

1. Description of the Site

Study is based on the EU H2020 LIQUEFACT project entitled “Liquefact: Assessment and mitigation of liquefaction potential across Europe: a holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters. Figure 1 shows the Marmara region, past earthquakes, study area and the active faults in the region. Figure 2 presents the boundaries of the Canakkale city test site. The structures are generally 4-6 storey reinforced concrete buildings. In the recent years, some high rise buildings, especially hotels and trade centers are being constructed in the area.

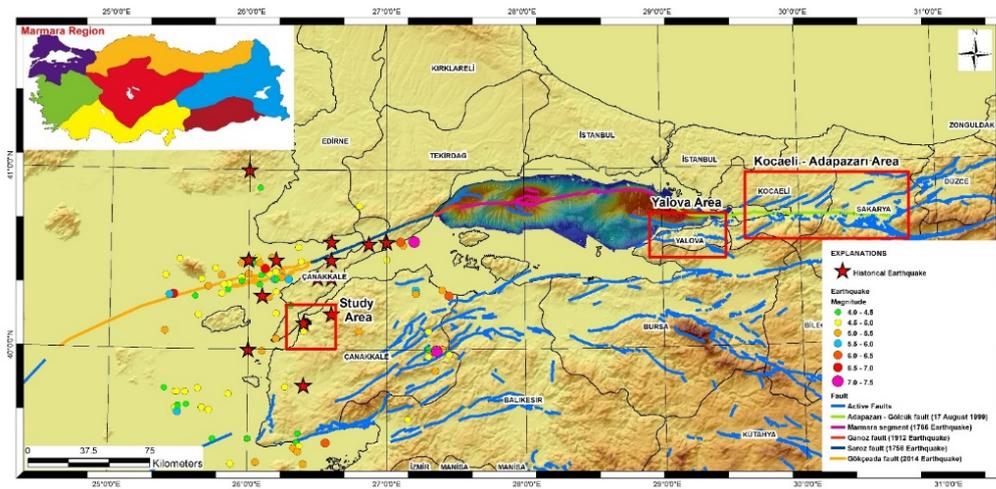


Figure 1 Marmara Region, past earthquakes, study area and the active faults in the region.



Figure 2 Boundaries of Canakkale city test site.

2. Seismic Hazard Analysis of Çanakkale

City of Troia is situated within a tectonically active region occurring these two seismically most active zones of region. City is surrounded by a number of active faults it is only about 50 km away from these

major fault systems (Figure 3). These major fault zone have produced many earthquakes greater than magnitude 6.0 in past. Periodicity of these big earthquake may be estimated to be 110 year. Earthquake with a magnitude between 5 and 6 appear to have occurred in 20-30 year interval. Any earthquake greater than 5 in and around this zone is assumed to have caused severe damage in Troia area (Yilmaz, 2003).

In order to determine the expected accelerations, a probabilistic seismic hazard analysis was carried out for the test site in this study. The coefficients of a Poisson distribution were calculated, and return periods for several magnitudes were found. From these coefficients, peak ground acceleration and earthquake hazard for a set of return periods and epicentral distances were estimated, and substantial variations in the probability of occurrence were noted. The range of earthquakes for analysis was taken to be from magnitude 4.5 to 7.5 within approximately a 100-km radius. Also micro-seismicity of the region from magnitude 3.5 to 4.5 was determined. Figure 4 shows ground motion map for 50 years and exceedance rates of 2 with return periods of 2475 years for the project site. Based on the seismic hazard analyses performed for the region, the ground accelerations for exceedance rates (2%, 5% and 10% with return periods of 2475, 975 and 475 years) for project site were estimated as 0.17g, 0.39g, 0.51g and 0.78g.

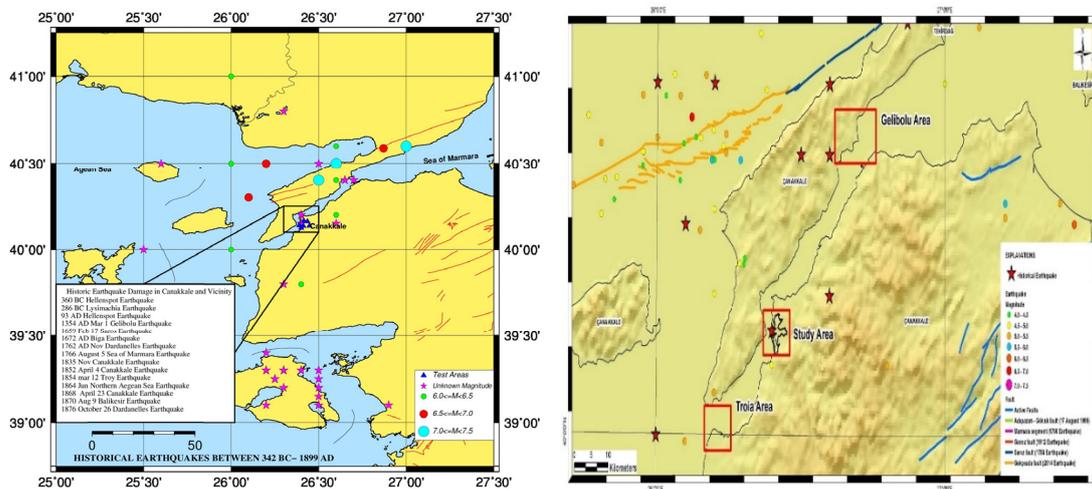


Figure 3 Historical earthquakes in Çanakkale and surrounding region,

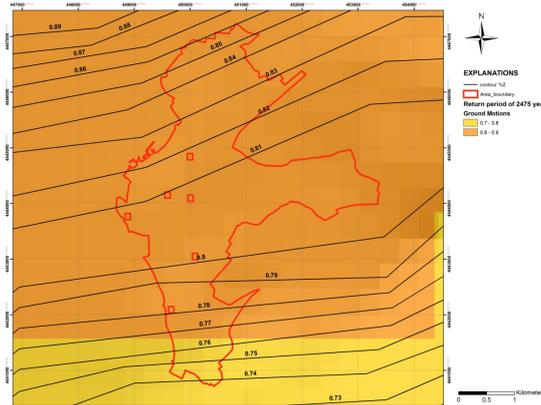


Figure 4 Ground motion map for 50 years and exceedance rates of 2% with return periods of 2475 years in Project Site.

3. Objectives and Ground Characterization

Objectives and extent of ground characterization for Canakkale test site are listed in this section. The data from pre-existing soil investigation studies was gathered in the first stage. Pre-existing data showed that there are lithological units of Quaternary (Holocene) soil deposits. Within the context of

complementary field studies, these unit were given more emphasis. There were several SPT tests carried out in the study area. These data were studied and evaluations were made. Within the context of the complementary tests, six (6) study areas in the test site were chosen and complementary tests were carried out in these areas. In these areas, additional boreholes were opened and SPT tests were performed. There was no evidence of energy applied during SPT tests in pre-existing studies, therefore it was decided by the team that energy measurements were needed during SPT testing in the complementary field work. There was not any CPT or any other field test data in the area. It was decided that additional CPT (CPTU and SCPT) and Marchetti Dilatometer (DMT) tests should be carried out within the scope of the complementary testing. Seismic refraction, MASW and micro tremor measurements had been carried out in pre-existing studies. Shear wave velocities obtained from MASW measurements were evaluated to the most rigorous level. Within the context of the complementary field studies, additional non-invasive geophysical investigations were carried out. These tests were downhole seismic, PS-logging, seismic refraction, 2D-ReMi, MASW, micro tremor (H/V Nakamura method), 2D resistivity and resonance acoustic profiling (RAP). RAP is a new technique which will be explained briefly in the relevant section. Dynamic soil properties had not been measured in pre-existing studies, therefore these properties were investigated within the scope of the complementary tests. Selection of specific experimental tests of the complementary campaign was based on cost-benefit considerations. It should be emphasized that in today's Turkish practice, it has not become a routine practice to perform laboratory experiments for dynamic soil properties. Within the context of complementary field studies, dynamic soil properties were measured using resonant column and cyclic direct shear tests. As defined in the Guideline, ground characterization through laboratory testing focused on coarse-grained soils including clean sands, silty-sands and non-plastic sandy-silts deposits in view of the susceptibility of these geomaterials to liquefaction. Several sieve analyses and Atterberg Limits tests which were documented in the pre-existing studies were evaluated. In the complementary study carried out, additional sieve analyses and Atterberg Limit tests were carried out. It was aimed to make some correlations between geophysical measurements and other field measurements; such as SPT, blow count values. These correlations were attempted with the new data in the complementary studies and some correlations were recommended.

4. Complementary Investigation Campaign

4.1. Study Areas in the Test Region

In relation with the recommendations of the relevant guideline, in the test site, six (6) different areas shown in Figure 5 were selected. These areas were chosen so that the recommendations and the requirements listed above can be accomplished through complementary testing. The main frame of the complementary test study is given below in Table 1 and Table 2.

Table 1 Field tests carried out in the areas.

Area	Tests
1, 2, 3	SPT (with energy measurements), DMT, SCPT, downhole seismic, PS-logging, seismic refraction, 2D-ReMi, MASW, microtremor, H/V Nakamura prospecting, 2D resistivity, resonance acoustic profiling (RAP)
4, 6	SPT, CPTu, MASW, resonance acoustic profiling (RAP)
5	SPT, SCPT, MASW, resonance acoustic profiling (RAP)
City center	2D resistivity (for deep investigation of bedrock and aquifer characteristics)

Table 2 Laboratory tests.

Area	Tests
All	Sieve analysis, hydrometer, consistency limits, resonant column test (RCT), torsional shear test (TST), dynamic simple shear (DSS) tests

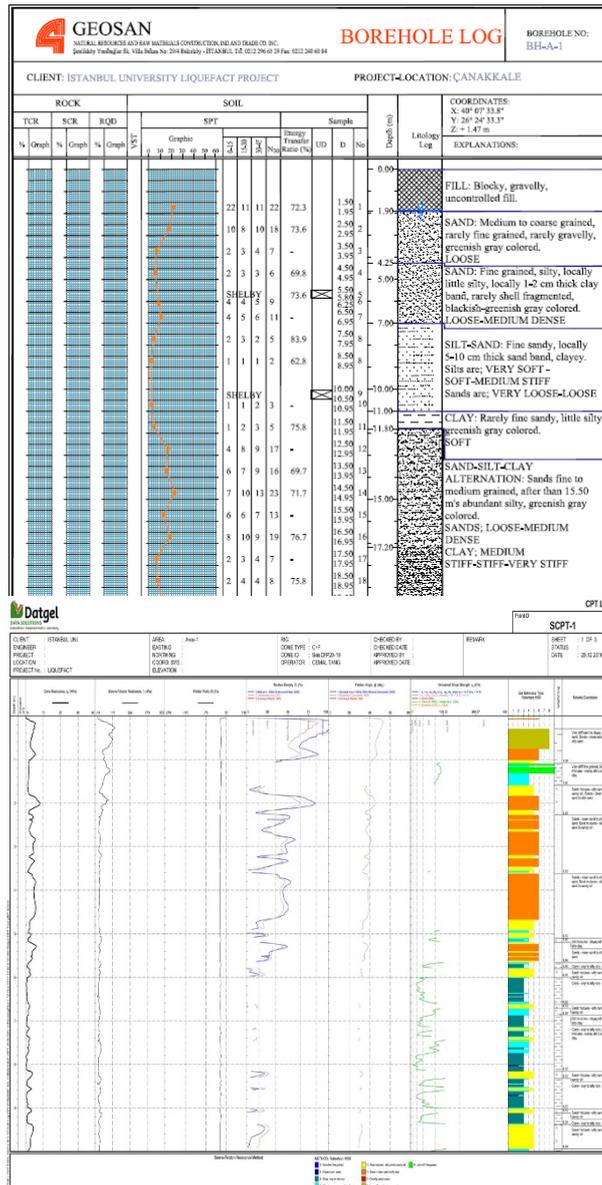


Figure 6 Borehole in Area 1, BH-A-1 SCPT-1 results for Area-1.

4.3. LABORATORY TESTING

Sieve analysis, hydrometer, consistency limits, resonant column test (RCT), torsional shear test (TST), and cyclic direct simple shear (DSS) tests were carried out within the context of complementary testing. Classification testing is important and therefore several tests were carried out within this context. In this regard, laboratory testing was carried out for determining grain size distribution (particularly the fine content), plasticity index and moisture content of potentially liquefiable layers. Stress-strain laboratory tests were carried out to measure the low-strain and large-strain dynamic properties of soils. During the planning of laboratory experiments, it was aimed to determine the dynamic soil properties of the soils encountered in the first 20 meters. It was not possible to get undisturbed samples from sandy soils in our study. However, in case careful reconstitution is applied in the laboratory, laboratory tests performed on *reconstituted* specimen may represent an acceptable alternative in coarse-grained materials. Based on the above argument, samples were reconstituted carefully and using innovative approaches.

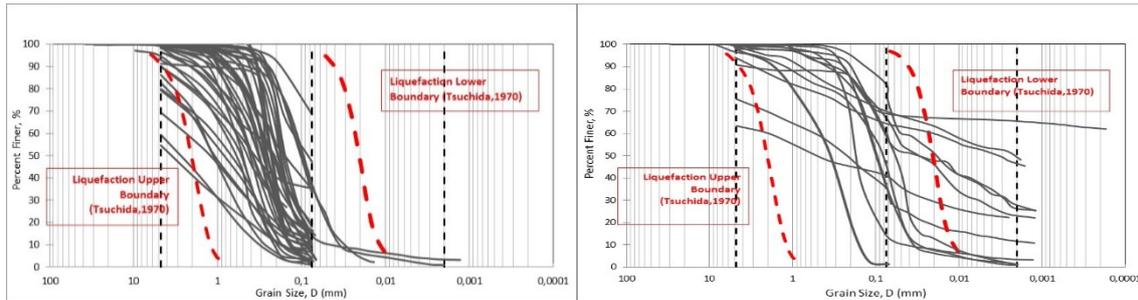


Figure 7 Sieve analyses.

Sieve analyses are presented in Figure 7. Tests revealed that majority of the samples contained less than 25% fine content. This means that the behaviour is governed by the coarse particles in the matrix. Liquid Limits were measured to be between 20%-56% and some samples did not show plastic behaviour. Majority of the soils are sandy soils, with varying amounts of silts.

Experiments related to dynamic soil properties were carried out within the complementary soil investigation study. There are different soil tests that can be performed to determine the dynamic soil behaviour. The main difference between these methods is the strain levels associated during testing. Based on the strain level for which the measurements are made, there should be differences in measured dynamic properties. In this study, different dynamic tests were performed so that dynamic behaviour under a large spectrum of strain levels can be measured. In this context, resonant column, torsional shear and cyclic direct shear tests were performed on several samples. The details of the tests and their results are given the following sections.

- **Resonant column tests**

In this study, the resonant column tests were carried out by Istanbul University Team in Eskisehir, Osmangazi University Soil Mechanics Laboratory. Example photos are given in Figure 8. For sample preparation of dynamic tests, specimens with different void ratios were prepared and resonant column tests were carried out on trial samples. It was aimed to determine the relative density values for which shear wave velocities measured in the field could be achieved in the laboratory. After several trials, it was determined that at relative densities of 35% and 65%, shear wave velocities measured in the field could be measured in the laboratory. Relative densities obtained from field tests were also found to vary in this range. Tests were carried out on twelve (12) clean sand and silty sand samples. The relative densities were adjusted between 35% and 65% under 100 kPa and 200 kPa confining pressures. Clean sands do not contain any fines, since the soil was washed to be cleaned out of fines and silty sands contained 15% fines.

Figure 9 exemplifies the results for the shear modulus degradation and damping ratio of fine sand. The results showed that G_{max} values range between 52 MPa to 116 MPa for fine sand (silty sand) samples and between 61 MPa and 107 MPa for clean sand samples. The values changed with applied confining pressure and relative densities. G_{max} values are consistent with the values measured with geophysical tests. This shows that if care is given so that reconstituted samples are representative of field conditions, the dynamic properties can be correctly measured in the laboratory.

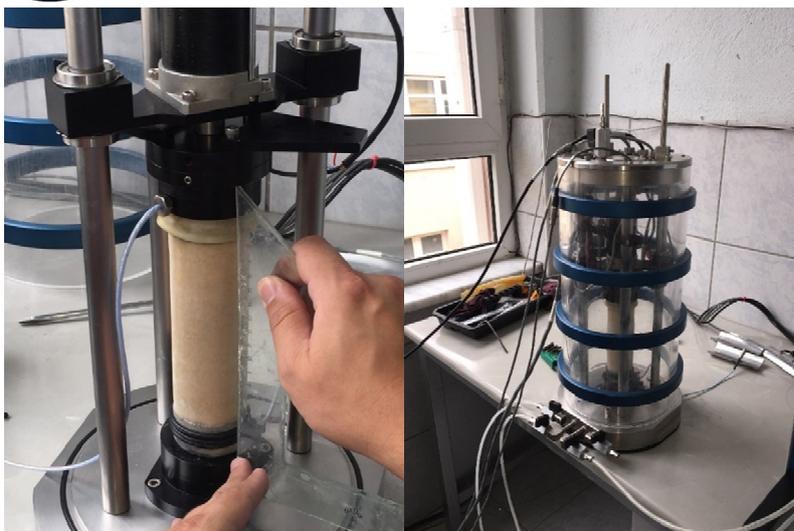


Figure 8 Resonant column test photos.

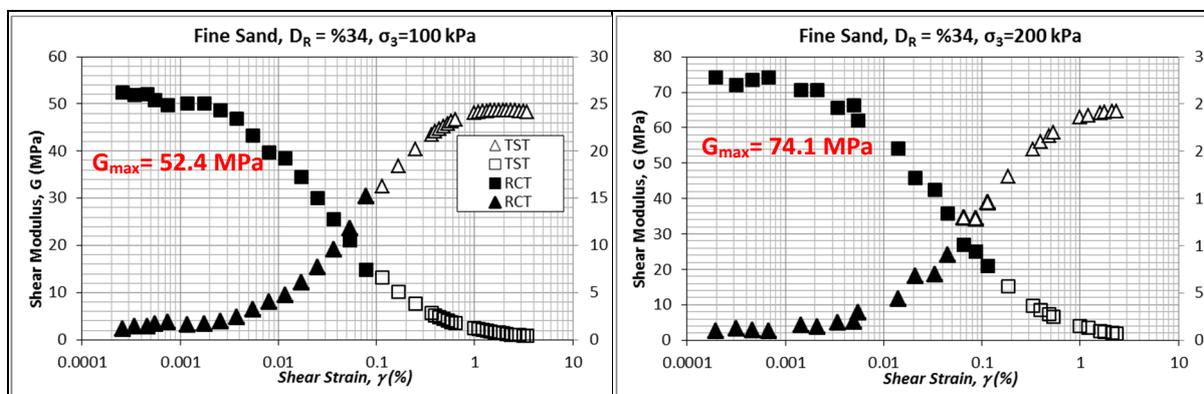


Figure 9 Shear modulus degradation and damping ratio of fine sand (silty sand).

- **Cyclic direct simple shear (DSS) test**

Within the scope of the complementary study, cyclic direct simple shear tests were carried out on two different soil types; clean sands and silty sands samples. In this study, it was decided by Istanbul University team that some samples be tested as saturated and some as dry based on the recent studies carried out in recent years. One of the papers published in this context is by Monkul et al. (2015). Soils obtained from in the complementary 6 boreholes were used in DSS testing. Two different type of soils were tested. These soils can be grouped as “Clean sands” which do not contain any fines, since the soil was washed to be cleaned out of fines and “Silty sands” which contained 15% fines. 14 DSS tests on silty sand samples were carried out as saturated, while 16 DSS tests on sand samples were carried out as dry in this complementary laboratory study. 6 clean sand samples were also tested as saturated so that comparisons between dry and saturated testing can be made. The details of the tests are presented in the original report. An example output is given in Figure 10. The results of DSS tests revealed that; under tested CSR values, both soils were highly liquefiable.

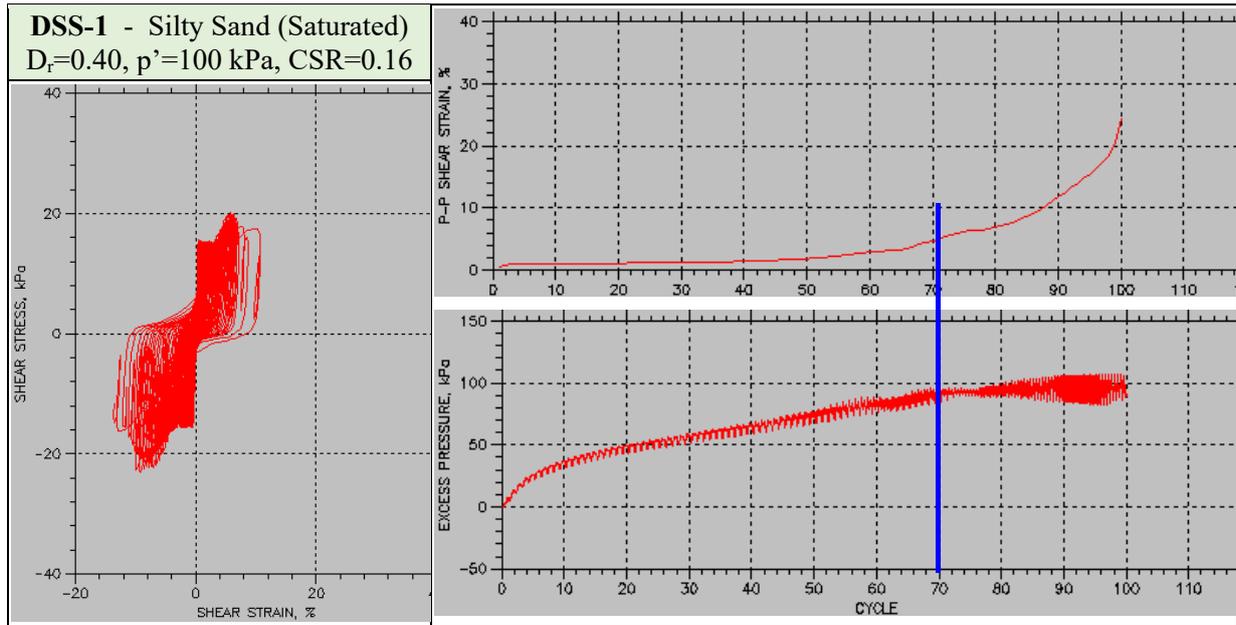


Figure 10 Summary of test results of DSS-1 sample.

4.4. Hydrogeophysical Tests

Data obtained from hydrogeophysical tests revealed the following findings. Based on the tests, thickness of first layer is 0.6 m and is the topsoil. It has a resistivity of 25.1 ohm-m. Thickness of second layer is a man-made fill and is 4.95 m and has a resistivity of 84.3 ohm-m. Under the man made fill, lies the third layer. This is clayey soil and 18.8 m thick and has a resistivity of 15.1 ohm-m. Under the clayey soil, there is a saturated aquifer with 6.02 ohm-m resistivity and 26.8 m thickness. Below this layer there is impermeable zone that has 188 ohm-m resistivity and 56.1 m thickness. When we look at the chargeability values (obtained by IP measurements) of this last layer (Figure 11), we see that there are some conductive zones in this layer.

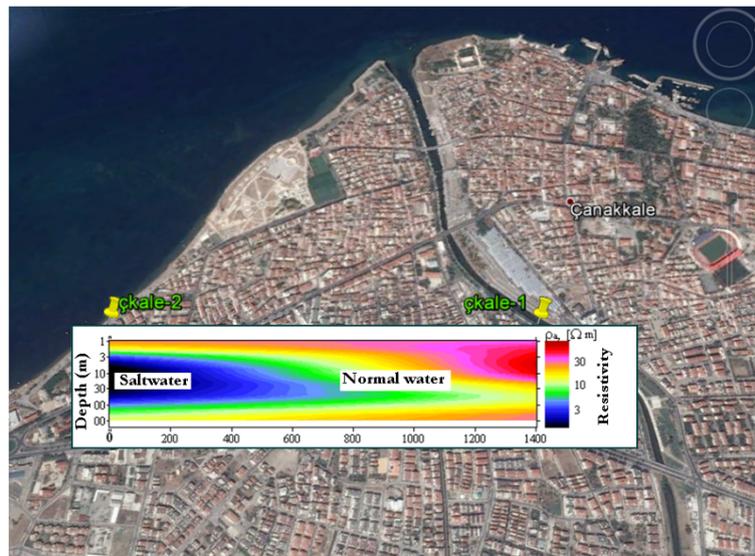


Figure 11 Cross-section between Çkale-1 and Çkale-2 measurement sites.

5. Conclusions

Within the context of the complementary tests, six (6) study areas in the test site were chosen and complementary tests were carried out in these areas. SPT, CPTU, SCPT, DMT and several geophysical tests were performed with great care. Dynamic soil properties had not been measured in pre-existing



studies, therefore these properties were investigated within the scope of the complementary tests. Dynamic soil properties were measured using resonant column and cyclic direct shear tests. The tests revealed that Canakkale test site consists of a subsoil profile, majority of which is dominated by silty sands and sands. There are also layers and spots of clean sands. At about 20 m depths, plastic silts and clays are encountered in most of the boreholes. A gravel layer lies beneath this layer. Results of field tests showed that tests for all the areas, the shear wave velocities were low. In the first 10-15 meters, for all sections, the shear wave velocities were lower than 200 m/s. For gravel layers at about 20 m depth, there were increases in shear wave velocities, however in all cases, shear wave velocity values were lower than about 350 m/s. In terms of liquefaction consideration, all the sites were susceptible to liquefaction based on shear wave velocities. In the first 30 m, the corrected SPT values ($N_{1,60}$) are very low ranging from 2 and 27. Soil types are sands, gravels, silts, silty sands, clays, silty clays, fills and sand-silt-clay mixtures. Fine contents values range from 2% to 54 % in average. Most of the time, low fine contents are dominating in the area. Soil classes can be listed as SP-SM, SP, SM, ML, SW, SW-SM, SC. It should be recalled that these soil classes are highly liquefiable. The dynamic laboratory tests also showed that the liquefaction susceptibility of the clean sands and silty sands were high. Based on all these solid and reliable information taken from the six study areas in Canakkale test site, it is clear that the study areas are highly susceptible to liquefaction.

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