Diagnosing liquefaction potential by the dissipation test in fine grained soil

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ABSTRACT: Extensive ground failures observed in the city of Adapazari, Turkey, during the 1999 Marmara earthquakes have generally been attributed to liquefaction. The main culprit for liquefaction were not the fluvial sands deposited by River Sakarya but silts and sandy silts deposited by the annual floods in the form of overbank sediments. The CPTU has proved to be an efficient way to diagnose liquefiable and non-liquefiable soils. The Adapazari Criteria, developed as a follow up to the so called Chinese Criteria was used to diagnose liquefiability by physical properties. Observations of surface features right after the quakes were also used to confirm liquefaction sites. The pore pressure dissipation approach was then attempted to perform a faster diagnosis of liquefiability, because the ground water table is almost at the surface, and non plastic silts are very difficult to sample for laboratory testing. About 226 dissipation tests were performed in situ, 49 of which were conducted by u_1 measurements. The penetration was arrested at depths where the presence of silts had been detected by previous sounding and drilling and t_{50}, t_{90} and t_{100} were determined analytically. Results indicate that t_{90} values have a potential for diagnosing soils susceptible to liquefaction. This was demonstrated by a $t_{90} < 300$ seconds for liquefiable layers, whereas considerably longer periods are required for non-liquefiable silts. This feature is illustrated by presentation of several typical dissipation curves.

1 INTRODUCTION

The city of Adapazari with a population of 350,000 is one of the rare cities in the region that carries extraordinarily high seismic risk. It is located almost on the North Anatolian Fault (NAF), which is known to have become active ($M_w \geq 7$) almost every decade. The NAF shows a striking similarity to the San Andreas fault both showing right-lateral strike-slip. Almost whole of the city is founded on recent alluvial deposits of the River Sakarya flowing northwards toward the Black Sea. A recent borehole drilled at the center of the city failed to reach rock at 200 m (Bol 2003) and it was claimed that the depth of the alluvium here may be as deep as 1000 m (Komazava et al. 2001). Numerous investigations carried out following the 1999 event concluded that a major part of the soils had liquefied throughout the city and building damage had been caused by those poor soils. The surveys and research carried out by Sakarya University since then have proven that this was a hasty diagnosis. It was discovered that non-plastic silts with sand layers were dominant at sites of liquefaction, from which the Adapazarı Criteria were derived and a liquefaction map was drafted (Bol et al. 2005, Bol et al. 2008b).

The CPTU porewater dissipation test has been used to determine the horizontal coefficients of permeability and there are only a few publications showing its use for liquefaction susceptibility studies. Yang & Elgamal (2002) had determined that permeability is of primary importance for the rise and dissipation of excess porewater pressures leading to liquefaction. This was investigated by a layered soil model with different hydraulic conductivities comprising alternating silt and gravel layers. It was emphasized that determining the permeabilities in the soil profile was an important part of any liquefaction study. Sharp et al. (2003) reached a similar conclusion, stating that permeability was an important factor in the dissipation rates, leading to surface settlements after liquefaction takes place. Permeability and cyclic triaxial test results by Bol et al. (2008a) show that mixtures with clay contents above 10% do not exhibit initial liquefaction and this transition is marked by a coefficient of permeability of around 2.1×10^{-8} m/s. Soils with higher values of k are likely to liquefy. It is only logical then that one can infer from the rise and dissipation of pore pressures during a CPTU whether liquefaction is possible because dissipation is a clear demonstration of permeability.

Boreholes have been drilled at silty sites where there was no liquefaction and those where liquefaction was clearly detected and undisturbed sampling was implemented. The samples were tested for consistency, grain size distribution, consolidation with single or double drainage as well as cyclic triaxial compression. Simultaneous CPTUwas performed next to the borehole and dissipation tests were performed.

2 LIQUEFACTION OF FINE GRAINED SOILS

Because of high SPT N values and cone tip resistances of sands along the buried channels, and their conspicuous absence in other parts of the alluvium, the liquefaction potential of fine grained soils were evaluated. The most popular plasticity based criteria are the "Chinese Criteria" which was developed following the earthquakes in China between 1966 and 1976 (Wang 1979). "Modified Chinese Criteria" (Wang 1979, Seed & Idriss 1982), which represents the criteria widely used for defining potentially liquefiable soils over the past two decades. According to these criteria, fine (cohesive) soils that plot below the A-line are considered to be of potentially liquefiable type and character if: (1) there are less than 15% "clay" fines (based on the Chinese definition of "clay" sizes as less than 0.005 mm), (2) the liquid limit w_L is $\leq 35\%$, and (3) a current in-situ water content greater than or equal to 90% of the liquid limit.

A detailed comparison of the laboratory test results and field observation revealed that the so-called Chinese criteria worked much better for Adapazari nonsensitive/nonplastic silts if they were revised to satisfy the following conditions: A silt is identified as liquefiable if it classifies as ML and the liquid limit is less than

30%, clay content (<2 μm) less than 15%, and liquidity index higher than 1. Subsequent investigators developed similar approaches to judge submerged silts during earthquakes of M_w>7 by requiring (Önalp et al. 2006, Bol et al. 2008b): a) Liquid limit < 33%, b) Liquidity index I_L>0.9 (or w_n/w_L if soil is NP), c) Clay content less than 10% and d) Average particle size D_{50} smaller than 0.06 mm. In addition, a description of the "gray" zones where advanced testing would be required is given in Table 1 (Önalp et al. 2008).

The Adapazari Criteria were then applied to points where silty layers were encountered by making use of Table 1. Accordingly, a layer of soil was graded 1 if the criteria were satisfied and zero if it did not liquefy. 0.5 was used for cases that required further testing. This enabled the investigators to appoint four values to each layer using different properties in Table 1. The totals in the end varied between one and four, where 4 represented soils that are liquefiable and 0 shows soils satisfying none of the criteria employed. Since the values may attain values between 0 and 4, thus requiring further testing, a classification shown in Table 2 was adopted.

Table 1. Evaluation of the Adapazari Liquefaction Criteria

Criteria ⇒	w_L	Clay (%C)	D_{50} (mm)	I_L or w_n/w_L	Value
Liquefaction	$w_L \le 33$	%C ≤ 10	$D_{50} > 0.06$	I_L or $w_n/w_L \ge 0.9$	1.0
Test zone	$33<w_L\le35$	10<%C≤15	$0.02<D_{50}\le0.06$	$0.75 \le I_L$ or $w_n/w_L < 0.9$	0.5
No Liquefaction	$w_L > 35$	%C > 15	$D_{50} \le 0.02$	I_L or $w_n/w_L < 0.75$	0.0

Table 2. Liquefaction evaluation for fine grained soils

Liquefaction	Total Values
Yes	$3.5 \le \Sigma$ Value ≤ 4.0
Test	$2.5 \le \Sigma$ Value < 3.5
No	Σ Value < 2.5

3 DISSIPATION TESTS

The pore pressures that have increased due to the formation of a spherical cavity formed by the penetration of the cone will start dissipating as soon as the penetration is halted. The rate of dissipation is a function of the coefficient of consolidation, the compression index and therefore the hydraulic conductivity k_h. The test is carried on until a fixed period of dissipation or a degree of dissipation is reached. Dissipation ratio U is expressed by

$$U = \frac{u_t - u_o}{u_i - u_o} \qquad (1)$$

where u_t is the porewater pressure u at time t, and u_i is its value at the start of dissipation. The test is continued until at least 50% of the dissipation is recorded. The test has to be kept running until no changes in the u value is observed if an equilibrium value is desired. Equilibrium is attained rapidly in sands whereas several days may be required to reach the same state in clays of high plasticity. Dissipation test performed in soft, fine grained silts and clays measure monotonically decreasing pore-water pressures. However, dissipation tests performed in heavily overconsolidated silts and clays often record dilatory pore-water pressure behaviour, showing a temporary increase in pore-water pressure with time followed by a decrease and return to hydrostatic pressure (Burns & Mayne 1998).

About 226 dissipation tests were performed in situ, of which 49 were conducted with u_1 measurements. The tests yielded six different shapes of dissipation curves. These are illustrated in Figure 1, using t (log) abcissae, where t is in seconds. Included in Figure1 are the number of tests with u_1 and u_2. It is believed that the different curves emanate from the type of soil, overconsolidation ratio, plasticity and the permeability of the layers above and below the level where dissipation was measured. It can be seen that the majority of measurements were made in silt layers, the level of which had been determined by previously made borehole investigation.

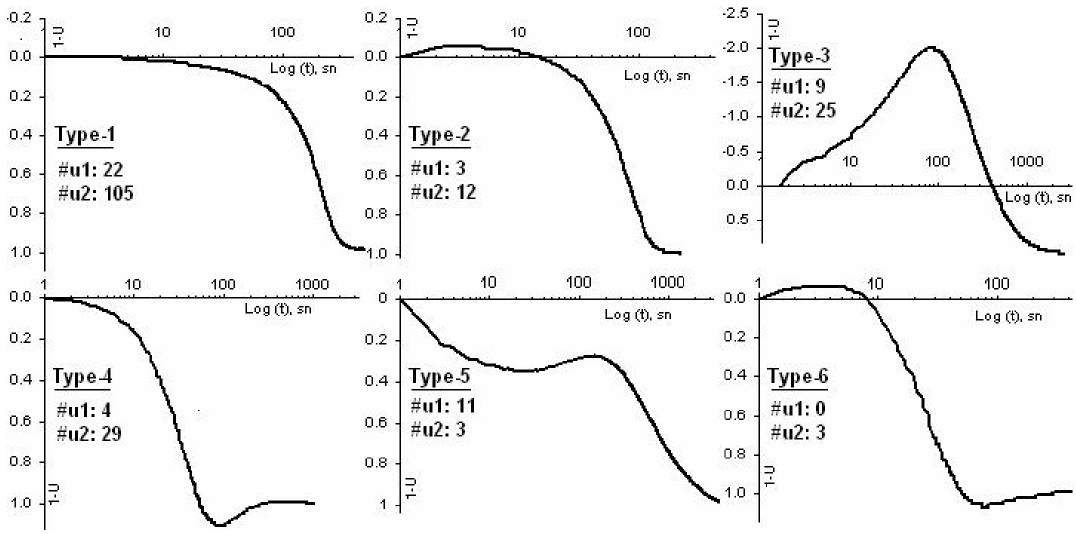


Figure 1. Six types of dissipation curves plotted on Log t – (1-U) axes

It is found that 183 of 566 total laboratory index tests correspond to in-situ dissipation test levels. The results of 175 classification tests for the samples corresponding to the u_1 and u_2 dissipation measurements are given in Table 3. It can be seen that Type 1 dissipation curves predominate for the low plasticity to non plastic ML type silts.

Table 3. Number of soil types where dissipation tests were peformed

Soil Class →	CH		CI		CL		ML		MI		MH		SM	
u_1 or u_2 →	u_1	u_2	u_1	u_2	u_1	u_2	u_1	u_2	u_1	u_2	u_1	u_2	u_1	u_2
Type-1	0	1	1	17	2	12	10	30	0	4	0	0	1	16
Type-2	0	2	1	0	0	1	2	3	0	0	0	0	0	2
Type-3	1	5	1	8	2	3	2	4	0	0	0	1	0	1
Type-4	0	3	0	7	1	3	2	5	0	2	0	0	0	3
Type-5	2	2	3	1	0	0	2	0	3	0	0	0	0	0
Type-6	0	1	0	0	0	0	0	2	0	0	0	0	0	0
Σ	3	14	6	33	5	19	18	44	3	6	0	1	1	22

3.1 *Liquefaction Evaluation Based on Dissipation Curve*

Table 4 shows the liquefaction potential classification made by the use of different filters. Type 1 appears as a characteristic curve for the dissipation curve in ML soils and it may be claimed that silts that exhibit Type 1 curve have a high probability that they will liquefy in earthquakes of $M_w \geq 7$. In contrast, soils that yield Type 4 and Type 5 curves for u_1 measurements are unlikely to liquefy. ML silts do not exhibit Type 6 curves. It can be claimed inspecting Table 4 that similar results have been obtained for u_2 measurements, suggesting that the position of the filter may not be significant in diagnosing liquefaction susceptibility.

Table 4. Comparison of liquefaction susceptibility in ML soil using different type of filter

Filter	Liquefaction	Type-1	Type-2	Type-3	Type-4	Type-5	Type-6
u_1	Yes	9	1	1	0	0	0
	No	1	1	1	2	2	0
u_2	Yes	20	2	1	1	0	1
	No	10	1	3	4	0	1

3.2 *Dissipation Rates and Liquefaction Evaluation*

Soil samples procured from sites of liquefaction and non-liquefaction were tested and their liquefaction susceptibility were evaluated using the Adapazari Criteria (Table 1). Samples carrying the symbol S were assumed as susceptible with the knowledge of their conditions of deposition in Adapazari. Table 5 summarises the results of Type 1 dissipation curves with their averaged dissipation rate values as well as their conformity to the Adapazari Criteria.

The values in Table 5 indicate that liquefiable silts indicate u_2 dissipation curves with U_{50} values of 55 seconds or less whereas non liquefiable ones show U_{50}=327 s. The corresponding times for 90 per cent dissipation are 125 s or less for liquefiable and 713 s for non liquefiable silts. U_{90} values were measured as 125 s or less and 713 s and U_{100} times at 315 s or less and 1285 s, respectively. These values suggest that a careful examination of dissipation values can lead to detection of liquefiable layers. The values calculated for MI silts, although not too many in numbers and of a different curve type, seem to contradict the statement above because U_{50} of MI silt was found to be smaller than that of ML. U_{90} on the other hand is markedly higher. It can therefore be stated at this stage.that U_{90} may be a good indicator of liquefaction susceptibility

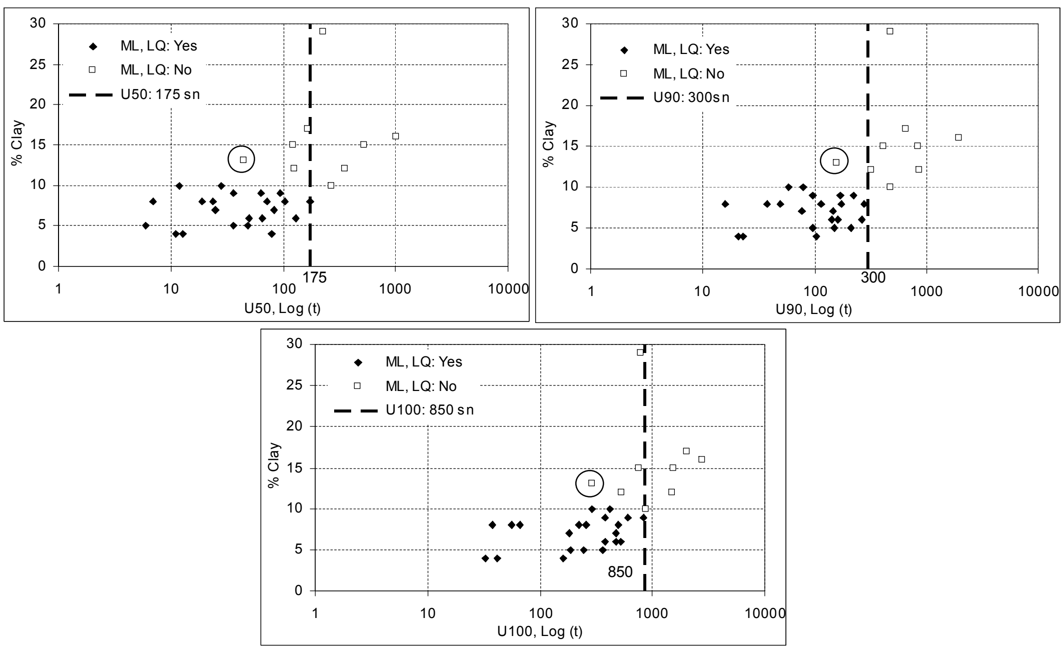
Tablo 5. Average values of dissipation rates for Type-1 curves

Class	Filter	U_{50}	U_{90}	U_{100}	Adapazarı Criteria
S	u_2	31	86	256	Yes
ML	u_2	55	125	315	Yes
ML	u_1	21	191	947	Yes
ML	u_2	327	713	1285	No
MI	u_2	113	300	768	No
CL	u_2	235	687	1185	No
CI-CH	u_2	460	1048	2001	No

The U_{50}, U_{90} and U_{100} times are plotted against clay content in Figure 2. One can see from these data that dissipation times tend to increase with increasing clay contents as expected. It is however difficult to make a distinction of liquefiable and non-liquefiable silts looking at U_{50} ve U_{100} values. It is evident that U_{50} values for liquefiable and non-liquefiable soils overlap at around 175 s, and U_{100} values similarly overlap at around 850 s, and one is unable to differentiate the two states. The U_{90} values on the other hand, seem to separate the two zones for ML silt at around 300 s with the exception of a single point.

Although more data is clearly needed to assert as a rule, one tends to state that liquefaction in ML silts with U_{90} of 300 s or less is "possible and highly probable" with the existing evidence. In addition, we are now making the classification as "liquefaction", "test" and "no liquefaction" as opposed to "yes" or "no" as done in the preceding section.

Table 6 lists the average dissipation times corresponding to the evaluation criteria described above. The dissipation curve types 1, 2, and 3 have been used for the evaluation as these types were applicable to ML silts.



Şekil 2. The U_{50}, U_{90} and U_{100} times versus clay contents measured in ML silts

Tablo 6. Dissipation times for liquefaction states for Type-1 curves

Liquefaction	Σ Value	U_0	U_{50}	U_{90}	U_{100}
No	0-1	193.3	734.21	1524.2	2231.92
No	1.5-2	24.73	263.63	762.53	1388.47
Test	2.5-3	6.97	189.79	424.03	805.13
Yes	3.5-4	5.31	66.54	148.17	344.65

4 CONCLUSIONS

A great number of CPTU dissipation tests conducted in different soils of Adapazari have shown curves which are dissimilar. The curves were eventually identified in six typical groups. The different types of curves observed in various types of soils are formed depending on the consistency limits, overconsolidation ratio, the thickness of the layer and the permeability of the over- and underlying strata.

When dissipation measurement is done with the u_2 filter, Type-1 curves are exhibited by silts of low plasticity (ML), silty sands (SM), and possibly clays of low and intermediate plasticity (CI, CL). Type-3 curve is characteristic of clays of high plasticity (CH). Type-5 and Type-6 dissipation curves are seldom encountered when measurement with u_2 is performed. In Adapazari soils the majority of measurements showed Type-1, Type-3 and Type-4 in order of frequency while the other types were obtained occasionally.

The fact that dissipation times are increased by increasing clay content of the soils was confirmed. Data collected so far suggest that time corresponding to 90 per cent of dissipation is a realistic indicator of liquefaction potential. It was determined that a U_{90} of 300 seconds formed a significant limit between liquefiable and non liquefiable ML silts, where one can state that any ML silt showing $U_{90} < 300$ s is liquefaction susceptible. So, soil behaviour type (SBT) zones 4 and 5 in the Robertson (1990) CPT SBT chart that are encountered in the CPTU profile may be judged by this criterion.

The study implemented over five years has shown the authors that dissipation measurements in the CPTU may be a powerful and rapid method in the prognosis of liquefaction. Further studies are therefore being done to extend it to other types of soils.

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