CRITERIA FOR LIQUEFACTION OF SILTY SOILS

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SUMMARY

This paper promotes simple criteria based on “key” soil parameters that help partition liquefiable and non-liquefiable silty soils. A brief review of the physical characteristics of silts and clays is first given to help clarify some misconceptions about silty soils. Clay content and liquid limit are then considered as two “key” soil parameters that help partition liquefiable and non-liquefiable silty soils. Several case histories are presented that illustrate the applicability of using clay content as a “key” soil parameter. Attention is drawn to an analogy between the liquid limit and the shear strength of a soil. This analogy is expanded to show that the liquid limit can be regarded as a “key” soil parameter that gives a relative measure of liquefaction susceptibility. Inadequacies of basing criteria for liquefaction of silty soils on just one “key” parameter are finally discussed, leading to the promotion of simple criteria for liquefaction of silty soils, utilising together both the clay content and the liquid limit soil parameters.

INTRODUCTION

The majority of liquefaction studies to date have concentrated on relatively clean sands. Comparatively little liquefaction research has been undertaken on soils within the grain size range of very silty sand to silt with or without some clay content. These silty soils are frequently encountered in engineering practice, and there is an abundance of evidence to show that they can be susceptible to liquefaction. As designers of earthquake resistant infrastructure, often in silty soil environments, engineers need to know which silty soils are susceptible to liquefaction. This paper promotes simple criteria based on “key” soil parameters that help partition liquefiable and non-liquefiable silty soils.

In the context of this paper, liquefaction is defined as the phenomenon where high excess pore pressures are induced under cyclic earthquake loading (approaching initial vertical effective confining pressures), leading to severe loss of strength and stiffness.

LIQUEFACTION SUSCEPTIBILITY OF SILTY SOILS

There is a degree of confusion in the engineering profession about the liquefaction susceptibility of silty soils. Because the grain size of silt falls between that of sand and clay, it is often assumed that the liquefaction susceptibility of silts must also fall somewhere between the high susceptibility of sands and the non-susceptibility of clays. Confusion about the liquefaction susceptibility of silty soils is further exasperated whenever silts and clays are coupled under the one heading - “fines”.

Silt in fact can essentially be viewed as very fine sand. The grain size boundary between sand and silt is set at 0.074mm. This corresponds to that which can and cannot be seen by the naked eye. The fact that silt grains cannot be seen, does not bestow on them any significantly different physical characteristics to those of sand grains. To illustrate, silt grains and sand grains both generally comprise rock-forming minerals. The shapes of

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silt grains come in the same forms as those of sand grains. Moreover, attraction forces, such as hydrogen bonds and van der Waals bonds are negligible between silt grains, just as they are between sand grains (Mitchell, 1976).

Clay bears little resemblance to sand and silt. The grain size boundary between silt and clay is generally set at 0.002mm. Japan and China set the boundary at 0.005mm. Significantly, most grains finer than 0.002mm tend to comprise clay minerals, and most grains larger than 0.002mm tend to comprise rock-forming minerals. Because of their mineralogy, clay grains tend to be platey shaped, and exhibit plasticity. This plasticity is caused by Hydrogen bond and van der Waal bond forces of attraction between the platey shaped grains.

Based on the physical characteristics of silts and clays described above, the liquefaction susceptibility of silts would be expected to be similar to that of sands and dissimilar to that of clays. The question is, at what clay content does the liquefaction susceptibility of a silty soil change from resembling the susceptibility of sands to resembling the non-susceptibility of clays?

KEY SOIL PARAMETERS THAT PARTITION LIQUEFIABLE & NON-LIQUFIABLE SILTY SOILS

Seed et al. (1983) outlined criteria, derived from case histories in China (Wang, 1979), which provided a basis for partitioning clayey soils vulnerable to severe strength loss as a result of earthquake shaking. The clayey soils vulnerable to severe strength loss appeared to have the following characteristics:

Clay Content (defined as % finer than 0.005mm)	<15%
and Liquid Limit	<35
and Water Content	>0.9 x Liquid Limit

This paper utilises further case histories and theory, to reinforce the above criteria outlined by Seed et al., and refine and promote their application to silty soils. Clay content and liquid limit only are considered as “key” soil parameters that partition liquefiable and non-liquefiable silty soils. Water content is not considered as a “key” soil parameter, due to its sensitivity to fluctuating environmental factors, and errors arising during soil sampling.

Clay Content

There are ample case histories that show silty soils with a low natural clay content (clay defined as grains finer than 0.002mm in this paper) are susceptible to liquefaction. A brief discussion of several case histories follows:

Figueroa et al. (1995) examined the grain size distribution of soil samples collected from liquefaction related sand boils generated at the Lower San Fernando Dam, California during the Northridge earthquake of 1994. The grain size distribution of the boils is shown in Figure 1. The grain size distribution indicates that the soil liquefying was very silty sand with a clay content less than 10%.

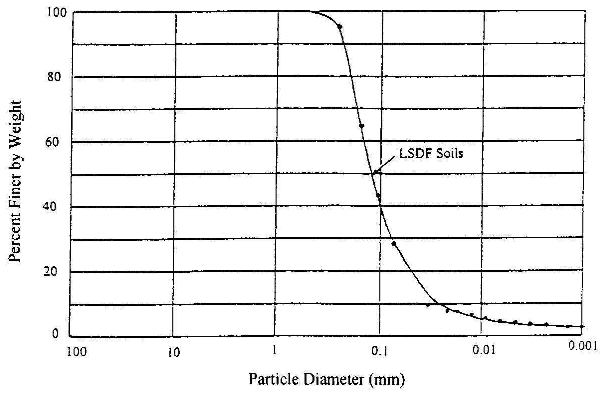

Figure 1 Grain Size Distribution of LSFD Soils (after Figuroa et al. 1995)

Kishida (1970) observed the grain size distribution of boils ejected at Nanaehama Beach, Japan during the Tokachioki earthquake of 1968. The boils consisted of sandy silt with clay contents less than 10% (Figure 2). Kishida indicated that the grain size distribution of the boils showed good agreement with the grain size distribution of soils located at a depth of 1m to 12m. These soils ranged from silty sand to sandy silt also with clay contents less than 10% (Figure 3). The grain size distribution of the boils did not however match those soils at a depth of 12m to 17m. These soils had a clay content greater than 10% and appeared to have not liquefied.

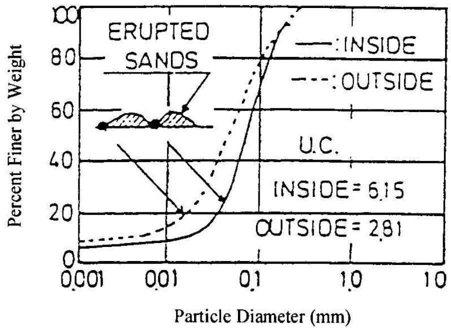

Figure 2 Grain Size Distribution of Sand Boils (after Kishida, 1970)

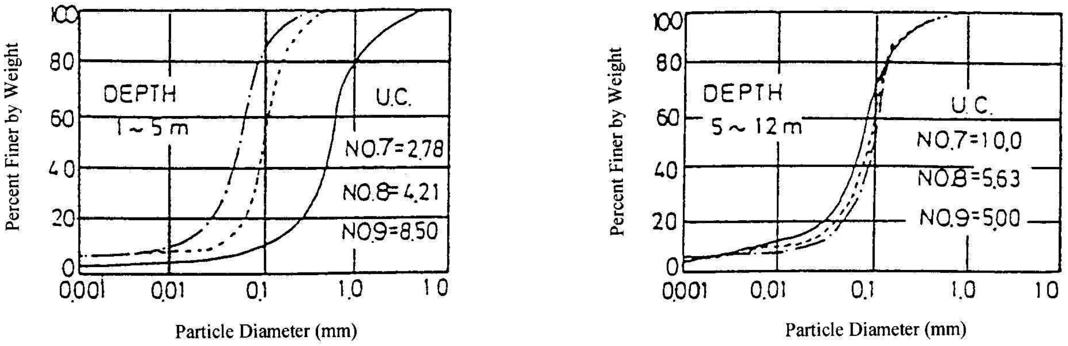

Figure 3 Grain Size Distribution of Soils (after Kishida, 1970)

Tokimatsu and Yoshimi (1983) documented 70 case histories of liquefaction inside Japan resulting from 10 earthquakes, as well as about 20 case histories of liquefaction outside Japan. A triangular classification chart showing the grain sizes of the silty sand to slightly sandy silt soils which liquefied was prepared (Figure 4). Tokimatsu and Yoshimi show a cut-off for liquefaction susceptibility at a clay content of 20%. However, a cut-off at a clay content of about 15% may be more suitable. Furthermore, the clay is defined as grains finer than 0.005mm. For clay defined as grains finer than 0.002mm, as used throughout this paper, a final cut-off for liquefaction susceptibility at a clay content of about 10% would be appropriate.

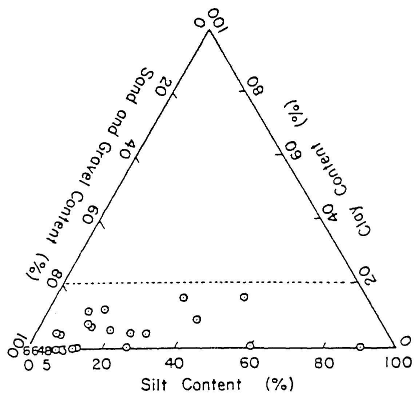

Figure 4 Grain Size of Liquefied Soils (after Tokimatsu and Yoshimi, 1983)

Tuttle et al. (1990) documented damaging liquefaction that occurred at Ferland, Canada during the Saguenay earthquake of 1988. Grain size distribution curves of the boils that erupted indicated that the soil liquefying was a very silty sand to slightly sandy silt with a clay content less than 10% (Figure 5). This soil was present at a depth between 1.5 and 9.0 m. Clayey silt at a depth of about 0.5 m to 1.5m, and silty clay at a depth of about 9m to 11m, were not present in the boils and appear to have not liquefied.

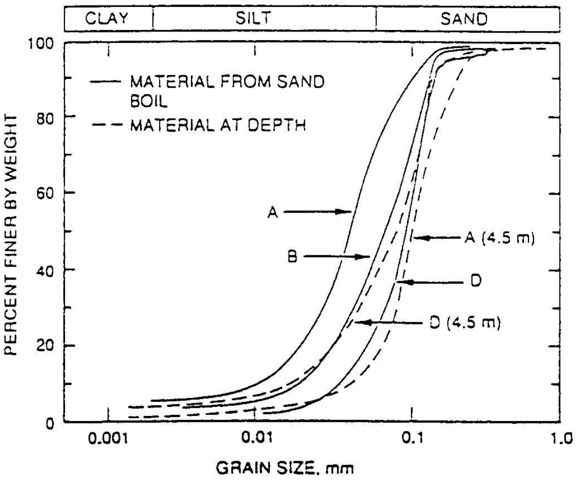

Figure 5 Grain Size Distribution of Soils (after Tuttle et al. 1990)

Wang (1979) recorded the occurrence of liquefaction in silty sand to slightly sandy silt soils during the Haicheng, China earthquake of 1975 and the Tangshan, China earthquake of 1976, and prepared a very revealing chart indicating the grain sizes of these soils (Figure 6). Wang shows a cut-off for liquefaction susceptibility at a clay content of 15%. However, the clay is defined as grains finer than 0.005mm. For clay defined as grains finer than 0.002mm, as used throughout this paper, a cut-off for liquefaction susceptibility at a clay content of about 10% would be appropriate.

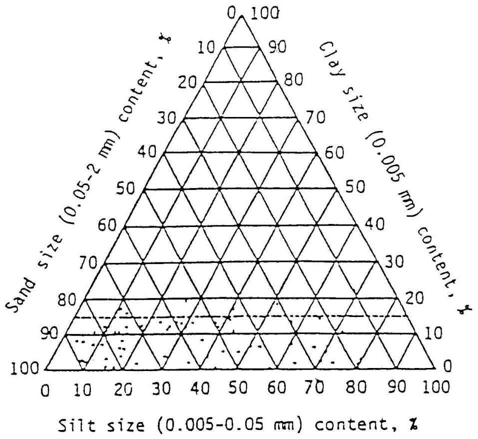

Figure 6 Grain Size of Liquefied Soils (after Wang, 1979)

Zhou (1981) studied the extensive liquefaction that resulted in Tangshan, China during the Tangshan earthquake of 1976. An area where widespread liquefaction occurred was in Lutai, southwest of Tangshan, 48km from the epicenter. A typical cross section of this area, showing several soil layers, is shown in Figure 7. Many boils erupted during and after the earthquake. The grain size distribution envelope of the sandy to slightly sandy silt soils ejected is shown in Figure 8. It can be seen from the grain size distribution envelope that soils ejected had a clay content less than 10% (clay defined as grains finer than 0.005mm). It follows that for clay defined as grains finer than 0.002mm, the clay content must also be less than 10%.

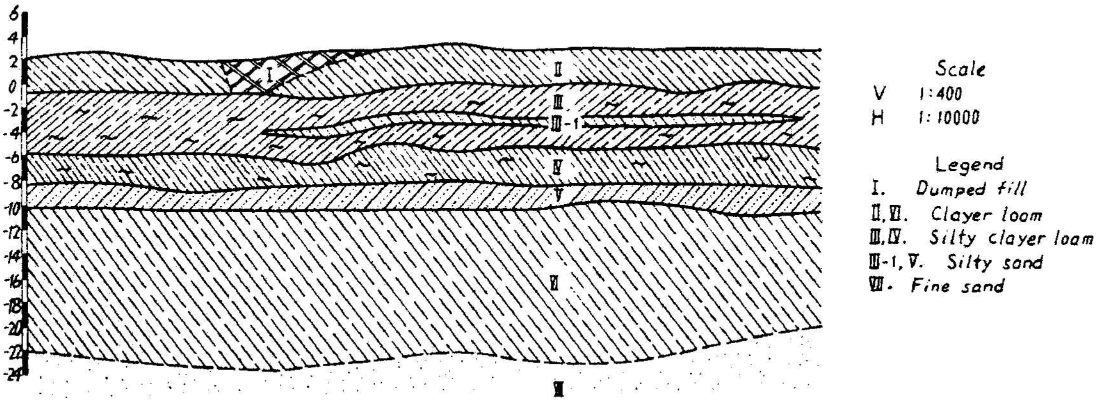

Figure 7 Lutai Area Stratigraphy (after Zhou, 1981)

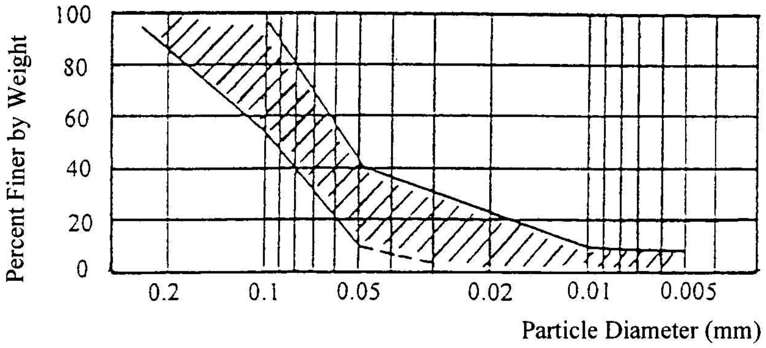

Figure 8 Grain Size Distribution of the Ejecta (after Zhou, 1981)

Zhou (1981) presented the grain size distributions of Layer III-1 and Layer V of the Lutai area stratigraphy (see Figure 7 for location of layers), as shown in Figures 9 and 10 respectively. The grain size distribution of Layer III-1 (Figure 9) indicates this soil is a sandy silt with a clay content less than 10% (clay defined as grains finer than 0.005mm). Again it follows that for clay defined as grains finer than 0.002mm, the clay content must also be less than 10%. According to Zhou, Layer III-1 is present in only some parts of the Lutai area, and consists of a lense deposit 0.5m to 1.0m thick, positioned at a depth of about 6m. For Layer V, the grain size distribution (Figure 10) indicates this soil is a sandy to slightly sandy silt with a clay content up to about 19% (clay defined as grains finer than 0.005mm). For clay defined as grains finer than 0.002mm, it could be supposed that the clay content is up to say 15%. According to Zhou, Layer V is scattered all over the Lutai area, is about 2.5m thick and positioned at a depth of about 10m. Significantly, a macro-survey undertaken found that severe eruptions occurred in the areas where the lense layer III-1 and the layer V were both present. However, practically no significant eruptions occurred where only the relatively high clay content Layer V was present.

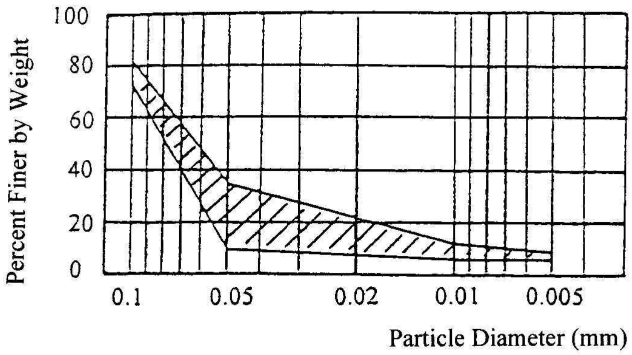

Figure 9 Grain Size Distribution of Layer III-1 (after Zhou, 1981)

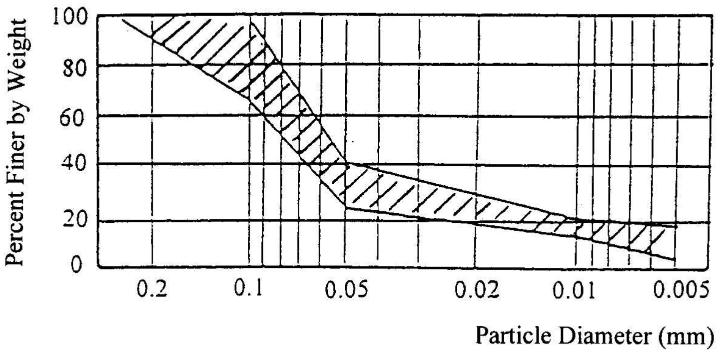

Figure 10 Grain Size Distribution of Layer V (after Zhou, 1981)

The above case histories illustrate liquefaction of silty soils, and further the applicability of using clay content as a "key" soil parameter that partitions liquefiable and non-liquefiable silty soils. Moreover, the above case histories reinforce the clay content criterion outlined by Seed et al. (1983). This criterion is further reinforced by the observation of Seed et al. (1964) where it was shown that at about a 10% natural clay content, skeleton voids in a sand would be filled with clay. Hence for clay contents greater than about 10%, the clay would control the physical properties of a clayey sand.

Liquid Limit

A liquid limit criterion was among three criteria outlined by Seed et al. (1983) which partition clayey soils vulnerable to severe strength loss. The liquid limit criterion is considered appropriate as discussed below:

The liquid limit of a soil can be defined as the water content at which the soil has a shear strength of approximately 25 gram/cm2 (Seed et al. 1964). The shear strength of a plastic soil can be attributed mainly to the net attractive force between clay grains. As water content can be used to determine the void ratio of a soil, and the void ratio is a measure of the average inter-grain spacing, the liquid limit can be visualised as a measure of the grain spacing at which the net attractive force produces a shear strength of approximately 25 gram/cm2 (Seed et al. 1964). Hence a silty soil with a high liquid limit will have a high net attractive force mainly between any clay grains present. This attractive force will tend to inhibit liquefaction, bestowing on the silty soil a relatively low susceptibility to liquefaction. It follows that a silty soil with a low liquid limit should be expected to have a relatively high susceptibility to liquefaction, therefore justifying the applicability of using liquid limit as a "key" soil parameter that partitions liquefiable and non-liquefiable silty soils. In addition, the liquid limit is proportional to the clay content as discussed by Seed et al. (1964), where is was also noted that the maximum liquid limit of a naturally occurring clay is about 300. For a liquefiable soil, a liquid limit upper bound of about 30 (10% of 300) is consistent with the 10% clay criterion discussed above.

REFINEMENT OF CRITERIA FOR LIQUEFACTION OF SILTY SOILS

A criterion for liquefaction of silty soils based on the clay content parameter alone, does not adequately address cases where at one extreme, clay sized grains are non-plastic, and at the other extreme, non-clay sized grains are plastic. An example of the first extreme is mine and quarry tailings. Mine and quarry tailings often have high contents of crushed rock derived, non-plastic clay sized grains. Studies have shown these soils to be highly liquefiable (Rogers et al. 1991 and Ishihara, 1985). An example of the other extreme is Mica. Mica is a rock-forming mineral that alters to the clay minerals, illite and montmorillonite. Mica exhibits plasticity and is frequently found in the silt sized range. Use of a liquid limit criterion together with a clay content criterion helps address this predicament.

The liquid limit criterion outlined by Seed et al. (1983) was based on Chinese (PRC) data (Wang, 1979). In the PRC, liquid limit is determined by the PRC fall cone penetrometer apparatus. Koester (1992) compared liquid limits determined by the PRC fall cone penetrometer apparatus, with liquid limits determined by the Casagrande-type percussion apparatus, and found that the PRC fall cone penetrometer apparatus gave higher liquid limits. Based on the work of Koester, a liquid limit of 35 determined by the PRC fall cone penetrometer apparatus, is equivalent to a liquid limit of about 32 determined by the Casagrande-type percussion apparatus.

CONCLUSIONS

The following concluding observations can be made:

- There is an abundance of evidence to show that silty soils can be susceptible to liquefaction.
- Clay content can be regarded as a "key" soil parameter that partitions liquefiable and non-liquefiable silty soils.
- Liquid limit can be regarded as a "key" soil parameter that partitions liquefiable and non-liquefiable silty soils.
- Use of a liquid limit criterion together with a clay content criterion helps address cases where clay sized grains are non-plastic, and non-clay sized grains are plastic.

Based on the further case histories and theory presented above, the criteria outlined in Seed et al. (1983) are reinforced, refined and promoted for silty soils as shown in Table 1.

Table 1 Liquefaction Susceptibility of Silty Soils

	Liquid Limit < 32 (1)	Liquid Limit ≥ 32
Clay Content < 10% (2)	Susceptible	Further Studies Required *(Considering plastic non-clay sized grains - such as Mica)*
Clay Content ≥ 10%	Further Studies Required *(Considering non-plastic clay sized grains – such as mine and quarry tailings)*	Not Susceptible

Notes:

1. Liquid Limit determined by Casagrande-type percussion apparatus
2. Clay defined as grains finer than 0.002mm

ACKNOWLEDGEMENTS

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