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ORIGINAL RESEARCH PAPER

Liquefaction of silts: the Adapazari criteria

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Abstract Ground failures in the form of liquefaction, loss of bearing capacity and soil softening have been observed during the 1999 Marmara (Turkey) earthquake. Research to understand the failure phenomena has been carried out since the earthquakes. This paper attempts to provide explanations to the liquefaction failure of silts in seismic conditions. Findings from a large amount of data collected in the city of Adapazari on the physical and mechanical properties of soils is presented. A geomorphological map of the city has shown that there are surprising horizontal and vertical variations of the facies due to the activity of rivers in the past. Cases of liquefaction appear to have concentrated in former backswamp areas where silts and sandy silts were deposited by crevasse splays. Properties of the soils in zones of liquefaction and non-liquefaction have been determined down to a reasonable depth by measuring the average size, clay content and liquidity index as well as cone penetration resistances with porewater pressures to discover that there is significant discrepancy among those profiles susceptible to liquefaction and non-liquefying deposits. A set of "Adapazari Criteria" is proposed which is intended to improve over the "Chinese Criteria" and is simple enough to be universally applicable. This classification is similar to the existing criteria but emphasizes more on the clay content in addition to measuring the liquid limit and the liquidity index as well as the average size.

Keywords Turkey · Adapazari · Earthquake · Ground failure · Liquefaction · Fine-grained soils · Clay content · Liquidity index · Average size · Sand content

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List of Symbols

CI Clay of intermediate plasticity
D_{50} Average grain size
I_c Soil type behavior index
I_L Liquidity index
I_P Plasticity index
MI Silt of intermediate plasticity
M_w Magnitude
NP Non plastic
t Duration
w_L Liquid limit
w_n Natural water content
w_P Plastic limit
η Sand influence factor

1 Background

The ever active transform fault of North Anatolia (NAF) moves at approximately decade long intervals with catastrophic results. The last two relatively well documented earthquakes of 1967 and 1999 devastated the city of Adapazari with different consequences. The most striking difference is the relatively widespread appearance of the phenomenon of liquefaction of silts during the 1999 event. This hitherto regionally unknown phenomenon was rapidly taken up by the media, academicians, the local and central government agencies and the city of Adapazari was declared an area of liquefaction, as this type of ground failure was the only plausible explanation at the time. The record of ground motions and the details of the regional seismicity have been reported in detail by the US Geological Survey (2000). Several investigators have blamed the inferior soils for the hundreds of buildings that suffered damage during the 1999 Kocaeli earthquake and speculated on the causes of ground failures. The findings vary from the effect of the plasticity index and liquidity index on liquefaction (Bray et al. 2001, 2004a; Sancio et al. 2002) to the decay of the shearing resistance under cyclic loads (Yilmaz et al. 2004).

Exhaustive geological, geomorphological and geotechnical studies were undertaken by this team during the next seven years by means of surface observations and recording of damage to the superstructures right after the 1999 event, drilling of boreholes, laboratory testing accompanied by standard penetration resistance measurements as well as seismic piezocone testing (SCPTU) have been carried out. Results have indicated quite a different picture than initially visualised. The established database to date indicates that about only 21% of the total area of study might have actually liquefied, while ground failures in the form of bearing capacity and soil softening in the upper 5 m of clays and silts by repetitive loading constituted the other types of failure.

2 Geomorphology and geology

The city of Adapazari is situated on the western end of the alluvial plain of Adapazari (Akova) formed by the rivers Sakarya and Mudurnu. River Sakarya, which currently flows northwards along the eastern limits of the City (Fig. 1), appears to have dominated the development of the soil profile throughout the study area during the past few millennia. It originates in the

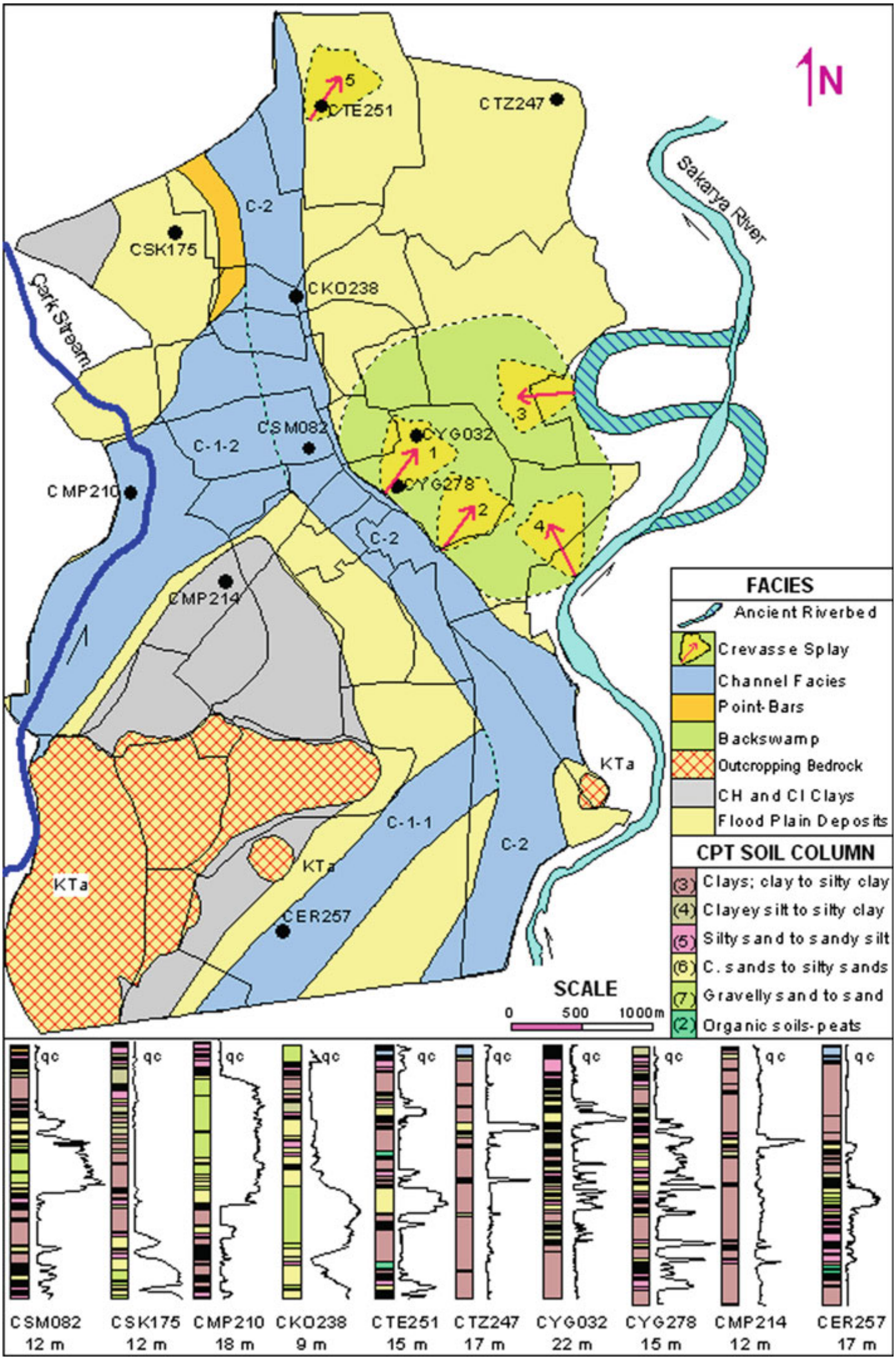

Fig. 1 Geomorphological features of Adapazari and CPT profiles from various formations

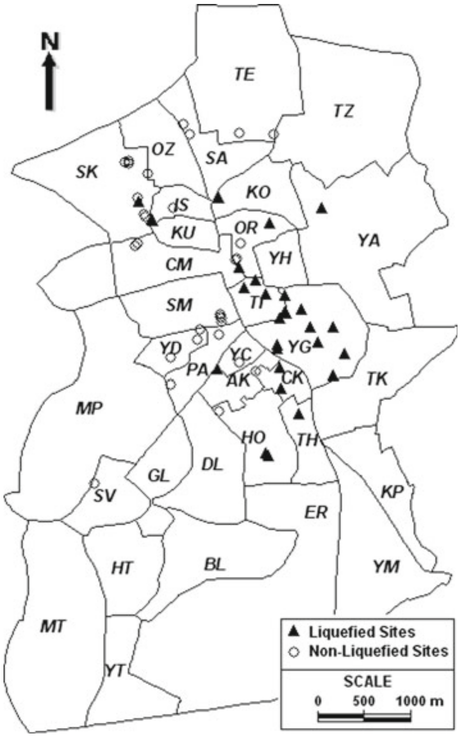

Fig. 2 Administrative districts of Adapazari City and sites studied

mountains of Anatolia flowing Northwards to Black Sea at high gradients, and appears abruptly on the plain exiting the gorge of Geyve, the southern limit of the plain, laden with sediment.

At present, the city of Adapazari is surrounded by River Sakarya to the east and the Cark stream to the west. The latter is currently draining the nearby Lake Sapanca at relatively low flow rates. The existence of a 12 span, 429 m long Roman bridge (AD560) near its exit to the Cark stream raises doubts whether this stream was as tame as it is today or whether it was meant for another river in the past and Cark is a subsequent formation. It is highly probable that Sakarya was actually flowing under this very bridge and its bed shifted eastwards.

The area of study was selected to embrace the 29 administrative districts of metropolitan Adapazari (Figs. 1 and 2) and covers an area of 25.7 km^2. The altitude within the area of study is almost constant at 31–28 m along an 8 km S-N axis. The proximity of ample sources maintains a high and rapidly fluctuating groundwater table throughout the city, the GWT occasionally rising to the surface during the wet season.

A total of 650 boreholes and 295 CPT soundings performed in the study area have been used to establish a database which is expected to reveal the distribution and nature of the sediments since 1995 (Onalp et al. 2001; Bol and Onalp 2002; Bol 2003; Bol et al. 2008). The selected sites for further study are mostly those where SPT and CPT testing have been performed simultaneously. The same drilling team and laboratory personnel have been employed throughout the research work.

Studying the information collected so far, the geomorphological past of Adapazari during the last 7000 years can be summarised as the existence of a strait joining the Black Sea to the Marmara (Ryan and Pitman 1999), blocking of this strait resulting in extremely rapid fluvial sedimentation, meandering and shifting of one or more rivers with high rates of flow across the present city area, the appearance of the modern river Sakarya which flooded the region almost biannually during the past 1000 years and finally the cessation of the processes of sedimentation as a result of the construction of two large dams upstream in the sixties, thus ending floods.

3 The soil profile

The processes described above have resulted in a complex and unpredictable fluvial and possibly lacustrine soil systems. The top 50 m consist of sub-facies like point bar deposits, backswamps, abondoned channel deposits, levees, crevasse splays that are typical of the floodplains of large rivers. The established database revealed for example, the existence of a large riverbed traversing the city about 1000–2500 years ago. The C2 channel in Fig. 1 representing this relict river appears at depths 3–7 meters today. The finding is supported by the existence of dense SW and SP type deposits in addition to the rare gravel layers, which do not often appear elsewhere. The C1-1 and C1-2 channels similarly appear at depths of 11–12 m. The river must have broken out of its bed along the convex bend in the present city center forming the crevasse splays and the resulting backswamps.

The arrows 1, 2 and 5 show the direction of the sediments carried from channel C2 and arrows 3 and 4 delineate a more recent movement, but all appear to have deposited younger sediments in the districts TI and YG where not surprisingly, non plastic silts dominate the soil profiles and extensive ground failures have been observed in these heavily populated districts during the earthquake. Sands such as SP and SW are confined to the flow channel areas. The findings are represented in Fig. 1, illustrated by radically different CPT profiles in each subfacies zone, which could not have been detected by borings and SPT measurements in such detail.

A typical soil profile from the city center can be described by no less than ten relatively thin layers of extremely loose or soft layers dominated by silts interspersed with clays and fine silty sands in the top 5–8 m that were deposited during the floods of the last millenium. The colours are consistently green and green/brown. They change to gray and occasionally black in certain areas, depending on the organic content where waters have dwelled beyond the period of flooding and formed marshes and lakes. Layering below depths of 10 m becomes thicker and alternating layers of silt and clay are replaced by lacustrine clays and sands down to a depth of 200 m, the deepest borehole log available in the city. It is claimed that the bedrock is at a depth of over 1000 m in the city center (Komazawa et al. 2002).

4 Effect of earthquakes

The considerable difference in casualties and damage to the superstructure in the 1967 and 1999 earthquakes could at first sight be attributed to the rapid increase of the population and the building stock in the city since the early seventies, not to mention the number of storeys that went up to six from a typical three of the past.

There are however, significant differences of the two events from the viewpoint of the geotechnical engineer. Interviews with the engineers and credible eyewitnesses who lived through both events indicate that apart from ground oscillation, ground failure and liquefaction was limited to rare sites in 1967 ($M_w = 6.8, t = 34$ s). In contrast, there was widespread and extensive ground failure in the form of liquefaction, bearing capacity failure and differential settlement in the 1999 ($M_w = 7.4, t = 48$ s) event. Lateral spreading was not observed in the study area, due to almost horizontal and uninterrupted ground surface.

One of the reasons why several investigators might have been misled in differentiating liquefaction from other types of ground failure is the practice of assuming an allowable bearing capacity for footings of 80 kPa throughout the city without performing any sort of soil investigation, in the past. It has nevertheless been subsequently determined that σ_{all} can be as low as 35 kPa within the top 5 m depth at many sites, that led to the observed bearing capacity failures of continuous footings as well as rafts during the earthquake.

5 Evaluation of ground failure

A detailed study was implemented starting the morning after the 1999 event. This was initiated by recording sites of ground failure, photographing damage zones and selecting possible liquefaction sites for immediate soil exploration.

In accordance with the main aim of this study, a site was given priority in the case where the building had undergone visible settlement and silt/fine sand ejecta around the building often accompanied by the exit of water was obvious to the assessors, practically conforming to the textbook definition of liquefaction. Alternatively, a non failure/non liquefaction site was selected to be an area where there was no visible ground failure and damage to the superstructure. Both judgments were then tested using the existing criteria before confirming the conditions at that particular site. The database was then queried for those sites where simultaneous SPT and CPTU measurements had been satisfactorily performed. Ultimately, 34 nonliquefied and 29 liquefied silt sites were selected for further study.

Tables 1 and 2 provide a list of the sites which were deemed to have liquefied and not liquefied respectively, in conformity to the above observations.

6 Classification based on physical properties

There are several approaches for determining the liquefaction potential of fine grained soils. This subject has been discussed in detail recently (Bray et al. 2004b) and it is now reevaluated in the light of additional data.

All previous investigators emphasized the primary importance of liquid limit in the liquefaction process of silt. Table 3 summarises the upper limits for the initiation of liquefaction in silty soils, proposed by several investigators. They vary within the interval 30–37, the majority adopting 34 and higher to denote non-liquefiable soils. However, values above 35 indicate silts of intermediate plasticity and appear to be conservative, considering the fact that their plastic limits would also assume appreciable values rendering the liquefaction process inefficient by lowering the permeability.

The second property used to diagnose a liquefiable silt is its natural moisture content. The so called Chinese Criteria was the first (Wang 1979; Jennings 1980) to propose that for a silt to liquefy, the ratio of the natural moisture content to its liquid limit (w_n/w_L) should be equal to or greater than 0.9. Most investigators followed the same line. The liquidity index I_L on the other hand, defined as the ratio of the difference between the natural moisture content and plastic limit to the plasticity index $(w_n - w_P)/I_P$, appears as a more realistic expression since it includes the plastic limit in the definition. Its significance can be shown with the following example: A soil with a liquid limit 35, natural water content 30 and no plastic limit (NP) has identical I_L and (w_n/w_L) values at 0.86, showing possible liquefaction susceptibility. If however, the same soil has a plastic limit of 25, the result $w_n/w_L = 0.86$ is still pointing to highly probable liquefaction whereas the corresponding $I_L = 0.50$ indicates low or no

Table 1 Properties of silts at liquefied sites

SiteID	Depth	Colour	w_L	w_P	w_n	I_L	FC%	Clay%	n(Clay/Silt)	Class	D_{50}	D_{10}	I_c
SKO568	2.6	BG	31	–	32	1.032	82	5	0.053	ML	0.050		
SKO568	3.85	B	NP	–	30	>1	59	5	0.055	ML	0.070	0.018	
SKO568	4.6	G	NP	–	23	>1	66	15	0.194	ML	0.050		
SIS570	4.4	G	30	–	29	0.967	90	14	0.166	ML	0.027		2.46
SIS570	6	G	31	–	29	0.935	53	11	0.139	ML	0.070	0.001	1.83
SIS573	4.4	B	NP	–	29	>1	51	14	0.193	ML	0.070	0.003	
SCK141	3.8	B	31	–	27	0.871	55	10	0.122	ML	0.062	0.002	2.27
STI095	3.3	–	20	–	34	1.700	59	11	0.135	ML	0.053	0.001	
SYG098	1.07	dB	28	–	32	1.143	72	7	0.078	ML	0.060	0.004	2.78
SYG098	1.8	B	27	–	28	1.037	68	9	0.104	ML	0.048	0.007	2.34
SYG098	5.1	B	30	–	28	0.933	77	14	0.171	ML	0.041		2.64
SYG098	5.7	G	28	–	27	0.964	51	6	0.068	ML	0.070	0.013	2.06
SYG098	6.4	G	28	–	34	1.214	72	15	0.189	ML	0.050		2.2
SYG098	8.3	BdG	31	–	29	0.935	80	13	0.155	ML	0.034		2.22
SYG097	3.8	–	33	26	35	1.286	78	6	0.065	ML	0.028	0.003	2.57
SYG097	12	GN	35	–	36	1.029	97	15	0.177	MI	0.021		2.30
SYA322	5.15	dG	31	–	33	1.065	80	7	0.077	ML	0.045	0.009	2.47
SYA322	5.7	dB	33	–	31	0.939	80	5	0.053	ML	0.040	0.005	2.09
SYG102	2.84	B	25	–	38	1.520	65	13	0.163	ML	0.041		
SOR567	2.3	G	26	–	31	1.192	74	5	0.054	ML	0.060		
SOR567	3.85	B	28	–	31	1.107	79	5	0.053	ML	0.059	0.02	
OR567	4.6	B	31	–	33	1.065	57	6	0.067	ML	0.063	0.005	
SOR567	5.55	B	33	27	34	1.167	87	4	0.042	ML	0.030	0.004	
SOR567	8.7	G	31	–	36	1.161	80	5	0.053	ML	0.060		
STI246	3	B	22	–	30	1.364	77	15	0.186	ML	0.054		2.29
STI246	6	dGB	NP	–	27	>1	58	11	0.136	ML	0.062		1.54
STI600	1.5	dB	32	–	34	1.063	86	13	0.153	ML	0.023	0.001	2.63
SYC414	3	B	32	–	32	1.000	99	15	0.177	ML	0.028	0.001	2.49
SYC414	6.25	N	NP	–	28	>1	88	15	0.181	ML	0.038	0.001	
SYC414	10.5	N	NP	–	22	>1	54	10	0.123	ML	0.070	0.0035	
SYG050	3	BN	NP	–	34	1.214	71	12	0.144	ML	0.055	0.001	2.43
SYG050	5.96	BN	19	–	22	1.158	59	13	0.167	ML	0.067	0.001	2.37
SYG079	1.5	B	NP	–	34	>1	67	10	0.118	ML	0.042	0.001	2.21
SYG079	2.5	B	NP	–	37	>1	76	11	0.129	ML	0.030	0.001	2.54
SYG079	4.65	dG	25	–	29	1.160	54	10	0.123	ML	0.062	0.0014	2.59
SYG244	2.4	B	25	–	31	1.240	69	12	0.145	ML	0.045		2.25
SYG244	7.3	BN	32	–	30	0.938	96	10	0.112	ML	0.024		2.42
SYG245	6.1	GN	30	–	30	1.000	82	14	0.169	ML	0.036		2.4
SYG245	8	GN	33	–	30	0.909	58	12	0.151	ML	0.055		2.28
SYG597	1.5	lB	29	–	32	1.103	78	10	0.115	ML	0.040	0.002	2.76
SYG597	2.5	NB	30	–	33	1.100	88	11	0.126	ML	0.029	0.001	2.61
SYG610	2.5	B	NP	–	30	>1	81	10	0.114	ML	0.028	0.002	2.83
SYG610	3	B	NP	–	28	>1	93	14	0.165	ML	0.022	0.001	2.69

Table 1 continued

SiteID	Depth	Colour	w_L	w_P	w_n	I_L	FC%	Clay%	n(Clay/Silt)	Class	D_{50}	D_{10}	I_c
SYG610	6	N	30	–	28	0.933	87	14	0.167	ML	0.034	0.001	2.43
SYG626	6	G	38	26	37	0.917	94	11	0.125	MI	0.023	0.001	2.59
SHO602	2.6	B	25	–	29	1.160	54	10	0.123	ML	0.062	0.002	2.09
SOR415	3	B	28	–	37	1.321	82	15	0.184	ML	0.025	0.0004	2.58
SSK612	2	B	29	–	28	0.966	82	14	0.169	ML	0.030	0.001	2.55
SSK612	6	dB	34	–	39	1.147	85	12	0.140	ML	0.050	0.001	2.52
STH598	1.5	B	24	–	32	1.333	64	9	0.105	ML	0.056	0.003	2.63
STH598	6	GN	28	–	27	0.964	77	9	0.102	ML	0.042	0.003	2.82
STH598	9	N	NP	–	26	>1	65	14	0.178	ML	0.050	0.001	2.59
SYG078	1.5	B	25	–	32	1.280	67	10	0.118	ML	0.050	0.002	
SYG078	6	GdN	28	–	29	1.036	92	14	0.165	ML	0.034		
SYG078	7.5	GdN	29	–	28	0.966	93	15	0.179	ML	0.020		
SHO618	6	B	34	–	38	1.118	85	11	0.126	ML	0.035	0.001	
SHO619	1.5	dB	26	–	35	1.346	97	11	0.124	ML	0.021	0.0015	
SHO619	3	B	33	–	40	1.212	95	14	0.164	ML	0.025	0.001	
SYG080	1.5	lB	29	–	35	1.207	69	11	0.131	ML	0.042	0.0012	
SYG080	7.5	GN	25	–	28	1.120	67	11	0.132	ML	0.050		
SYG621	6	BN	NP	–	32	>1	65	15	0.195	ML	0.050		

Colour code d: dark, l: light, G: Gray, N: Green, B: Brown, Ic:soil type behaviour index

Table 2 Soil properties in non-liquefied sites

SiteID	Depth	Colour	w_L	w_P	w_n	I_L	FC%	Clay%	n(Clay/Silt)	Class.	D_{50}	D_{10}	I_c
SYD165	1.5	B	37	–	37	1.000	74	11	0.129	MI	0.040	0.001	2.86
SYD165	6	GN	NP	–	32	>1	77	26	0.393	ML	0.021		2.94
SYC234	10.5	N	26	–	24	0.923	75	15	0.188	ML			2.37
STE404	1.5	dN	39	26	41	1.154	98	20	0.251	MI			2.77
STE404	4.5	dNG	33	–	33	1.000	85	17	0.213	ML			2.36
STE404	6.25	dNG	NP	–	30	>1	56	16	0.224	ML			2.20
STE404	7.5	dNG	36	25	37	1.091	93	18	0.223	MI			2.60
SSM189	3	G	30	–	24	0.800	81	19	0.248	ML	0.030		2.36
SSM190	9	G	25	–	33	1.320	75	16	0.203	ML	0.027		
SSK352	3	lB	35	–	30	0.857	88	20	0.259	MI	0.017		2.44
SSK339	6	dN	29	–	30	1.034	93	21	0.271	ML	0.017		2.77
SSK338	4.5	B	34	–	29	0.853	87	20	0.260	ML	0.020		2.82
SSK338	6	NdG	34	–	34	1.000	91	20	0.256	ML	0.013		2.93
SSK338	10	N	26	–	27	1.038	70	11	0.131	ML	0.041	0.001	2.46
SSA394	1.5	BG	30	–	33	1.100	94	18	0.223	ML	0.022		2.63
SOR266	2.5	B	31	–	35	1.129	98	24	0.318	ML			2.81
SOR265	2.5	BY	35	–	37	1.057	93	19	0.239	MI	0.030	0.001	2.88
SOR265	3	dB	33	–	37	1.121	93	19	0.239	ML	0.019		2.79

Table 2 continued

SiteID	Depth	Colour	w_L	w_P	w_n	I_L	FC%	Clay%	n(Clay/Silt)	Class.	D_{50}	D_{10}	I_c
SOR265	6	NG	38	25	42	1.308	97	42	0.741	MI	0.003		2.41
SHO485	4.5	dG	35	24	31	0.636	86	17	0.212	MI	0.030		2.50
SHO485	6	G	26	–	27	1.038	86	17	0.212	ML	0.050		2.32
SYD632	3	B	27	–	30	1.111	63	18	0.252	ML	0.030	0.001	
SYD632	4.5	B	32	–	35	1.094	90	15	0.180	ML	0.021	0.001	
SYD162	3	B	35	–	37	1.057	99	25	0.334	MI	0.025		
SYD162	6	GN	23	–	28	1.217	70	20	0.280	ML	0.060		
SYD162	8.5	GdN	30	–	31	1.033	87	29	0.435	ML	0.015		
SYD162	9	GN	31	–	32	1.032	83	22	0.299	ML	0.025		
SSA615	2.5	B	30	–	32	1.067	88	20	0.259	ML	0.020		
SPA143	3	lB	31	–	32	1.032	89	27	0.388	ML	0.016		
SOR269	4.5	B	29	23	32	1.500	74	12	0.143	ML	0.040		
SOR269	6	NB	36	25	33	0.727	94	35	0.558	MI	0.009		
SMP653	9	B	33	24	37	1.444	84	16	0.198	ML	0.022		
SMP653	12	G	30	–	28	0.933	69	12	0.145	ML	0.022	0.001	
SMP653	13.5	G	23	–	30	1.304	74	9	0.102	ML	0.028	0.0022	
SIS634	10.5	G	31	25	26	0.167	73	18	0.239	ML	0.058		
SCM412	3	B	34	–	37	1.088	96	23	0.302	ML	0.015		
SCM413	3	BG	34	–	35	1.029	92	17	0.209	ML	0.033		
SCK601	3	lBN	30	–	32	1.067	96	22	0.285	ML	0.014		
SCK601	10	N	30	–	25	0.833	84	15	0.183	ML	0.032	0.001	
SCK601	12	N	32	–	31	0.969	91	13	0.152	ML	0.025	0.001	
SPA145	6	GdN	45	31	39	0.571	86	12	0.139	MI	0.040		3.14
SSK337	1.5	NK	25	–	25	1.000	64	15	0.196	ML	0.055		
SSK337	7.5	dN	30	–	36	1.200	86	29	0.438	ML	0.009		
SSK349	1.35	NB	30	–	32	1.067	93	21	0.271	ML	0.016		2.76
SSK349	3	B	28	–	32	1.143	87	12	0.139	ML	0.024	0.001	2.67
SSK349	7.5	N	25	–	32	1.280	58	10	0.121	ML	0.051	0.002	2.56
SSK349	9	G	22	–	26	1.182	93	10	0.112	ML	0.027	0.002	2.53
SSK350	3	lB	31	–	38	1.226	83	11	0.127	ML	0.030	0.0015	2.68
SSM191	3	B	34	–	34	1.000	54	10	0.123	ML	0.060	0.002	2.42
SSM191	7.5	dN	25	–	23	0.920	58	12	0.151	ML	0.060		2.56
SSM191	9	dN	31	–	32	1.032	73	26	0.404	ML	0.031		2.68
SSM192	3	dB	33	–	35	1.061	94	28	0.399	ML	0.011		2.56
SSM192	7.5	dGN	29	–	24	0.828	65	9	0.104	ML	0.060	0.003	2.58
STE411	1.5	B	28	–	23	0.821	83	16	0.198	ML			2.41
STE411	2.5	B	34	–	35	1.029	97	16	0.192	ML			2.48
ZSON203	4.5	GdN	31	–	34	1.097	92	21	0.272	ML	0.005		2.59
ZSON203	10.8	NdG	31	–	34	1.097	92	16	0.194	ML			2.51
ADADOK	2.5	B	35	26	38	1.333	93	10	0.112	MI	0.021	0.002	
ADADOK	7.5	GN	33	24	33	1.000	84	18	0.229	ML	0.025	0.001	
SOZ364	1.5	lB	35	25	34	0.900	96	18	0.222	MI	0.015		

Table 2 continued

SiteID	Depth	Colour	w_L	w_P	w_n	I_L	FC%	Clay%	n(Clay/Silt)	Class.	D_{50}	D_{10}	I_c
SOZ364	2.4	B	33	–	29	0.879	87	17	0.211	ML	0.022		
SOZ364	3.3	B	31	–	37	1.194	89	31	0.476	ML	0.011		
SOZ364	5.1	dN	38	25	29	0.308	97	22	0.285	MI	0.012		
SOZ364	6	N	36	25	28	0.273	97	30	0.434	MI	0.008		
SYC128	1.5	GdN	31	–	35	1.129	90	29	0.428	ML	0.009		
SYC128	3	B	28	–	31	1.107	84	30	0.467	ML	0.016		
SYC128	9	GdN	37	–	39	1.054	99	20	0.251	MI	0.020		
SYG091	3	B	24	–	29	1.208	67	17	0.228	ML	0.052		
SYG091	6	GdN	26	–	30	1.154	70	17	0.225	ML	0.045		
SYG091	7.5	GdN	29	–	32	1.103	97	22	0.285	ML	0.018		

Colour Code d: dark, l: light, G: Gray, N: Green, B: Brown, Ic:soil type behaviour index

Table 3 Liquid limit values to trigger liquefaction

Researcher/s	Liquid limit, $w_L \leq$
Wang (1979)	35
Seed et al. (1983)	35
Finn et al. (1994)	34
Koester (1994)	36
Andrews and Martin (2000)	32
Onalp et al. (2001)	30
Seed et al. (2003)	37

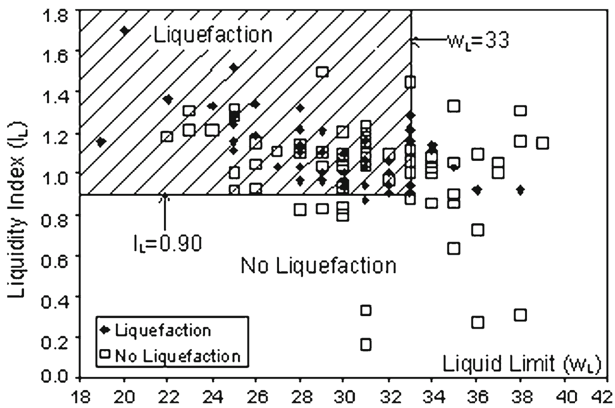

Fig. 3 The location of selected liquefied and nonliquefied silts on the $w_L - I_L$ space

probability of liquefaction, which actually is the case. The liquidity index was accordingly preferred here to represent the effect of in situ water content on liquefiability for this study. The liquidity index for non-plastic samples has still to be defined by (w_n/w_L).

Figure 3 represents the results obtained in this study. A liquidity index of $I_L = 0.9$ emerges as a well defined limit for liquefaction. Furthermore, a liquid limit of 33 is found to envelop

Table 4 Clay content in silts to initiate liquefaction

Researcher/s	Clay size	Clay%≤
Wang (1979)	<0.005	15
Jennings (1980)	<0.005	10
Finn (1982)	<0.005	10
Seed et al. (1983)	<0.005	15
Finn et al. (1994)	<0.005	10
Andrews and Martin (2000)	<0.002	10
Onalp et al. (2001)	<0.002	15

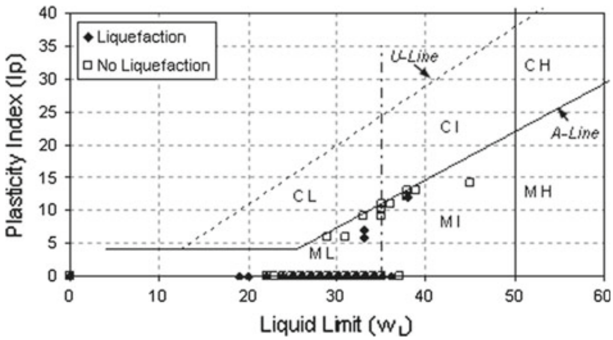

Fig. 4 Position of liquified and non liquified silts on the TS1500 (2000) plasticity chart

most of the points. The transgression of points for liquefied and non-liquefied sites within a liquid limit interval 26 to 33 the other hand, is a clear indication that the process cannot be considered to be controlled only by the liquid limit and the natural moisture content of the silt, but additional factors should be considered.

Several investigators have found that the percentage of clay fraction is another important factor affecting liquefaction susceptibility of silts (Wang 1979; Jennings 1980; Finn 1982; Seed et al. 1983; Finn et al. 1994; Andrews and Martin 2000; Onalp et al. 2001). The Chinese criteria adopted 5 μm clay size to identify liquefiable soils, setting 15% as the upper limit for the clay content. There is however, overwhelming agreement in the literature that clay size is actually two microns. Since clay particles in the soil matrix heavily influence or even control the permeability by forming domains and peds contributing to the efficiency of liquefaction, it would be justified to use the 2 μm size to realistically represent the texture. Considering that <0.005 mm size may include ample silt size particles and that Adapazari silts contain up to 99% fines most of which is silt, it was decided to adopt 0.002 mm as the upper limit of clay size and the samples were evaluated accordingly (Table 4).

This is reflected in the plasticity chart of the new Turkish Standard for Soil Classification TS1500 (2000) (Fig. 4). The likely liquefaction zone here is marked with the symbol ML with liquefiable soils overwhelmingly concentrated along the horizontal axis. The liquefaction potential of NP silts, those with negligible clay content, is obvious from this figure. The authors' experience to date suggests that the probability of liquefaction in zones of intermediate and high plasticity (MI, MH) of the chart is markedly low.

Another interesting observation concerning the composition of silt is illustrated in Fig. 5. Many samples were found to contain a considerable amount of fine sand fraction in addition

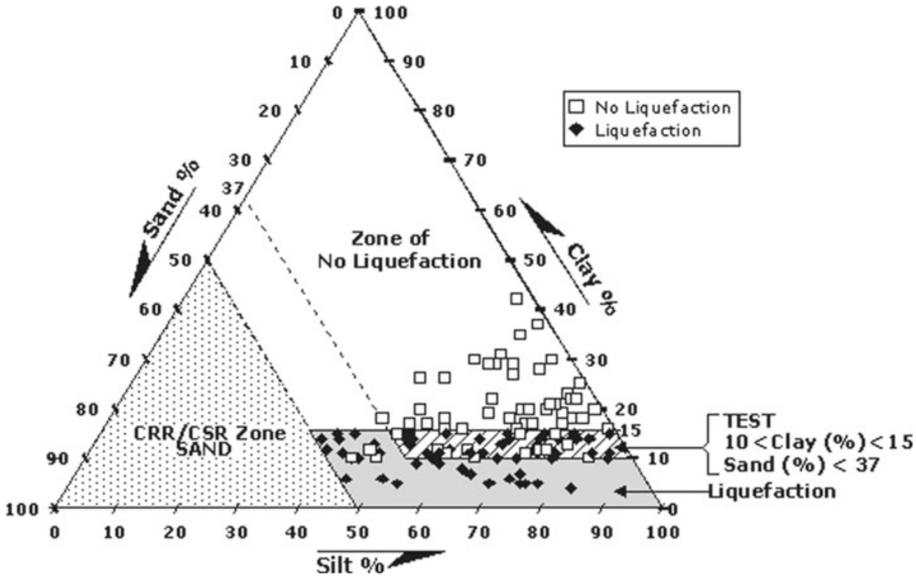

Fig. 5 Location of the studied sites on the USBR classification chart

to limited percentages of clay. The percentage of sand appears to have a pronounced effect on the ability of a silt to liquefy. A plot of the data on the USBR classification triangle suggests that silts with less than 10% clay have definite liquefaction potential and that no liquefaction is possible for silts with clay contents higher than 15%.

Furthermore, a sand content of 37% appears to envelop the majority of the non-liquefiable points on the chart. It may temporarily be concluded from here that the hatched area defined by a sand content of 37% and clay contents of 10–15% where liquefaction and non liquefaction zones appear to overlap is the gray or "test" zone, as evident from the figure. Such samples require confirmation of their susceptibility by other means, such as cyclic triaxial or simple shear testing.

The lower band where the sand content is 37% or more and consequently clay content of less than 15%, suggests other possibilities. While one can state that a mixture of 70% silt, 15% sand a clay content of 15% may prevent liquefaction, the same percentage of clay does not seem to be sufficient when the mixture contains for example, 47% silt and 38% sand, whereby the soil becomes liquefaction prone. This however, needs further evidence, as there are three no-liquefaction points in the liquefaction zone which cannot be ignored.

Jennings (1980) and Seed and Idriss (1971) emphasize the influence of the average grain size D_{50} on the efficiency of the liquefaction process. An attempt was made to represent the silts on a chart where samples with identical clay content are represented by a family of curves, as a sample with 15% clay may contain 85% silt whereas another with identical clay content might contain merely 35% silt, both being referred to by the symbol M. A normalising procedure was accordingly performed where a coefficient to be called "sand influence factor" η was defined as

$$\eta = 1 - \left[\frac{\%\,S}{100}\right]$$

S representing the sand fraction, since for a soil to classify as silt, the sand content must be less than 50%. Therefore, since sand content can only assume values between zero and 49%,

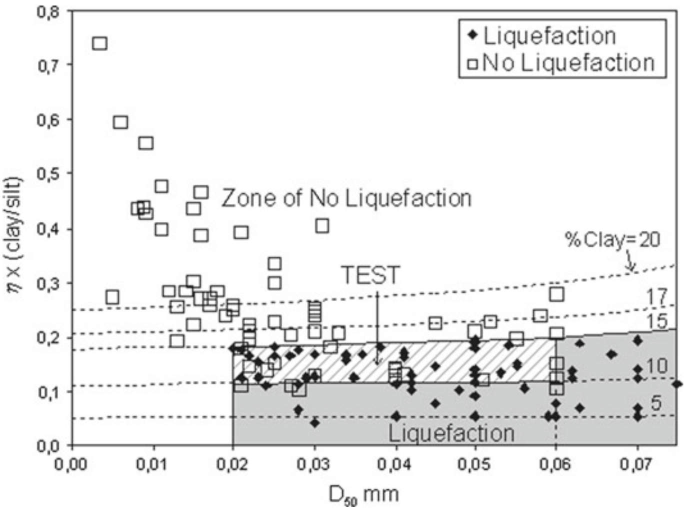

Fig. 6 $D_{50} - \eta$(Clay/Silt)-%Clay curves for Adapazari silts

the value $\eta = 1$ will imply no sand and $\eta = 0.51$ will indicate 49% sand. The decreasing percentages of sand or increasing values of η in a mixture of silt will basically diminish the ability to liquefy. Another plot was prepared showing average size D_{50} versus η(C/M) with curves of resulting clay contents for samples of a silt (Fig. 6). The clay/silt ratio multiplied with η in the ordinate reflects the relative weight of the clay in the fines content. It is once more observed from this graph that 15% clay size is the upper limit for liquefaction potential for silts, clay size being defined as 0.002 mm.

Another significant finding is that no silt with an average size $D_{50} < 0.02$ mm and $\geq 15\%$ clay content is likely to liquefy. The uncertain or "test" zone appeared in the interval 0.02 mm $< D_{50} <$ 0.06 mm bounded by 10% and 15% clay contents.

It is an interesting coincidence that the critical size for the Casagrande frost heave criterion (1931) had been determined to be as 0.02 mm and silts that possess 15% or more of the critical size were judged to be frost susceptible, demonstrating the influence of grain size in the establishment of an efficient process of water transport to the freezing front.

It can also be seen from Fig. 6 that the points representing non liquefying soils are bounded by the $D_{50} \geq 0.06$ mm line, suggesting once again that increasing particle size increases the probability of liquefaction. Stated in other terms, this study has shown that the sand content in a silt is a critical element in the mechanism of liquefaction.

The minerals of the clay fraction in Adapazari silts were determined to be montmorillonite and partly illite. The percentage of clay stipulated in the Adapazari Criteria may be questioned as to whether the same percentages would be valid for other types of clay minerals. This issue is being investigated.

7 The Adapazari criteria

Detailed field and laboratory testing of soils from the Adapazari basin have indicated that a silt is most likely to liquefy during earthquakes of $M_w \geq 7$ if all the requirements listed below are fulfilled:

(a) The liquid limit is 33 or less;
(b) The liquidity index I_L is higher than 0.9, the same ratio being valid for NP silts with the definition (w_n/w_L);
(c) The clay content is less than 10% (D < 0.002 mm);
(d) The average size D_{50} is greater than 0.02 mm.

"Test" intervals where no clear judgement as to whether a silt layer will liquefy are defined as those soils with $25 < w_L < 33$ and clay contents of 10–15%, where the average size is between 0.02 and 0.06 mm. This percentage has been confirmed through subsequent research by varying clay contents and testing the mixtures of silt/clay in the cyclic triaxial test (Ural 2008; Bol et al. 2008).

8 Conclusion and suggestions for further research

The 1999 earthquake that inflicted heavy damage in Adapazari has prompted detailed investigations on the properties of silts which are found to be widespread throughout the city. Ample soil profiles found in various sites where liquefaction was obvious and an equal number where no ground failure had been recorded, were chosen for study. These selected sites were investigated by boreholes accompanied by cone penetration testing (CPTU) and a set of "Adapazari Criteria" is hereby proposed:

A liquefiable silt must satisfy the conditions of liquid limit ≤ 33, liquidity index >0.9 and clay content of less than 10%, where clay size is defined as <0.002 mm. Non-plastic silts possess definite liquefaction potential. Consequently, all silts with less than 10% clay and average size $D_{50} \geq 0.06$ mm are liquefiable.

The city may experience another earthquake within the next decade if the statistics are correct. It would be interesting to observe soil behaviour by strategically placing accelerometers and piezometers at sites of possible liquefaction to assess the performance of silty layers during the strong motion.

Cyclic triaxial and simple shear testing of the diagnosed soils is of vital importance especially in defining the borderline silty soils and detailed investigations are currently being performed.

Another source of uncertainty is the influence of the clay mineral in the mixture. It is recommended that silts should be mixed with clays of different mineralogy at changing percentages and their behaviour in dynamic testing be compared to the criteria based on physical properties.

Accompanying field testing indicates that the piezocone test appears to be a rapid and reliable means of determining liquefaction potential of soil profiles and should be given priority in related research.

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