Pore Geometry Influence on the Liquefaction Potential of Silts

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SUMMARY:
Several methods ranging from the Chinese Criteria on dynamic properties have been employed to devise a quick way to predict the liquefaction potential of silt. From the work done following the 1999 earthquakes, a new method called The Adapazari Criteria has been proposed. A study to understand the contribution of the pores thus hydraulic conductivity, on liquefiability of fine grained soils was attempted.

The soil water characteristic curves for 16 reconstituted silty soils were prepared by the pressure plate and filter paper methods. This enabled the investigators to derive the curves both by these tests and the physical properties.

The results show that pore size distribution curves for liquefiable and non-liquefiable samples are significantly different. It is found that those samples with average pore size of r_{50}<0.0004 mm are not liquefaction prone. In addition a limit curve has been developed that separates zones of liquefaction and non-liquefaction.

Keywords: Silt, liquefaction, SWCC, pore geometry, pressure plate, filter paper

1. INTRODUCTION

The liquefaction of fine grained soils is currently being investigated extensively. Surface observations and subsequent measurements confirmed that the fluvial silts of the city of Adapazarı, Turkey, had indeed liquefied during the 1999 Marmara earthquakes. A research program is being implemented to understand the phenomena of cyclic mobility and liquefaction in silts.

The data obtained pertaining to ground failure in silts prompted the investigators to revise the so called Chinese Criteria where submerged silts will undergo initial liquefaction during earthquakes of M_w>7 provided all of the conditions below are met. The Adapazari Criteria are (Bol, et al., 2010)

- Liquid limit below 33
- Liquidity index below 0.9
- Clay content less than 10%
- Average size D_{50}>0.02mm,

Test intervals where no clear judgment as to whether a silt layer will liquefy are defined as those soils with 25<w_L<33 and clay contents of 10 to 15%, where the average size is between 0.02 mm and 0.06 mm. Evaluation of the work of other investigators (Idriss &Boulanger (2006) ve Bray & Sancio (2006) has shown that the liquefiable soils have “sand like” character and the transition from sand like to clay like soils which do not liquefy should be evaluated by dynamic testing.

The pore geometry of a soil is a significant indicator of its engineering properties. The most efficient method to determine pore sizes and their distribution is the mercury intrusion method where the metal is forced into pores of decreasing size by increased pressures. Alternatively, the soil water characteristic curve (SWCC) for a soil is obtained, similar to the grain size distribution curve, reflects the size and the distribution of the pores by the use of the capillarity equation

$$(u_a - u_w) = -\frac{RT}{\upsilon_w}\ln(RH) = \frac{2T_s \cos\alpha}{r} \tag{1}$$

and is derived by subjecting the pore water to increasing capillary tension values. T_s indicates the surface tension air-water (72MN/m), υ_w molar volume of water ($18x10^{-6}$ m^3/mol) and RH the relative humidity.

The pore size distribution has been employed in this work to diagnose the vulnerability of silty soil under dynamic conditions. The clayey sandy silts obtained from boreholes and inspection pits have been washed to clean the sand and reduce the clay contents down to about 4%. The washed silt was subsequently mixed with additional natural clay to form blends with increasing percentages of clay. The slurries thus formed were consolidated to predetermined pressures, to be tested in the pressure plate and filter paper tests to form the soil water characteristic curves. The pore size distribution curves were then developed from the SWCC curves to compare them with their potential of liquefaction determined according to the Adapazarı Criteria.

2. SOIL SAMPLES AND PHYSICAL PROPERTIES

The sample of silt to be tested was obtained from downtown Adapazarı, a part of the city where initial liquefaction was observed to have occurred during 1999 earthquakes at several sites. The silt was eventually mixed with local fine sand and clay to prepare mixtures with desired grain size distributions. Their physical properties were measured and classification was done by the USCS (ASTM). The results on two samples made up of two different silts mixed with the same clay obtained are listed in Table 1.

Table 1. Physical properties of natural soils used in this work

	Yenikent Silt (Natural)	T.Sert Silt (Natural)
Symbol (USCS)	ML	ML
Color	Light brown	Light brown
Liquid Limit (w_L)	30	34
Plastic Limit (w_P)	NP	23→NP
Plasticity Index (I_P)	NP	7→NP
Shrinkage Limit (w_S)	25	31
Specific Gravity (G_S)	2.69	2.72
Clay Content (C %)	*9*	10
Silt Content (M %)	*69*	60
Sand Content (S %)	22	30

The samples procured from Adapazarı were processed to obtain pure silt and clay. The operations consisted of sieving the samples through No.40 into the pool and thoroughly mixing it. The clay floating in the supernatant fluid was vacuumed out after 5 minutes into the neighbouring vessel. The operation was repeated six times to remove the clay (Figure 1a).

The water in the clay pool was drained and the clay slurry was then washed through No.200 sieve to remove the sand fraction, ultimately to be poured into buckets for subsequent use (Figure 1b). The silt fraction was placed in ovens at 40°C to remove the water for 24 hours. It was then laid out in the laboratory to dry at room conditions. Dry silt was broken by lightly tamping it and all was sieved through No.40 to finally arrive at "clean silt".

Figure 1. a) Removing clay by vacuum **b**) Removing sand by washing through No.200 sieve

The blends were prepared by proportioning the ingredients by weight. The two silts were mixed with the clay they contained and thirteen different mixes were obtained. The mixes were then mixed with water at 1.5 times the liquid limit, briefly boiled and left to stand for a week. The slurry was then consolidated to 100 kPa (Figure 2a) to be subsequently used in the pressure plate and filter paper tests.

Figure 2. Consolidation of the slurry and extraction from the mold

The classification of the silt-clay blends are summarised in Table 2 with the resulting grain size distribution curves in Figure 3.

3. SOIL WATER CHARACTERISTIC CURVES (SWCC)

Whatman No.42 filter paper was used in addition to the pressure plate test to establish the soil water charactersitic curves and ASTM D 5298 was used to determine the matric suction values (Figure 4).

The filter paper test was used for samples K080, K096, K112 and K144. This enabled the investigators to extend the results of the pressure plate tests the process lasted for 14 weeks (Figure 5). The pressure plate tests were conducted on samples of 5cm diameter and 2cm thickness that were placed on ceramic plates with air entry value of 1500 kPa (Figure 6). The top valve supplied the air pressure and water pressure u_w was supplied from the bottom entry. One week was allowed for pressure increases ranging from 10 kPa to 1500 kPa. The SWCC curves were developed based on moisture content due to difficulty of measuring volume for the silty samples.

Table 2. Physical properties of the silt mixtures

Sample no	w_L (Cas)	w_L (Cone)	w_P	$I_P=w_L-w_P$	% C	D_{50} (mm)		w_s	G_S	Symbol
						Hydrom.	Pipette			
K020	NP	38	NP	NP	2	0.037	0.037	29	2.72	ML
K024	NP	38	NP	NP	2.4	0.040	0.035	30	2.71	ML
K032	NP	36	NP	NP	3.2	0.039	0.038	29	2.72	ML
K040	NP	36	NP	NP	4	0.039	0.036	27	2.7	ML
K043	NP	35	NP	NP	4.3	0.037	0.035	29	2.7	ML
K048	NP	34	NP	NP	4.8	0.030	0.036	28	2.7	ML
K050	NP	35	NP	NP	5	0.031	0.035	27	2.7	ML
K056	NP	34	NP	NP	5.6	0.028	0.034	27	2.69	ML
K072	30	33	26	NP	7.2	0.030	0.034	25	2.7	ML
K080	32	36	23	9	8	0.025	0.027	24	2.73	ML
K096	33	37	24	9	9.6	0.024	0.024	23	2.72	ML
K112	34	37	22	12	11.2	0.021	0.030	23	2.72	ML
K144	35	37	22	13	14.4	0.016	0.020	26	2.72	MI
K184	55	52	27	28	18.4	0.007	0.007	22	2.71	CH
Tsert	NP	37	NP	NP	1.6	0.034	0.040	31	2.72	ML
Yenikent	NP	32	NP	NP	3.2	0.046	0.035	23	2.7	ML

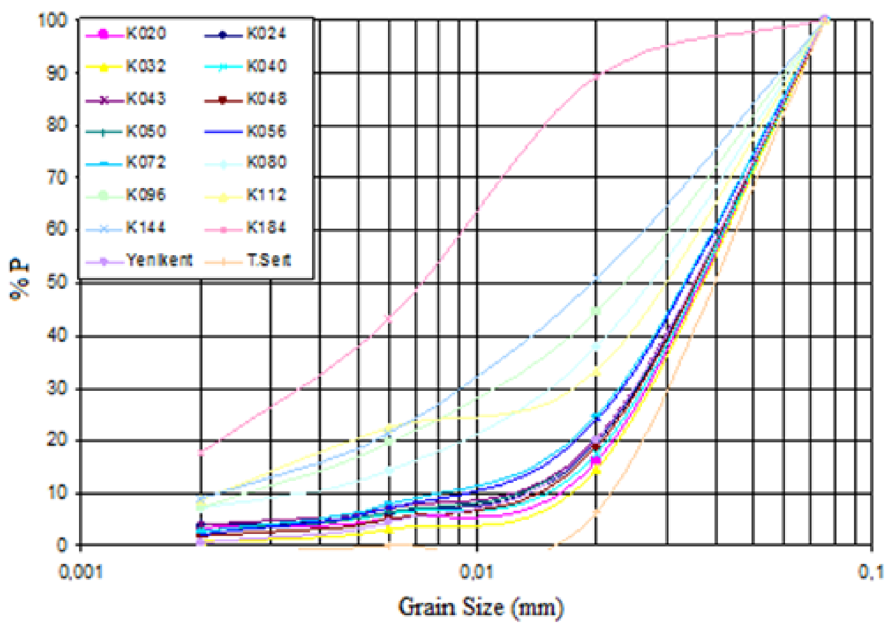

Figure 3. Grain size distribution of silt mixtures

Figure 4. Filter paper tests

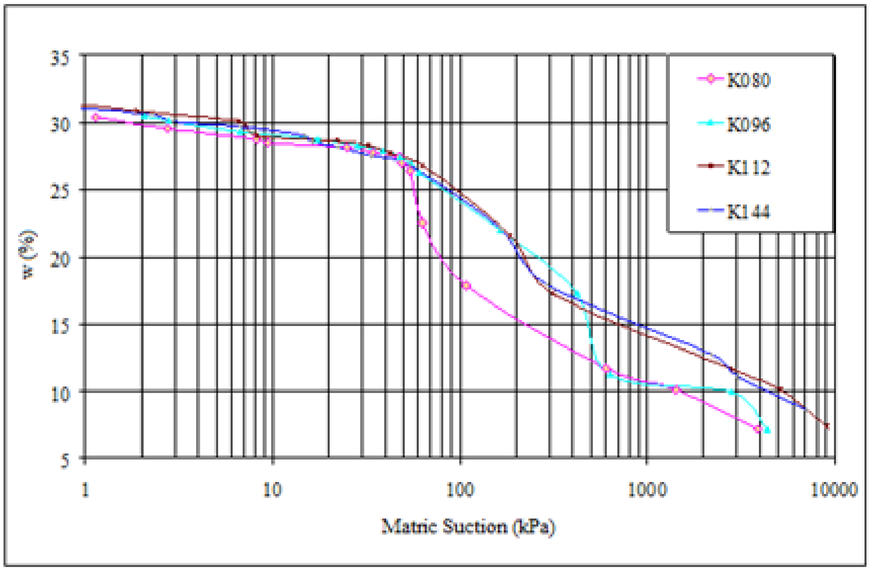

Figure 5. SWCC from filter paper tests

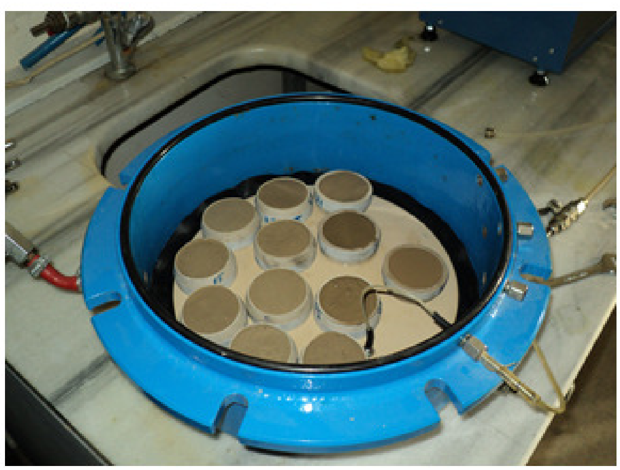

Figure 6. Pressure plate soil samples

The SWCC curves obtained are shown in Figure 7. Figure 8 illustrates the complete curves comprising the filter paper and pressure plate tests for samples with 8 to 18.4 per cent moisture content. The prominent feature of these curves is the vertical displacement with increasing clay contents. It can also be observed that the degrees of saturation increase with increasing clay contents. An "ideal" curve shows an almost horizontal path up to the bubbling point after which the slope shows an abrupt increase in the transition zone as air enters the pores. The last phase is the residual where the curve approaches horizontal because moisture withdraws to the tiniest pores. Figure 8 shows the two initial phases clearly and suggests that the curve would become horizontal had it been possible to increase the capillary tension to sufficiently high levels.

The situation is different in samples with relatively low clay content. Here the curves do indeed approach horizontal. This has been possible by the use of the filter paper test where capillary tension of 10000 kPa was reached as opposed to 1500 in the pressure plate.

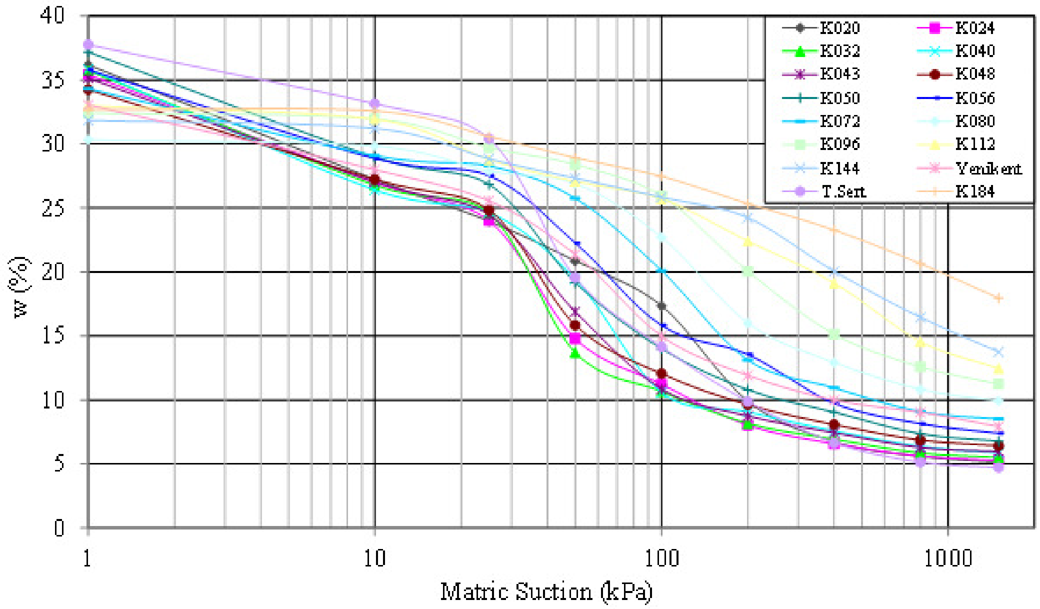

Figure 7. SWCC curves formed by pressure plate tests

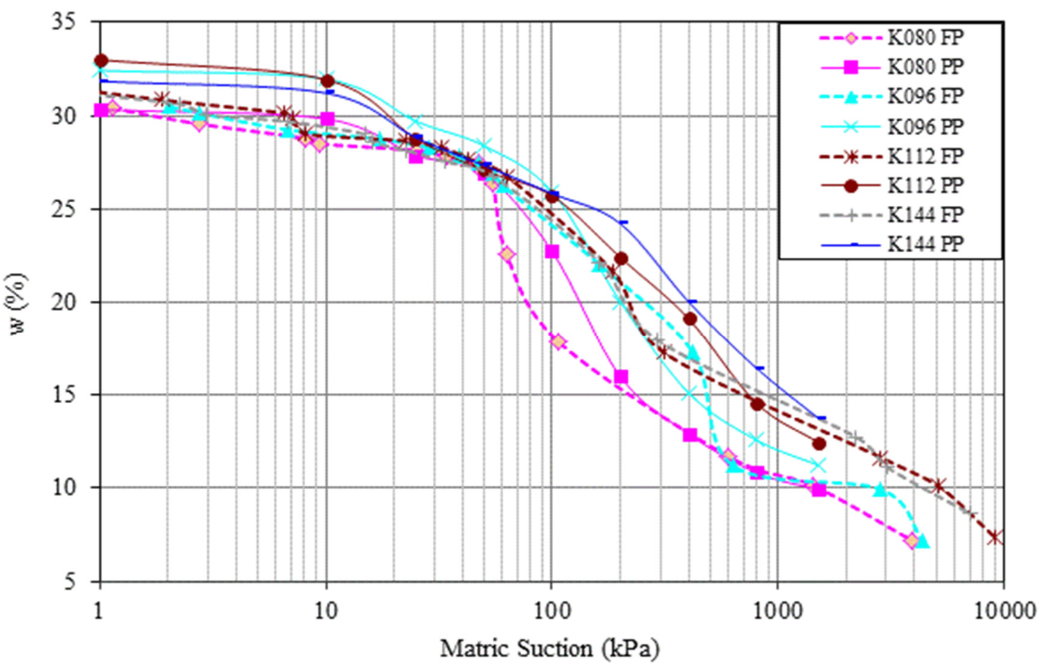

Figure 8. SWCC of four samples formed with both filter paper and pressure plate tests

4. PORE SIZE DISTRIBUTION

Pore geometry is a major factor determining mechanical behaviour. Pore size distribution can be predicted by the SWCC. This section describes the procedure for determining pore size distribution.

If one adds the equation of film thickness around a particle by

$$t_i = \tau\left[-\frac{5}{\ln(RH)}\right]^{1/3} \qquad (2)$$

in addition to the capillarity equation (1), the pore size distribution curves can be derived. Here, τ represents the effective diameter of the sorbate molecule (2.77 Å) (Lu and Likos, 2004).

Figure 9 depicts the pore size distribution by mean pore size, whereas Figure 10 uses pore Radius. It was found that average pore size varied between 10^{-4} ile 10^{-1} mm for the samples tested.

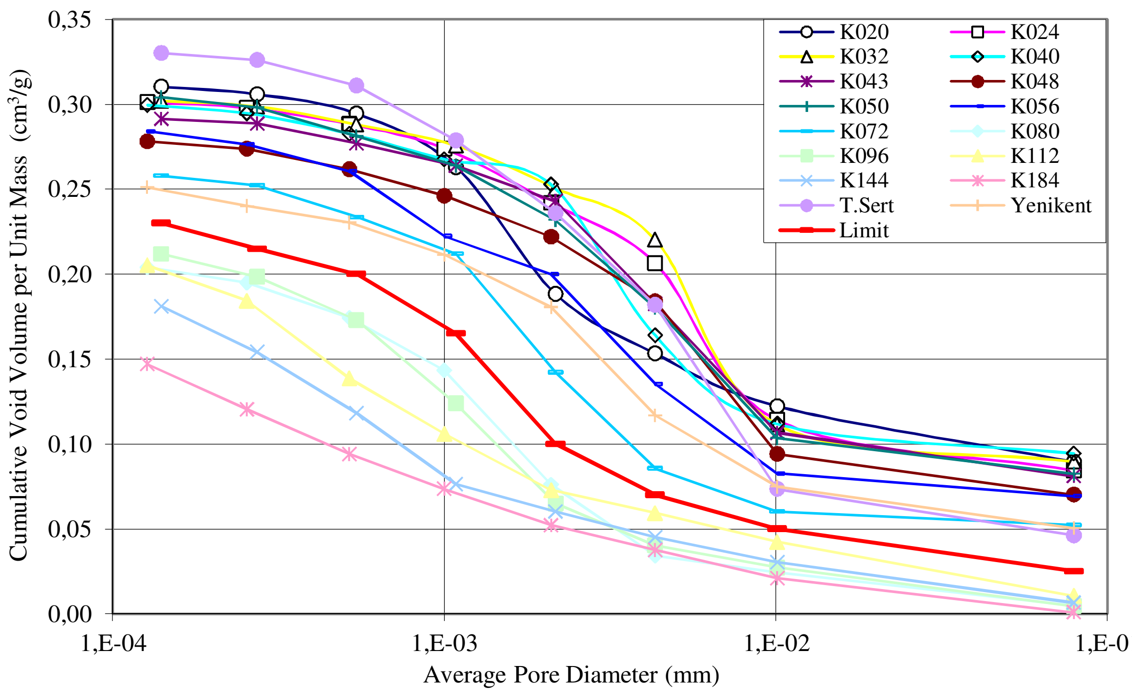

Figure 9. Average pore diameter variation of samples

Figure 9 shows that samples K184, K144, K112 and K096 (clay contents 18.4, 14.4, 11.2 and 9.6%) and Figure 10 shows that samples K184, K144 ve K112 form two separate groups. Table 3 shows the identification of these samples according to the Adapazari Criteria whether they are liquefiable or not. Samples K184, K144, ve K112 are diagnosed as liquefiable whereas the others are immune. This means that Figure 10 is a better tool to test possible dynamic response of the soil. The red curve thus appears to be a border for liquefiability where those samples located above the curve can be said to be non-liquefiable.

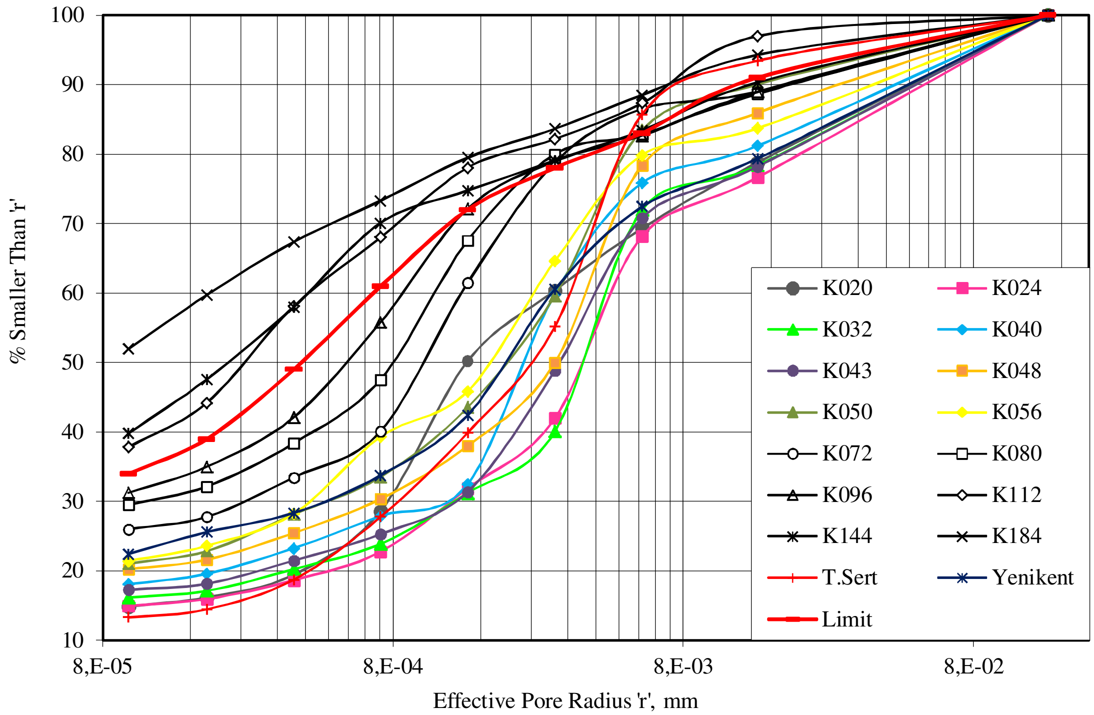

Figure 10. Pore size distribution curves of samples

Table 3. Evaluation of the samples according to Adapazarı Criteria for liquefaction potential

Sample no	w_L (Cas)	w_L (Cone)	w_P	$I_P=w_L-w_P$	% C	D_{50}		Symbol (USCS)	Liquefaction*
						Hydr.	Pipette		
K020	NP	38	NP	NP	2	0.037	0.037	ML	Yes
K024	NP	38	NP	NP	2.4	0.040	0.035	ML	Yes
K032	NP	36	NP	NP	3.2	0.039	0.038	ML	Yes
K040	NP	36	NP	NP	4	0.039	0.036	ML	Yes
K043	NP	35	NP	NP	4.3	0.037	0.035	ML	Yes
K048	NP	34	NP	NP	4.8	0.030	0.036	ML	Yes
K050	NP	35	NP	NP	5	0.031	0.035	ML	Yes
K056	NP	34	NP	NP	5.6	0.028	0.034	ML	Yes
K072	30	33	26	NP	7.2	0.030	0.034	ML	Yes
K080	32	36	23	9	8	0.025	0.027	ML	Yes
K096	33	37	24	9	9.6	0.024	0.024	ML	Yes
K112	34	37	22	12	11.2	0.021	0.030	ML	No
K144	35	37	22	13	14.4	0.016	0.020	MI	No
K184	55	52	27	28	18.4	0.007	0.007	CH	No
Tsert	NP	37	NP	NP	1.6	0.034	0.040	ML	Yes
Yenikent	NP	32	NP	NP	3.2	0.046	0.035	ML	Yes

* According to Adapazarı Criteria (It is assumed that all samples have $I_L \geq 0.9$.)

5. CONCLUSIONS

Evaluation of the seismic behaviour of fine grained soils has received considerable attention in geotechnical earthquake engineering after the 1964 earthquakes. In this study, sample of silt obtained from an area of intense liquefaction was washed to separate its sand and clay. Increasing amounts of its clay fraction was then added to it to prepare 16 mixtures of silt and clay. Samples prepared at 1.5 times its liquid limit were consolidated to 100 kPa, its typical overburden pressure. The Adapazari Criteria was applied to decide which mixes were liquefiable and which were not. The SWCC for the two groups were then evaluated in comparison to their pore size distribution curves. It is concluded that clayey silts with pore radii of $r_{50}<0.0004$ mm are immune to cyclic failure. Also, the soils with pore size distribution curves above and below the red line in Figure 10 are examples of liquefaction and non liquefaction. Further study is required to improve the identification curve.

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