LIQUEFIABILITY OF SILTS AND THE VULNERABILITY MAP OF ADAPAZARI

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ABSTRACT :

The city of Adapazarı, Turkey is notorious for the $M_w \geq 7$ earthquakes that strikes almost each decade. The event of 1999 was probably the worst in memory, because a major portion of the city was destroyed. The ground failures in the form of cyclic mobility, liquefaction and excessive settlements of buildings were widespread. A major investigation program was initiated at Sakarya University to diagnose the liquefaction potential of silts and clays intended to lead the investigators towards preparation of liquefaction and bearing capacity maps for the city. The program included drilling of 700 boreholes with standard penetration and laboratory testing, 300 cone penetration tests (CPTU, SCPTU) . A set of “Adapazarı Criteria” were proposed as a substitute for the Chinese Criteria. The criteria were compared to and aided by the surface observations made right after the quake. A database for the city of Adapazarı based on surface observations as well as field and laboratory test results using GIS methods is finally established. It is now possible to query the groundwater level, soil type, organic content, SPN N_{60}, undrained shear strength, allowable bearing capacity and liquefaction potential for the top 15m depth. The results indicate that the soil conditions in the City are quite different from what has been published to date. This discrepancy is due to the fact that the vertical and horizontal variability of the soils is extremely high because of the formation processes involved.

KEYWORDS: Liquefaction, Silt, Fine grained soil, GIS, Mapping, Adapazarı criteria

1. INTRODUCTION

The city of Adapazarı 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 become active ($M_w \geq 7$) almost every decade(Figure 1). It nevertheless continues to expand, its current population estimated at 300,000. In addition, 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 200m (Bol, 2003) and it was claimed that the depth of the alluvium here may be as deep as 1000m (Komazava et al.,2001).

Numerous geotechnical 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 proved that this was a hasty diagnosis. It is now confirmed that liquefaction had materialized in about 30% of the total area of 25.6 km^2. It was subsequently discovered that non-plastic silts with sand layers were dominant at sites of liquefaction, from which the Adapazarı Criteria (Bol, et al., 2005) were derived and a liquefaction map was drafted.

2. ADAPAZARI GEOTECHNICAL DATABASE

About 700 boreholes were drilled and 300 cone penetration tests (CPTU) were performed by Sakarya University during the investigation. Of these, 133 pairs were drilled side by side to enable correlations.

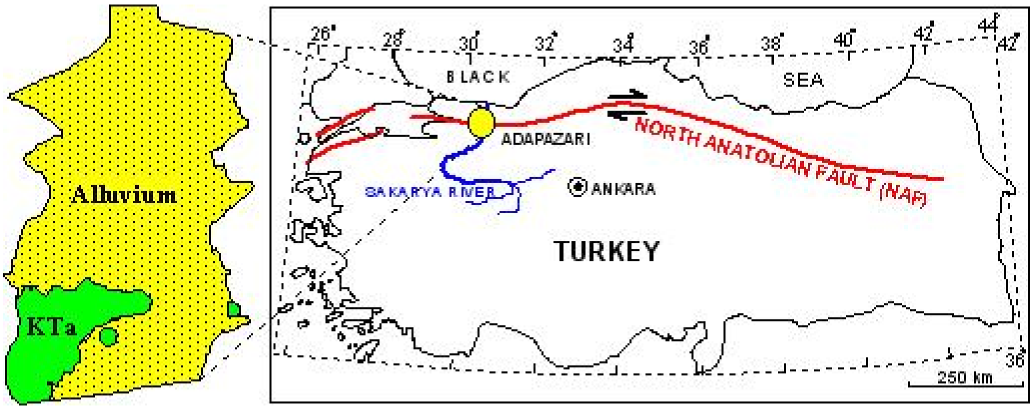

Figure 1 Geological formations and location of Adapazarı (KTa: Upper Cretaceous Rocks)

A total of 5729 SPT and 6000 standard laboratory tests were run. 62000 lines of output from the CPTU were added to the data. Occasional down hole seismic measurements (SCPTU) providing the shear wave velocities were also included. All available information including those of other credible investigators were ultimately collected in the "Adapazarı Geotechnical Database" which will be available to all researchers in the future. Geographical Information System was employed to derive thematic maps comprising soil classes, SPTN, qc, damage, bearing capacity and liquefaction.

3. GEOMORPHOLOGICAL PROCESSESS

The liquefiable silts intercalated by seams of fine sand have been deposited by the River Sakarya (Figure 1) during the past 7000 years. The extensive borehole information procured has indicated that the river has crossed the plain of Sakarya by meandering and traversing. Figure 2 illustrates a block diagram of the soil profile . It is observed that outcrops of the bedrock consisting of Upper Cretaceous claystone, siltstone, marl and limestones are intersected by an inactive fault defining the border of the deep alluvial deposits (Bol, 2003). The highly plastic clays (CH, CI) surrounding the hills are probably weathering products of the rocky slopes, intermixed with lacustrine deposits.

Figure 2 depicts two ancient(buried) river beds, one 4m and the other approximately 10m below the present ground surface that contain gravels rarely encountered elsewhere. These are characterised by notably high penetration resistances (N_{60}>50; q_c>10MPa) which are not recoreded anywhere else. It is possible that both channels coexisted whereby an island between them was formed that gives the City its name: Adapazarı-Island Market, where markets for different trades and crafts existed for several centuries. The main feature of these ancient rivers is that they flooded the plain of Adapazarı almost every year as the present River Sakarya did until 1965 when sedimentation was halted by the construction of two large dams upstream. The frequent rapid flooding by the ancient and the present streams often tore their banks at convex sections of the meanders (crevasse splays) and deposited the sediments as overbank deposits. There are certain sections of the city where this mechanism is more pronounced, indicated by appreciable amounts of fine sediments. It is believed that those special locations are presently sites of liquefaction. Consequently, there are districts of the city located on the bedrock that had not suffered serious damage, regardless of the quality of the superstructure and ground failures were not observed. On the contrary, there were damages of the structures founded on Holocene alluvial deposits (Bol, 2003; Bol, et al. 2007).

Studying the earthquake performance, it is clear that findings from these soils will solve some hitherto unexplained topics of geotechnical engineering like the effect of changing soil properties on deep alluvial basins, variation of bearing capacity which depend on sedimentation conditions and liquefaction of silty soils.

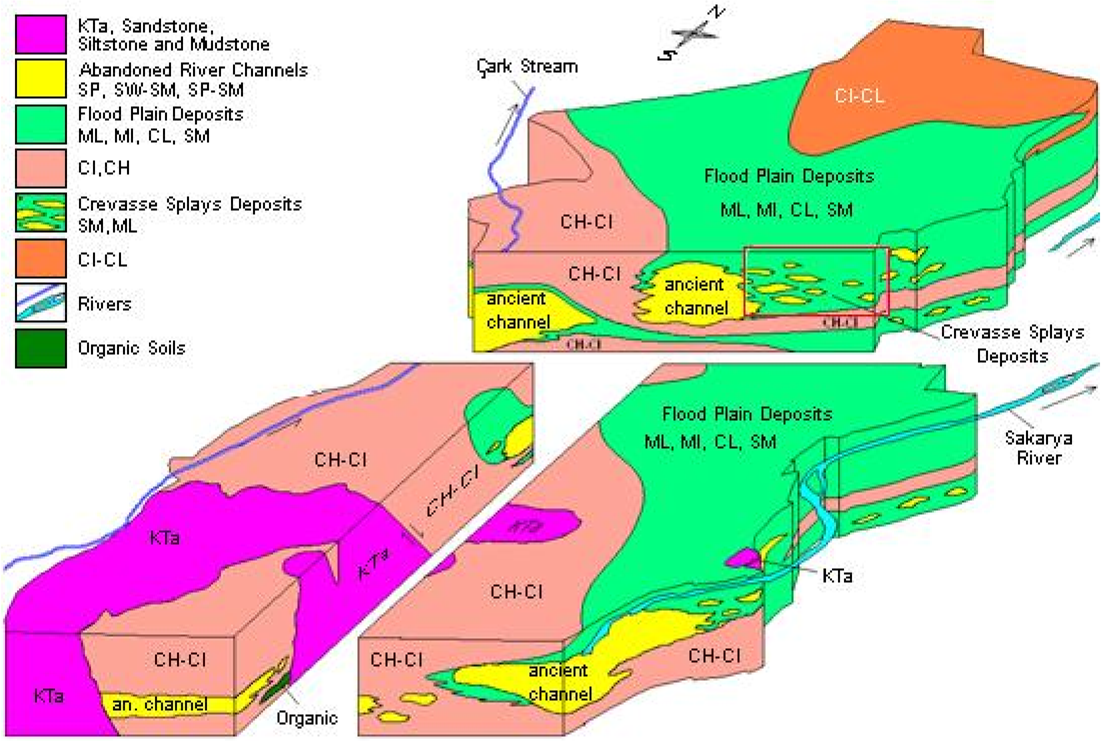

Figure 2 3D facies of the City

3.1. The Origin of Adapazarı Silt

Although it has widely been suggested that Adapazarı is a "city of silt", it has been discovered that frequently appearing low plasticity silts are in fact of limited thickness. Figure 3 depicts the locations of non plastic silts found in the alluvial sediments of the city. The top 10 m thickness, where most of the liquefaction occurred was divided into six zones. The map shows that no zones were found to consist of ML in all of six layers. Furthermore, zones with 5 or 4 layers of silt are also extremely rare. An appreciable number of sites with 3 or 2 silt layers were detected. Most significantly, an overwhelming part of the city contained soil profiles with a single or no layer of ML silt.

There is a wealth of publications on the liquefaction of Adapazarı silt (Sancio et al., 2002; Sancio, 2003; Bray et al., 2004; Bol, 2003; Bol et al., 2005 and 2007). Indeed, the observations and subsequent investigations by Sakarya University has shown that the section bounded by the broken line in Figure 3 was the obvious liquefaction zone. It is noteworthy that no dense sands were found in the soil profiles in this section but frequent lenses and layers of silt were encountered, a possible product of crevasse splays from the convex part of the meandering river. The envisaged direction of crevasse splays is shown by a thick arrow in the figure.

4. LIQUEFACTION OF FINE GRAINED SOILS

Because of high SPTN 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).

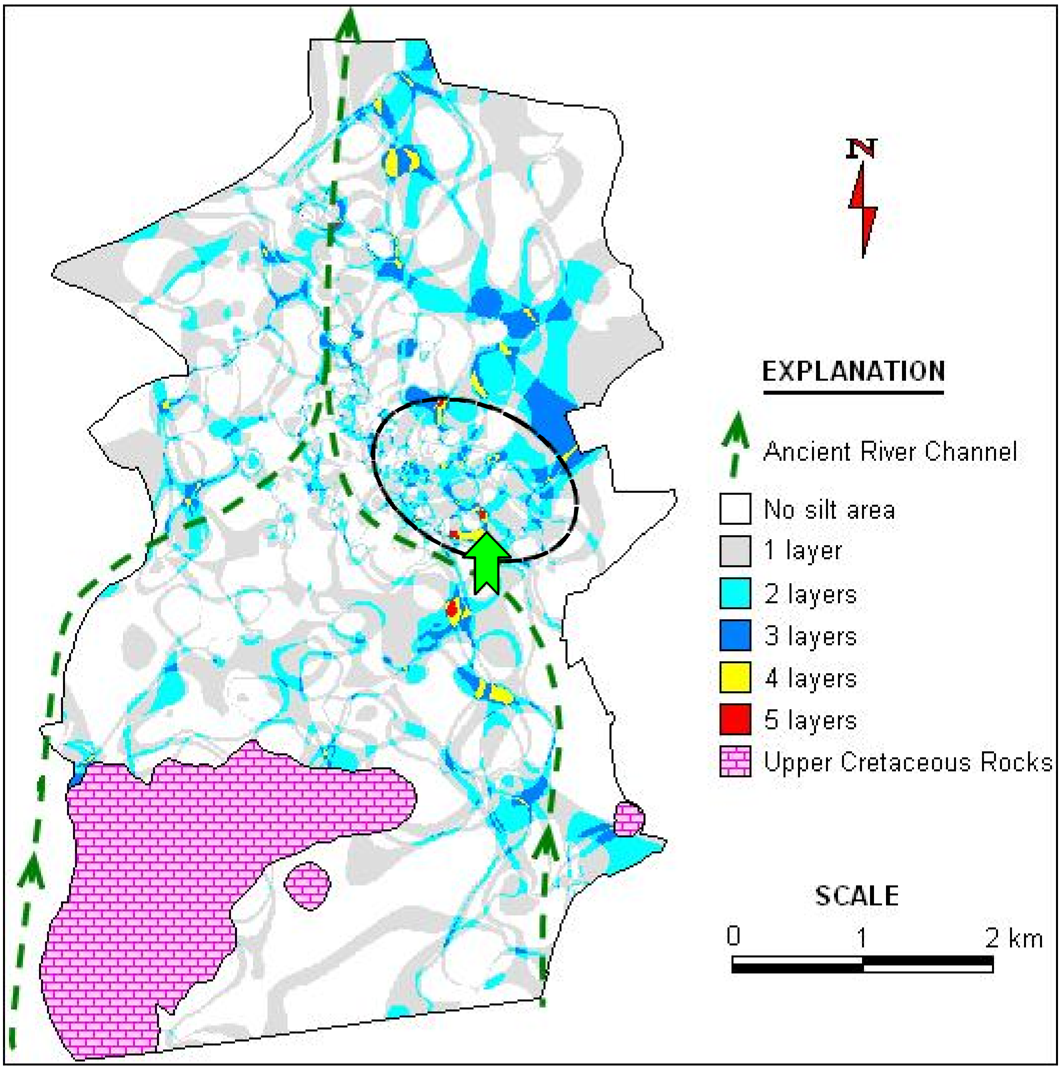

Figure 3 The distribution of silty layers in Adapazarı (total 6)

Figure 4 illustrates the “Modified Chinese Criteria” (Wang (1979), and Seed and 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 above 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.

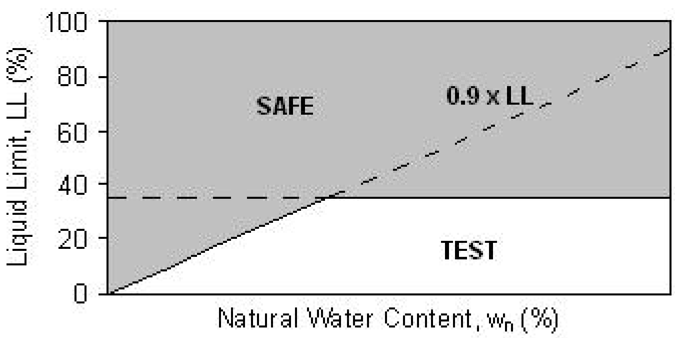

Figure 4 Modified Chinese Criteria (After Wang (1979) and Seed and Idriss (1982))

Tokimatsu and Yoshimi (1983) were of the opinion that soils with clay size particles greater than 20% are not susceptible to liquefaction. According to Ishihara et al. (1981) who studied mine tailings composed of silty sands and sandy silts, cyclic strength is independent of void ratio and grain size and increases with increasing plasticity index. Ishihara and Koseki (1989) and Yasuda et al., (1994) claim that as percentage of fines, clay percentage and plasticity index increase, cyclic strength increases slightly (as reported by Polito, 1999). Polito (1999) implied to obtain meaningful results that plasticity investigations should not be done only for fine particles of a soil sample, but whole sample should be tested evaluate liquefaction potential. Andrews and Martin (2000) reevaluated the liquefaction field case histories from the database of Wang (1979), as well as a number of subsequent earthquakes, and have transposed the "Modified Chinese Criteria" to U.S. conventions (with clay sizes defined as those less than about 0.002 mm). Andrews and Martin recommended: (1) that soils with less than about 10% clay fines (< 0.002 mm), and a liquid limit (w_L) in the minus #40 sieve fraction of less than 32%, be considered potentially liquefiable, (2) that soils with more than about 10% clay fines and w_L>32% are unlikely to be susceptible to classic cyclically-induced initial liquefaction, and (3) that soils intermediate between these criteria should be sampled and tested in laboratory to assess whether or not they are potentially liquefiable.

The so-called Chinese criteria worked much better and it is proposed that the liquefaction potential of Adapazarı nonsensitive/nonplastic silts can be identified by having satisfied all of the the following criteria (Önalp and Arel, 2002). A silt is identified as liquefiable if it classifies as ML and the liquid limit is less than 30, clay content (<2μm) 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).

a) Liquid limit < 33%
b) Liquidity index $I_{L\geq}$ 0.9
c) Clay content less than 10%
d) Average particle size D_{50} smaller than 0.06mm

In addition, a description of the "gray" zones where advanced testing would be required is given in Table-1 (Önalp et.al.,2008)

Table 1 Evaluation of Adapazarı Liquefaction Criteria

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

4.1 Liquefaction Map of Adapazarı

In preparing the liquefaction map of Adapazarı by the use of GIS, all soils were initially evaluated using the cyclic stress ratio method CRR/CSR (Seed and Idriss, 1971 and 1981). However, since fine grained soils were also encountered, the map was revised by excluding the sites where sands were not predominant. This provided the map for coarse grained deposits. The Adapazarı Criteria were then applied to points where silts were present 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 investigator 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 2 Liquefaction evaluation for fine grained soils

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

The database was then queried for class of soil, liquid limit, average grain size and liquidity index (or w_n/w_L) for each of the six 1.5m thick layers. This resulted in six maps for each layer, providing 36 maps. Each map was then evaluated for the parameter it represented. This resulted in maps with regions representing 0, 0.5 and 1. The maps were ultimately superposed to obtain the sums using Table 2 for evaluation. Figure 5 presents the maps obtained. Black regions indicate liquefiable coarse grained soils found using the CRR/CSR. It should be remembered that another evaluation would be necessary here, to take the influence of the overburden on liquefaction(Ishihara, 1985).

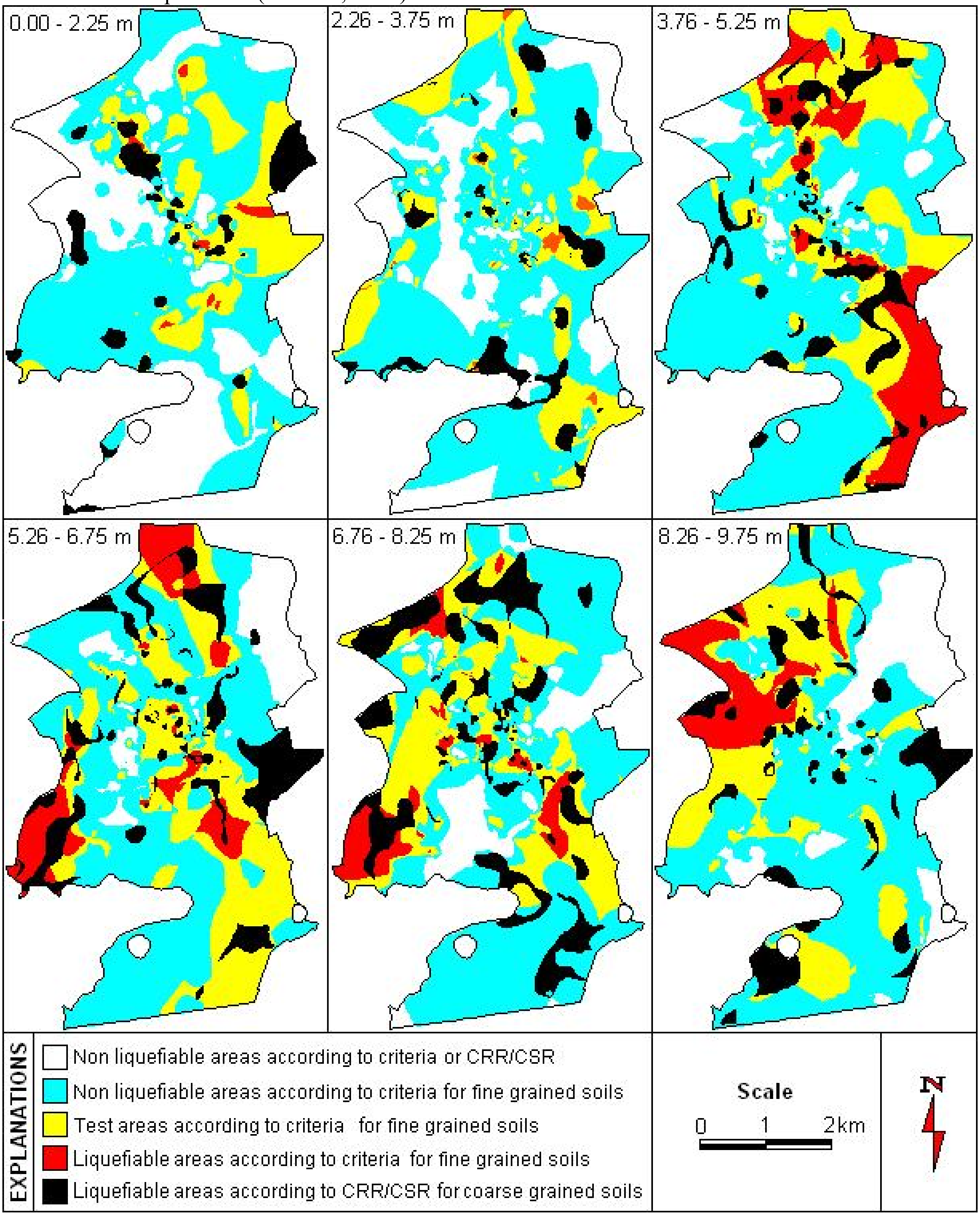

Figure 5 Liquefaction Vulnerability Maps of Adapazarı

Red areas represent soils which satisfy the Adapazarı criteria, blues the non-liquefiable, whereas yellow shades indicate regions where liquefaction is possible but may not be probable, thus requiring further testing. White shades indicate areas of coarse grained soils where the factor of safety against liquefaction is above unity and areas of fine grained soils where adopted total criteria value equals zero.

5. CONCLUSIONS

A detailed investigation following the 1999 Marmara earthquake concerning the liquefaction of fine grained soils of Adapazarı through in situ liquefaction observations, borings, soundings and laboratory testing has enabled the researchers to establish the Adapazarı Geotechnical Database.

The Adapazarı Criteria, similar to the Chinese Criteria, have been developed as a result of this research. The Adapazarı Criteria stipulate that a soil must classify as ML, have a liquid limit ≤ 33, contain less than 10% 2 μm size clay, have an average particle size D_{50} of ≥ 0.06mm, and an in situ (natural) water content higher than 90% of the liquid limit ($w_n/w_L>0.9$) in order to liquefy during earthquakes of $M_w>7$.

Silt content-depth-liquefaction maps extracted from the database were prepared for the top 10 m where liquefaction is most likely to occur. The seismic behaviour of fine and coarse grained deposits were evaluated. The CRR/CSR approach was used to for the sands, whereas Adapazarı criteria and observations on record were used for fine grained soils. Altough a picture indicating significant areas of liquefaction emerged, it would be necessary to consider the influence of the overburden on the ability to liquefy before passing a judgement on vulnerability.

Research is ongoing to include this feature to finalise the Adapazarı liquefaction map.

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