in specimens, C, D, and E is initiated at the points marked with an x. The dotted line passing through these points is a line of constant principal effective stress ratio, $K_L$. The FLS marks the boundary between stable and unstable states in undrained shear. If the stress conditions in an element of soil reach the FLS undrained conditions, whether by monotonic or cyclic loading, flow liquefaction will be triggered and the shearing resistance will be reduced to the steady state strength. Therefore, the FLS describes the conditions at which flow liquefaction is initiated.

Figure 6.16: Orientation of the flow liquefaction surface in stress path space

For isotropic initial conditions, the slope of the FLS is often about two thirds the slope of the drained failure envelope for clean sands. Specimens tested under anisotropic initial conditions, however, indicate that the FLS is steeper for soils with high initial
(drained) shear stress compared to soils with lower initial shear stress at the same void ratio (figure 6.17). The FLS may be very close to the initial stress point when initial shear stresses are large, in which case flow liquefaction may be initiated by only a very small undrained disturbance (Kramer and Seed, 1988). Case histories that have been attributed to spontaneous liquefaction probably involved initial shear stresses that were high enough that the small undrained disturbance required to initiate flow liquefaction was not observed.

![Figure 6:17](image_url) Variation of flow liquefaction surface inclination with initial principal effective stress ratio for constant void ratio

The limited liquefaction behavior exhibited by specimens C and d (figure 6.16) is significant for cases in which the static shear stress increases (as in the case of monotonic loading described in this section). In such cases the shearing resistance may drop to values at the point of phase transformation (or the quasi-steady state) that are lower than the steady state strength. This temporary drop in shearing resistance may produce shear strains of 5% to 20% (Ishihara, 1993) and result in unacceptably large permanent deformations. Because the effects of initial conditions are not erased completely at these strain levels, they influence the quasi-steady state strength. Procedure for estimation of quasi-steady state strength are given by Ishihara (1993). Because the static component of shear stress generally remains constant or decreases during earthquakes, the quasi-steady state is less likely to be reached as a result of earthquake shaking.

6.5.3 Cyclic Loading

Vaid and Chern (1983) first showed that the FLS applied to both cyclic and monotonic loading, and a considerable amount of independent experimental evidence supports that observation. Other experimental evidence (e.g., Alarcon-Guzman et al., 1988) suggests that the effective stress path can move somewhat beyond the FLS before liquefaction is initiated by cyclic loading. Whether liquefaction is initiated precisely at the FLS under cyclic as well as monotonic loading is not currently known with certainty. Because the FLS is used as part of a conceptual model of liquefaction behavior, and because it is slightly more
conservative to do so, the FLS will be assumed to apply to both cyclic monotonic loading.

Consider the responses of two identical, anisotropically consolidated, triaxial specimens of loose, saturated sand (Figure 6.18). Initially the specimens are in drained equilibrium (point A) under a static shear stress, \( \tau_{\text{static}} \), that is greater than the steady state strength, \( S_{\text{su}} \). The first specimen is loaded monotonically (under undrained conditions) : the shearing resistance builds up to a peak value when the stress path reaches the FLS (point B). At that point the specimen becomes unstable and strains rapidly toward the steady state (point C). The second specimen is loaded cyclically (also under undrained conditions): the effective stress path moves to the left as positive excess pore pressure develop and permanent strains accumulate. When the effective stress path reaches the FLS (at point D), the specimen becomes unstable and strains toward the steady state of deformation (point C). Although the effective stress conditions at the initiation of liquefaction (point B and D) were different, they fell in both cases on the FLS. The FLS therefore, marks the onset of the instability that produces flow liquefaction. Lade (1992) provided a detailed description of this instability from a continuum mechanics standpoint.

**Figure 6.18:** Initiation of flow liquefaction by cyclic and monotonic loading. Although the stress conditions at the initiation of liquefactions are different for the two types of loading (points B and D), both lie on the FLS

### 6.5.4 Development of Flow Liquefaction

Flow liquefaction occurs in two stages. The first stage, which takes place at small strain levels, involves the generation of sufficient excess pore pressure to move the stress path from its initial position to the FLS. This excess pressure may be generated by undrained monotonic or cyclic loading. When the effective stress path reaches the FLS the soil becomes inherently unstable and the second stage begins. The second stage involves strain-softening (and additional excess pore pressure generation) that is driven by the shear stresses required for static equilibrium. These shear stresses are the *driving stresses* - they must be distinguished from the *locked in stresses* that develop during deposition and consolidation of the soil (Castro, 1991).

Locket in shear stresses, such as those that exist beneath level ground when \( K_0 \neq 1 \), cannot drive a flow liquefaction failure. Large strains develop in the second stage as the effective stress path moves from the FLS to the steady state. If the first stage takes
the soil to the FLS under undrained stress-controlled conditions the second stage is inevitable.

6.5.6 Influence of excess pore pressure

The generation of excess pore pressure is the key to the initiation of liquefaction. Without changes in pore pressure, hence changes in effective stress, neither flow liquefaction nor cyclic mobility can occur. The different phenomena can, however, require different levels of pore pressure to occur.

6.5.7 Flow Liquefaction

Flow liquefaction can be initiated by cyclic loading only when the shear stress required for static equilibrium is greater than the steady-state strength. In the field, these shear stresses are caused by gravity and remain essentially constant until large deformations develop. Therefore, initial states that plot in the shaded region of (figure 6.19) are susceptible to flow liquefaction. The occurrence of flow liquefaction, however, requires an undrained disturbance strong enough to move the effective stress path from its initial points to the FLS.

![Figure 6.19: Zone of susceptibility to flow liquefaction. If initial conditions fall within the shaded zones, flow liquefaction will occur if an undrained disturbance brings the effective stress path from the point describing the initial conditions to the FLS.](image)

If the initial stress conditions plot near the FLS as they would in an element of soil subjected to larger shear stresses under drained conditions, flow liquefaction can be triggered by small excess pore pressure (Kramer and Seed, 1988). The liquefaction resistance will be greater if the initial stress conditions are farther from the flow liquefaction surface. The FLS can be used to estimate the pore pressure ratio at the initiation of flow liquefaction; it decreases substantially with increasing initial stress ratio (figure 6.20) for soils at a particular void ratio. At high initial stress ratios, flow liquefaction can be triggered by very small static or dynamic disturbances.
Figure 6.20: Variation of pore pressure ratio ($r_{u,t} = u_1 / \sigma'_3$) required to trigger flow liquefaction in triaxial specimens of Sacramento River Fine Sand with initial principal effective stress ratio

6.5.7 Cyclic Mobility

Although flow liquefaction cannot occur, cyclic mobility can develop when the static shear stress is smaller than the steady shear strengths. Therefore, initial states that plot in the shaded region of (figure 6.21) are susceptible to cyclic mobility. Note that cyclic mobility can occur in both loose and dense soils (the shaded region of (figure 6.21) extends from very low to very high effective confining pressures and corresponds to states that would plot both above and below the SSL). The development of cyclic mobility can be illustrated by the response of soils in cyclic triaxial tests. Three combinations of initial conditions and cyclic loading conditions generally produce cyclic mobility.

Figure 6.21: Zone of susceptibility to cyclic mobility. If initial conditions plot within shaded zone, cyclic mobility can occur.
The first, illustrated in (figure 6.22a), occur when $\tau_{\text{static}} - \tau_{\text{cyc}} > 0$ (no stress reversal) and $\tau_{\text{static}} + \tau_{\text{cyc}} > S_{\text{su}}$ (steady state strength is exceeded momentarily). Again cyclic loading will cause the effective stress path to move to the left. When it touches the FLS momentary periods of instability will occur. Significant permanent strain may develop during these periods, particularly if $\tau_{\text{static}}$ is greater than the quasi-static shear strength, but the straining will generally cease at the end of cyclic loading when the shear stress returns to $\tau_{\text{static}}$.

![Figure 6.22](image)

**Figure 6.22:** Three cases of cyclic mobility: (a) no stress reversal and no exceedance of the steady state strength; (b) no stress reversal with momentary periods of steady state strength exceedance; (c) stress reversal with no exceedance of steady state strength

The final condition is that in which $\tau_{\text{static}} - \tau_{\text{cyc}} > 0$ (stress reversal occurs) and $\tau_{\text{static}} + \tau_{\text{cyc}} > S_{\text{su}}$ (steady state strength is not exceeded). In this case (figure 6.22) the direction of the shear stresses changes so that each cycle includes both compressional and extensional loading. Experimental evidence (e.g., Dobry et al., 1982; Mohamad and Dobry, 1986) has shown that the rate of pore pressure generation increases with increasing degree of stress reversal. Hence the effective stress path moves relatively quickly to the left (because excess pore pressure builds up quickly) and eventually oscillates along the compression and extension portions of the drained failure envelope. Each time the effective stress path passes through the origin (it does so twice during each loading cycle), the specimen is in an instantaneous state of zero effective stress ($\tau_u = 100\%$). Although this state of zero effective stress is referred to as initial liquefaction (Seed and Lee, 1966), it should not be taken to imply that the sol has no shear strength. If monotonic loading is applied at the state of initial liquefaction the specimen will dilate until the steady state strength is mobilized (figure 6.23). Significant permanent strains may accumulate during cyclic loading, but flow failure cannot occur. Note that initial liquefaction can only occur when stress reversals occur.
Figure 6.23: Dilative behavior of specimen loaded monotonically after occurrence of cyclic mobility. Cyclic loading with stress reversal causes the effective confining pressure to decrease rapidly, eventually reaching momentary values of zero. Subsequent monotonic loading, however, causes dilation as the steady state strength is mobilized.

In contrast to flow liquefaction, there is no clear cut point at which cyclic mobility is initiated. Permanent strains, and the permanent deformation they produce, accumulate incrementally. Their magnitude depends on the static shear stress and the duration at nearly level sites, permanent deformations may be small. For moderately sloping sites or gently sloping sites subjected to ground motions of long duration, cyclic mobility can produce damaging levels of soil deformation.

6.5.8 Evaluation of Initiation of Liquefaction

The combination of steady state and flow liquefaction surface concepts provides a framework in which the basic mechanism of liquefaction can be understood. This framework integrates liquefaction susceptibility with liquefaction initiation and liquefaction effects. It also illustrated the important influence of excess pore pressure generation on the extent of liquefaction related hazards.

A number of approaches to evaluation of the potential for initiation of liquefaction have developed over the years. In the following sections, the most common of these-the cyclic stress approach and a useful alternative, the cyclic strain approach-are presented. Each has advantages and limitations, and each is preferred by different groups of engineers. For particularly important projects, it is not unusual to use more than one approach in a liquefaction hazard evaluation.