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THREE CONSTITUENT ELEMENTS REQUIRED FOR CAUSING LIQUEFACTION

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Abstract

Shear bands are formed in saturated dense sand layers under lateral compression when localization of deformation is produced under unstable volume-expansion conditions of plastic strain softening after the strain goes deep into the plastic range. Liquefaction is a special failure phenomenon caused by shear banding that occurs during tectonic earthquakes. The occurrence of liquefaction encompasses three constituent elements: (1) the shear band derived from the localization of deformation, (2) the highly concentrated excess pore water pressure that is locally present in the shear band, and (3) the groundwater entrainment of small to large grained granular soils (such as silt, sand, and gravel) and their ejection upward sequentially along the outlet channel formed by pore spaces in the shear band. In comparison, the conditions for liquefaction proposed by most scholars (1) define liquefaction as occurring outside the yielding surface where stress does not in fact exist, (2) imply that the farther the stress is from the yield surface, the higher the liquefaction potential, and (3) assess the alluvial plains along the coast of Taiwan as liquefaction potential areas. Because liquefaction only occurs locally in shear bands and the proportion of the area of the shear band is small, the authors suggest that the seismic design code of buildings should incorporate the results of this study, which more accurately reflect the real conditions, so that the liquefaction disaster reduction work can be carried out more economically and effectively.

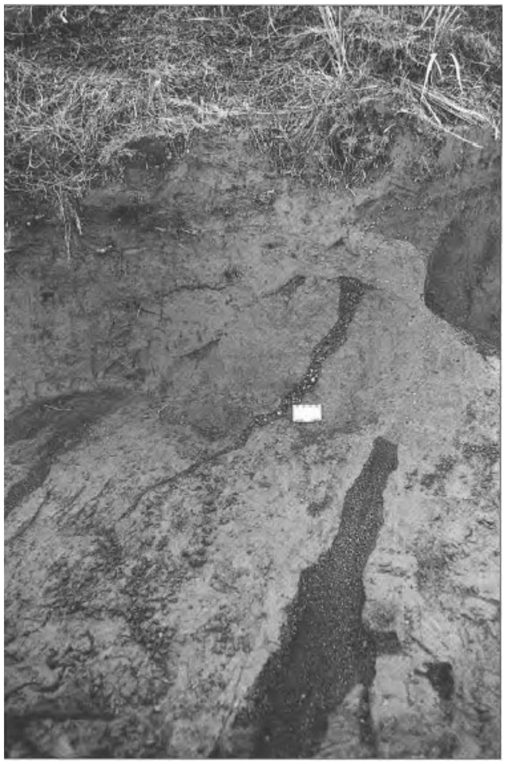
Keywords: tectonic earthquakes, liquefaction, three constituent elements, shear bands, pore water pressure, groundwater.

Introduction

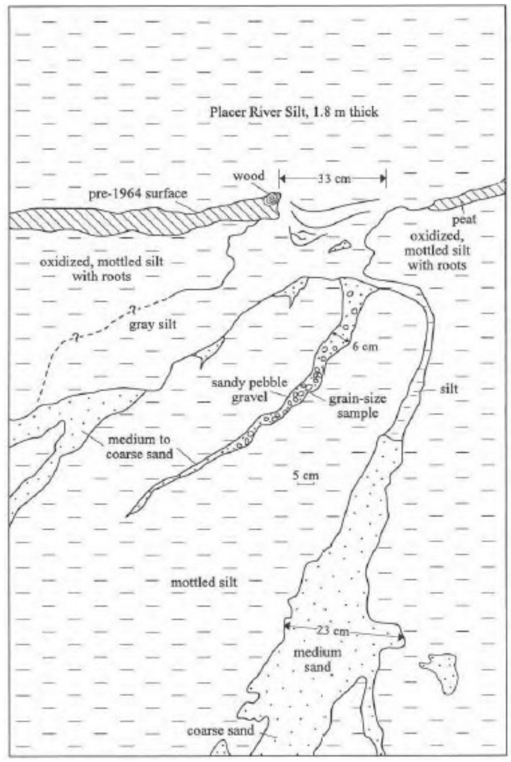
The liquefaction that occurs during tectonic earthquakes includes tubular liquefaction (Figure 1) and strip liquefaction (Figure 2). The main feature of liquefaction is that the groundwater entrains silt, sand, and gravel, which it ejects upwards through the tubular or strip channels formed by interconnected pore spaces in the shear band (Hsu et al., 2017). Figure 3 further shows that liquefaction only occurs in shear bands derived from the localization of deformation that occurs during tectonic earthquakes.

Figure 1. Tubular liquefaction that took place during the Jiji earthquake.

Figure 2. Striped soil liquefaction took place during the Meinong Earthquake (Liberty Time Net, 2016)



(a) On-site excavation profile



(b) Explanatory diagram

Figure 3. Typical liquefaction shear band profile (Walsh et al., 1995).

Comparison of Proposed Liquefaction Processes

Liquefaction Process Traditionally Proposed by Scholars

The liquefaction process proposed by traditional scholars is illustrated in Figure 4, which shows how the effective stress related to the shear strength of the saturated loose sand layer decreases with an increase in the excess pore water pressure during liquefaction. At point A in Figure 4, the void ratio for the saturated loose sand layer is e_0 and the vertical effective stress is σ_v'.

During ground vibration, the excess pore water pressure increases and the vertical effective stress decreases, meaning that point A moves left to point B. Liquefaction is traditionally defined to occur when the shear strength is less than or equal to the shear stress. After liquefaction, the excess pore water pressure dissipates to zero and the vertical effective stress returns to σ_v'; the sand layer becomes dense so that point B moves obliquely to the right and downwards to point C (Kramer, 1996).

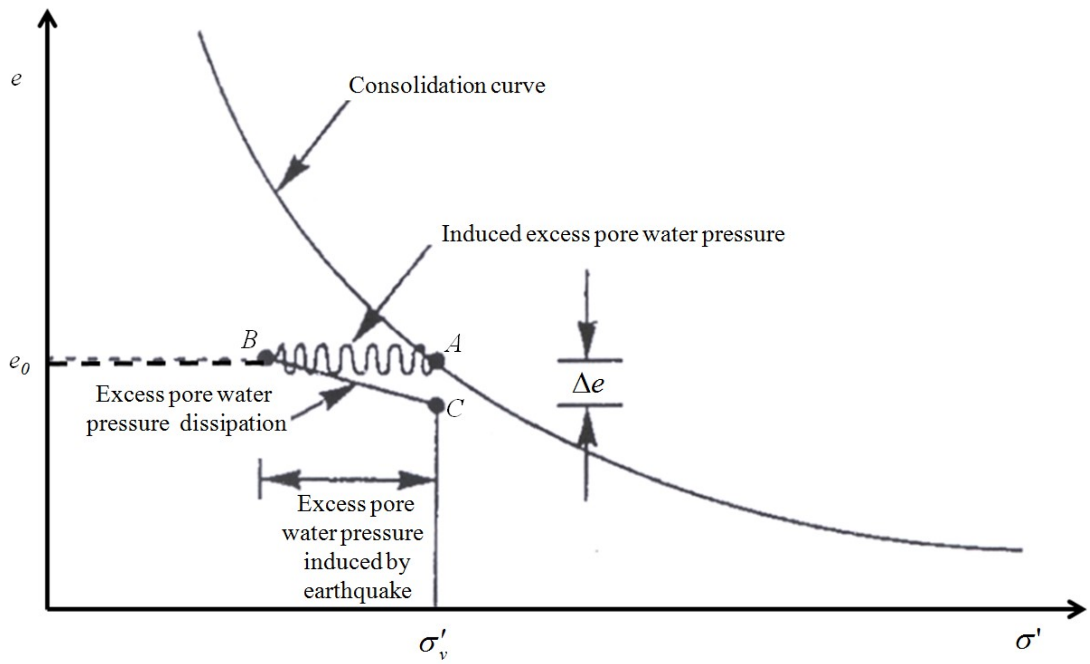


Figure 4. Relationship of decreasing the effective stress σ' with increasing the excess pore water pressure u_e during liquefaction for a certain point on the consolidation curve (redrawn from Kramer, 1996).

Liquefaction Process Proposed by the Authors

Under the continuous lateral compression of the saturated dense sand layer, when the strain goes deep into the plastic range, the dense sand layer will undergo plastic strain softening due to volume expansion, and thus localization of deformation will appear after the loss of stability and symmetry, resulting in shear banding (Rice, 1977; Rudnicki and Rice, 1975; Hsu, 1987). This changes the dense sand layer into a loose sand layer in the shear band. The shear banding also locally induces highly concentrated excess pore water pressure; therefore, groundwater can entrain small to large size granular particles such as silt, sand, and gravel and sequentially eject them upwards along the outlet channel formed by interconnected pore spaces in the shear band.

Comparison and Discussion

Traditional scholars (Japan Road Association, 1996; Seed and Harder, 1990; Tokimatsu and Yoshimi, 1983) define liquefaction as occurring when the safety factor of liquefaction resistance FS_L for the saturated loose sand layer is less than 1.0, where FS_L = CSRRL/CSRE, CSRRL is the cyclic stress ratio of liquefaction resistance, and CSRE is the cyclic stress ratio of the design earthquake. In other words, traditional scholars define liquefaction as occurring in a space where the stress is located outside the yielding surface $f = 0$ as shown in Figure 5. Traditional scholars also define liquefaction such that the farther the stress is located from the yielding surface $f = 0$, the higher the liquefaction potential.

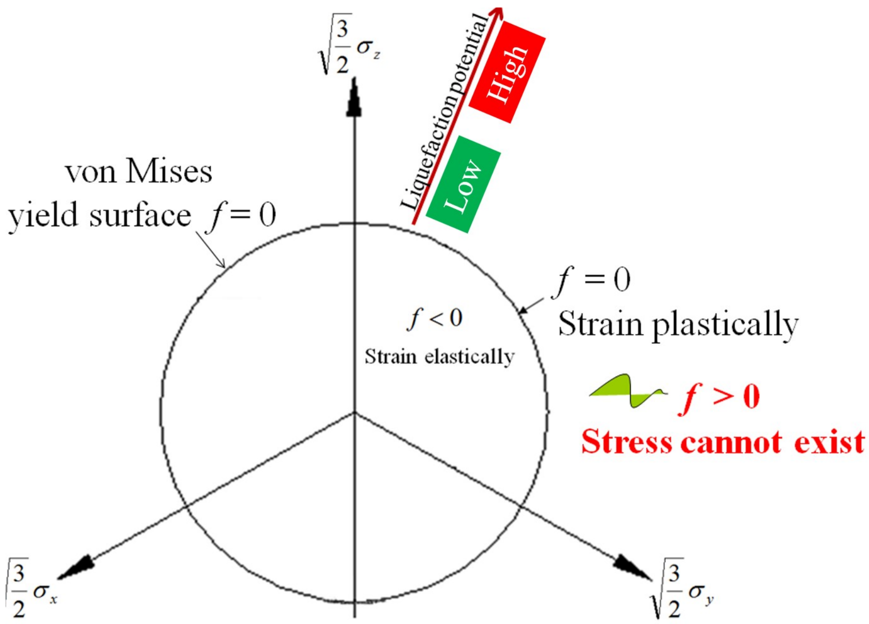


Figure 5. Traditional liquefaction and liquefaction potential defined as occurring in space where stress cannot exist (Tsao, 2019).

1) Based on the theory of plasticity (Hill, 1950; Hsu, 2022a), the stress can only be located in the inner space surrounded by the yielding surface (i.e., $f < 0$) or on the yielding surface ($f = 0$) but not outside the yielding surface where there is no stress ($f > 0$). Therefore, the definitions of liquefaction and liquefaction potential proposed by traditional scholars are contrary to the theory of plasticity.

2) Taking Tainan City as an example and using the traditional definition of liquefaction and liquefaction potential (that are contrary to the theory of plasticity), Figure 6 shows that the distribution map of liquefaction potential would cover the entirety of the alluvial plains in Tainan City.

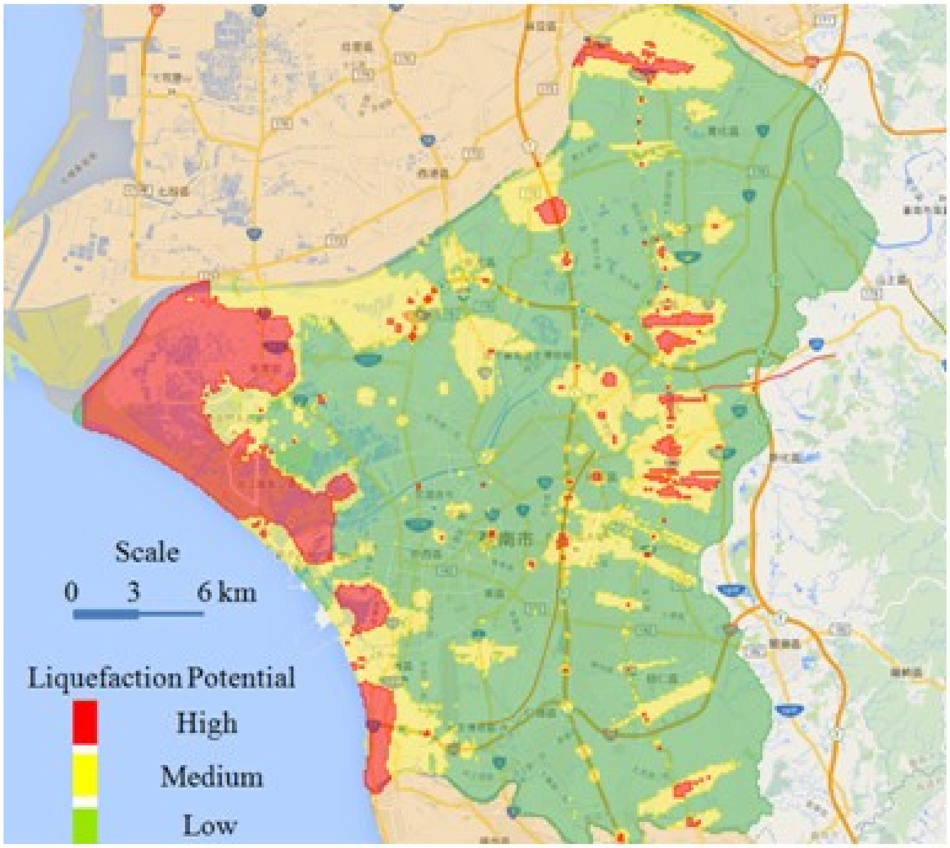


Figure 6. Distribution of liquefaction potential in Tainan City, Taiwan (Central Institute of Geological Survey, 2016).

4) The black dots in Figure 7 indicate the locations where liquefaction occurred in Tainan during the 2016 Meinong earthquake. From Figure 7, it is evident that liquefaction only occurs locally during tectonic earthquakes; therefore, the occurrence conditions for liquefaction and liquefaction potential as defined by traditional scholars do not meet the actual requirements.

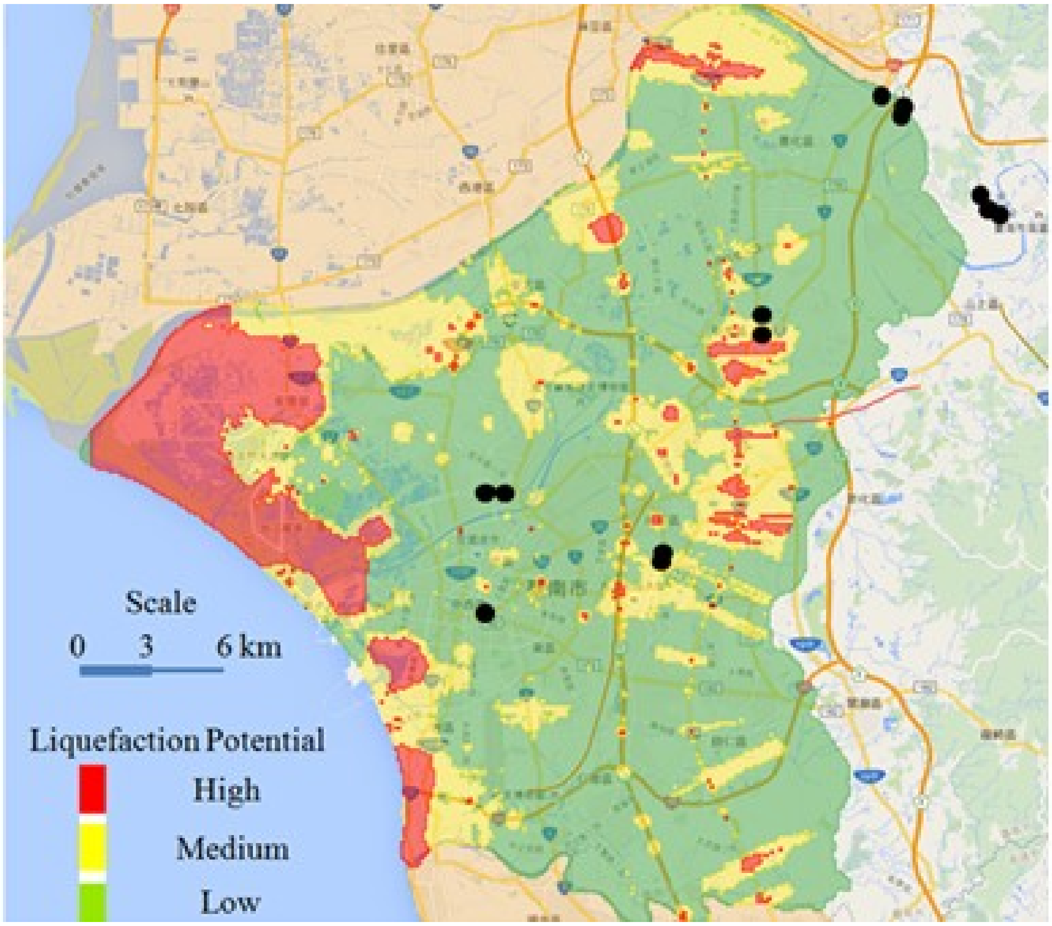


Figure 7. Locations of liquefaction induced by the Meinong earthquake and the distribution of liquefaction potential as proposed by traditional scholars (Central Institute of Geological Survey, 2016; Hsu, et al., 2017).

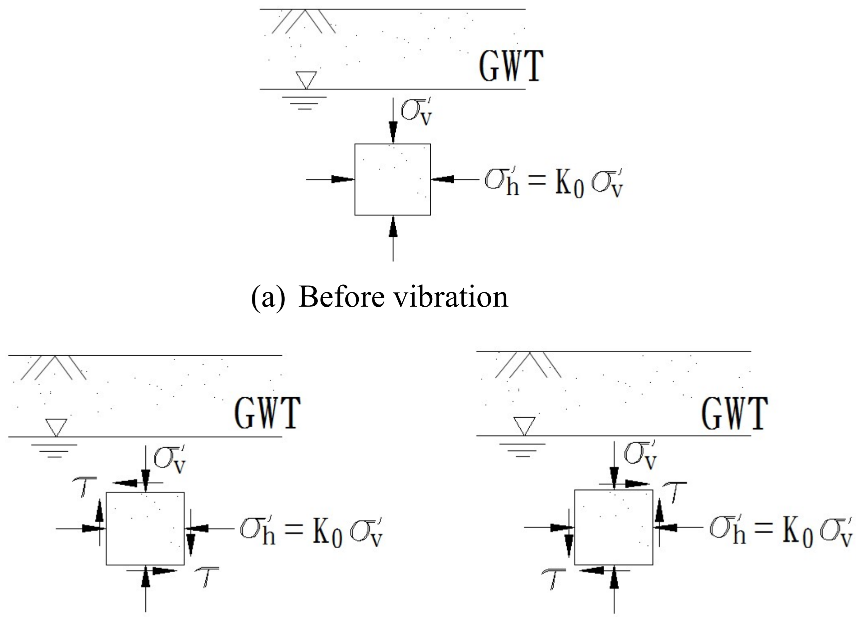
5) In addition to defining the conditions for liquefaction by $FS_L < 1.0$, the traditional scholar also define "flow liquefaction" as liquefaction that occurs when the shear resistance strength of the saturated loose sand layer decreases to less than the static shear stress as the excess pore water pressure increases (Kramer, 1996). In addition, liquefaction that occurs when the sum of the static and dynamic shear stresses of the saturated loose sand layer is greater than the shear resistance strength is known as "cyclic mobility" (Kramer, 1996). However, neither flow liquefaction nor cyclic mobility have the three constituent elements required for liquefaction to occur, so they result in phenomena that differ from liquefaction phenomena.

6) Traditional scholars use a shaking table such as that shown in Figure 8 to carry out liquefaction simulation

testing of the saturated loose sand layer. However, in a simulation test, no matter how great is the vibration force on the saturated loose sand layer, it will not induce shear bands and the upward ejection of the sand. Therefore, the simulation analysis results of such shaking table tests can only reveal punching shear failure of the building model and not liquefaction of the saturated loose sand layer.

Figure 8. Punching shear failure test of a building model conducted by traditional scholars through a simulation test of the saturated loose sand layer by means of a shaking table (Tsao, 2019).

7) Figure 9 shows the stress conditions of the saturated loose sand layer when a liquefaction simulation test is carried out using a shaking table (Seed and Lee, 1966). From Figure 9, it is evident that if the size of the test body in the simulation test is large enough, the test results are not affected by the boundary conditions of the instrument, and the stress on the sand layer will only include periodic shear stress. Furthermore, when the volume remains constant throughout the test, no excess pore water pressure will be induced in the test body and therefore no liquefaction will occur.



(a) Before vibration

Positive shear stress τ Negative shear stress τ

(b) During vibration

Figure 9. Stress conditions of the saturated loose sand layer during a shaking table liquefaction simulation test (Seed and Lee, 1966).

Figure 10. In-situ drilling operations performed by traditional scholars in a non-shear band area in Tainan where liquefaction will not in fact occur.

8) Figure 11 shows that the rear line region of caisson piers often suffers different types of failure, such as from large-scale subsidence, large piping holes, and sand ejection during tectonic earthquakes. Traditional scholars believe that these three different types of failures are all caused by the liquefaction of the saturated loose sand layer. However, the rear line region of caisson piers is formed by the compaction of backfilled gravel sand or sandy gravel, which must meet the quality standards stipulated in the relevant contract or specification before completion. Thus, the sand in these regions is dense and not loose.

Figure 11. Three different types of seismic failure that occurred in the rear line region of the caisson piers at Taichung Port during the 921 Jiji earthquake (Hsu, 2022).

9) Hsu (2022) pointed out that the large subsidence of the rear line region of the caisson piers during tectonic earthquakes was caused by the movement or rotation of the caisson towards the sea, and the cause of the large piping hole was backfill flowing along the bottom of the caisson towards the sea side. In addition, since the conditions of the large subsidence and large piping hole in the rear line region of the caisson piers do not meet the three requirements for liquefaction, their cause cannot be liquefaction.

10) When the cause of the large subsidence and the large piping hole in the rear line region of the caisson piers during the tectonic earthquake is misidentified, the design and construction of the repair project after the tectonic earthquake will be misguided and similar damage will reoccur during future tectonic earthquakes.

Conclusions and Suggestions

Liquefaction is a special failure phenomenon that occurs during tectonic earthquakes. This paper critically evaluates the conditions for liquefaction to occur as defined by traditional scholars and highlights the three constituent elements that liquefaction must in fact have by a comparison and discussion. The following four conclusions are drawn:

1) Based on the three constituent elements necessary for liquefaction to occur, the process of liquefaction is that the saturated dense sand layer undergoes lateral compression and, after the strain goes deep into the plastic range, the plastic strain softens due to volume expansion, resulting in the loss of stability and symmetric conditions. Shear bands are therefore induced due to the localization of deformation, and highly concentrated excess pore water pressure is induced in the shear bands. Thus, the groundwater can sequentially entrain silt, sand, and gravel, which it ejects upward along the outlet channel formed by the interconnection of pore spaces in the shear band.

2) Liquefaction is a failure phenomenon induced by shear banding in the saturated dense sand layer under the unstable condition of strain softening. In the process of liquefaction, the saturated sand layer in the shear band changes from a compact state to a loose state.

3) Liquefaction only occurs locally in the shear-banding region and not in the non-shear banding region.

4) The definition of the liquefaction occurrence conditions and liquefaction potential proposed by traditional scholars deviates from the theoretical understanding of soil plasticity, and so the distribution map of the liquefaction potential of various regions proposed by traditional scholars does not accurately reflect the real conditions.

Based on the above four conclusions, the authors put forward the following two suggestions:

1) The seismic design code should replace the liquefaction occurrence conditions proposed by traditional scholars with the liquefaction occurrence conditions proposed in this paper. Only in this way can the liquefaction potential evaluation results meet the actual requirements.

2) For various civil engineering projects constructed by earthwork compaction, quality control must be carried out according to contract requirements before completion; e.g., all compacted gravel sand and sandy gravel must be dense. It is also suggested that scholars should not consider the occurrence of liquefaction in a saturated loose sand layer as the cause of damage to structures constructed using earth compaction when they investigate the causes of various civil engineering failures after future tectonic earthquakes.

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