Geotechnical and Geo-environmental characterization of the Lara-Kundu coastal zone (SW Turkey)

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Received 01 August 2014; revised 30 October 2016

This study assesses geotechnical properties and probable natural hazards of the Lara-Kundu area, regarding the impacts of urbanization on the geological environment and vice-versa. Soils of the area are of dune and lagoon origin. Plasticity index of the clays varies from 39 to 57 % and the water content is between 26-45%. Plasticity index of peats varies from 65 to 117 % and the water content is between 226-405%. Su values are 29 -91 kPa. Compressibility index of clay samples are Cc=0.217-0.385 and OCR values range from 0.86 to 1.06. Compressibility index of peat samples range from 0.387 to 0.637. Some buildings constructed in the study area suffer from foundation-settlement problems. Tilting or differential settlement in the study area occurs due to high compressibility. Seismic activity can be grouped into two; crustal earthquakes (0-40 km) and subduction zone earthquakes (40-140 km). Maximum observed magnitude of the subduction earthquakes is Mw=6.0, and that of the crustal earthquakes is Mw=6.6. It can be concluded that the study area is prone to hazardous earthquakes. Another issue which should be considered is that saturated soft clay, peat and loose sand can result in ground amplification. For some loose sand levels liquefaction potential should be considered. Antalya has Mediterranean climate and after a dry summer a heavy rainfall comes resulting in flood with economic and life loss.

[Keywords: Characterization, Clay, Geo-hazard, Lagoon soils, Sand Dune.]

Introduction

Lara-Kundu coastal strip, which is located at the southwest of Antalya city, is the study area (Figure 1). Lara name comes from Luvi language (the language of Anatolian race Luvi's, coeval of Hittites) 1. Lara means sand and this name was given to geographic places as Laraia, Lariia, Laraissa, Laraassa meaning “sandy place” 2. The study area is a well-known touristic site of Antalya which is famous for its wide beaches. During last decade 25 five star hotels were constructed on the seaside. Many other touristic facilities were planned in the area. Such attractive features of the study area, rapidly increasing population of Antalya and scenic beauty of the Mediterranean coast, increased the value of the land of Lara strip. Former fields and former peaty and marshy areas, which were dried by canals, became land parcels and high rise buildings started to be constructed after 90’s.

Altitude in the area is 1-9 m above mean sea level (mean 3 m). In the residential and commercial city development plan, northern part of the area was planned for houses and the southern part for resort and hotels. Some of the buildings in the northern part suffer from foundation instabilities. Cracking and fissuration of the walls and overall tilting are typical indications of foundation problem that buildings are suffering. Some are still unstable and unused and some are repaired by underpinning techniques. Almost every year most of the area is covered with water due to flood. Geodynamic behavior of sandy and peaty soils during an earthquake is still a question.

This study aims to elucidate the geological and geotechnical conditions of the Lara-Kundu coastal strip for better understanding the causes of instability problems in the area and for planning the future engineering works. Environmental geology is concerned with the impact of urbanization on the geological environment, as well as the influence of the geological environment on urbanization. Accordingly, environmental geological aspects are the other issues of the study. Thus, the present study is focused on determination of geological profiles, sedimentary facies, the index and mechanical properties of the soils, natural hazards and geo-
environmental problems of the study.

Materials and Methods

Geology of the Antalya region

Antalya is located at the southern margin of the Western Tauride Belt. The main rock units of the region are divided into allochthonous and autochthonous units (Figure 1). One of the main autochthonous units is the Anamas-Akseki (relative autochthonous); this unit consists of platform-type carbonate sediments that were deposited between the Late Cambrian and Eocene. Another autochthonous unit is the Beydağları (relative autochthonous), comprising platform-type carbonate sediments of Jurassic to Miocene age. Together, these two units comprise the basement onto which the allochthonous units were emplaced and younger autochthonous units were deposited conformably.

Fig. 1—Regional geological setting (after Akay et al. 1985)

The younger autochthonous units are divided into two groups. The first group comprises sediments deposited in the Antalya Miocene basin. Basin contains sandstone, conglomerate, limestone, clayey limestone, brecciated limestone, claystone and shale. The basin opened during the Oligocene and closed in the Late Miocene. The second basin is an Upper Miocene-Pliocene basin located west and south of the Aksu Stream. Basin opened in the Messinian and closed in the Early Pliocene, and contains conglomerate, sandstone, limestone and calcareous claystone. The youngest autochthonous unit of the area is the Antalya tufa (Plio-Quaternary), which extends from the Aksu Stream in the east, to the Antalya Nappes in the west, and to the Beydağları in the north. Antalya tufa unconformably overlies Miocene deposits to the east and a Cretaceous ophiolitic complex to the west. The main allochthonous unit of the area is the Antalya Nappes, comprising mainly marine sediments deposited in the basin between the Beydağları unit and the Anamas-Akseki unit. After deposition was completed, the Antalya Nappes were thrust over the Beydağları and Anamas-Akseki units.

Geological evolution of the Lara-Kundu strip

Formation of Aksu Basin was related to the subduction along African-Eurasian plate boundary and westward movement of the Anatolian block. This tectonism resulted in an alternation of two compressional and two extensional regimes. Aksu Basin was formed by southeastern emplacement of Lycian Nappes in a NW–SE compressional regime. This is followed by NW–SE extensional regime which is related with the activity of Hellenic-Cyprus subduction zone. Subsequent NE–SW compressional regime known as ‘Aksu Phase’ is the third phase and it is involved with the westward escape of Anatolian block started in Late Tortonian. Neotectonic regime is represented with a NE–SW extensional regime in the Aksu Basin. This mechanism resulted in formation of "Isparta angle", which separates two important continental blocks; the Bey Dağları to the west and southwest, and the Western Taurus to the east and northeast (Figure 2).


The Aksu thrusting was the last major tectonic event in the formation of the Isparta Angle. Measurement of fault-planes with slickensides, showed that the translation was from east to west initially, rotating to NNE–SSW soon afterwards. The Aksu Thrust is not a single reverse flat
fault. Several parallel fault planes are instead superimposed, producing a complex imbricate fan of tectonic slices. Some of these thrust slices involve the underlying Antalya Nappes and their basement. Basement of the present Aksu valley should be a Messinian palaeovalley which existed before the Pliocene, and it was occupied by a marine transgression and filled by marls and coarse clastic sediments. During Pliocene in the west Antalya tufa was deposited and in the east Aksu formation was deposited. Collision of the African and Eurasian plates results in active subduction along the Hellenic and Cyprus Arcs.

Another important factor which shapes the study area is sea-level changes. The sea level fell about 100 m in the south-east Anatolia during the last glacial maximum and raised to present level during the Holocene. Following very rapid sea-level rise which occurred between 18,000 and 6,000 BP, former valleys and embayment turned into bays in the west of Antalya (Teke Peninsula). However in the east, due to continental uplift, relative sea-level rise was less than in the west. The ruins of ancient cities (Faselis and Kekova; 2000-2500 years BP), located in the west, are submerged 2-3 m below sea level. However Aspendos, which is located 50 km east of the study area, once a river-mouth harbor city at sea level, is now 15 m above sea level. After sea level rise granular material carried by Aksu stream was deposited in front of the bay by sea currents and began to form a barrier beach. When the barrier beach sealed off the entire bay, the area became a lagoon that is fed partly by the Aksu stream and groundwater seeped from Antalya tufa. At the North-west of the area a marshy wet-land exists. Boreholes around this wetland show that in the geological history marsh environment active in the same location. In the low-velocity and shallow water environment of the lagoon peat was deposited. Between beach barrier and swamp area sand dunes developed. Borehole data show that in the southern part of the plain, the dominant soil unit is fine grained poorly graded (well sorted) sand. Domination of fine grained well sorted sand signifies the dunue origin (Figure 3). In the present, in the mid part of the strip the dune environment is still active. The present-day elevation of the coastal plain is about 3 m above sea level. The mean groundwater level is at 2.5 m (almost 0.5 m above sea level).

**Facies of Holocene Sediments**

On the basis of grain size, texture, color and elevation, 5 different lithofacies within the Holocene sediments were identified from borehole samples. The data set consists of 20 continuously cored boreholes with depths of 10 to 22 m. The lithofacies may be described as follows:

**Barrier Beach (BB):** This facies comprises coarse sand with varying amounts of fine gravel. The dominant grain size is 1-5 mm and the fines content is less than 1%. No organic material was detected in the boreholes. The barrier-beach facies comprises grains originated from limestone, chert and serpentinite. Grains are well-rounded but not spherical; in particular, gravel-size particles are ellipsoidal. Maximum elevation of the barrier is 3 m above sea level.

**Fluvial Alluvium (A):** Recent river-bed deposits and other fluvial deposits which have been deposited in old river beds were grouped into this facies. This facies is the coarsest of all facies and comprises coarse gravels and medium to fine sands.

**Dune Sand:** Present wind dunes are located between 300-1000 m intervals from the coast line. The maximum height of the dunes is 10 m. The main source of these terrigenous sandy sediments is the Aksu Stream. The Lara coast is influenced by two main monsoon wind regimes and any explanation of the aeolian processes should be based on this regime. Two distinct wind directions were determined; one is from S, which prevailed from April–July, and from NNW, which prevailed from December–February. Long axes of dunes are perpendicular to these wind directions. Mean particle diameter (D50) is 0.256 mm and all of the dune samples are poorly graded sand (SP).

**Mud:** This facies consists of more than 95% fines and observed between sand layers. The maximum thickness is 3 m, and the color of the sediment varies from light to dark grey. This facies should be the oxbow lake sediments behind the back-barrier plain Around Kopakçayı Stream.

**Marsh (Peat):** A marsh is a type of wetland that is dominated by herbaceous plant species and mosses. Peat forms when a plant is inhibited from decaying fully by acidic and anaerobic conditions in marsh environment. Peats are soft, earthy, organic materials containing recognizable fragments of mosses or roots of woody or herbaceous plants and aquatic macrophytes. Peats in the study area are black, completely decomposed and fibrous materials. Moisture content can reach to 400%.
Results and Discussion

Geotechnical properties of soil units

Boreholes and standard penetration tests (SPT) Geotechnical data from 20 boreholes, ranging from 10 to 22 m in depth, were evaluated to elucidate the geological profiles of the study area (Figure 4). In order to perform thorough evaluation and testing, a detailed drilling program was conducted. Drilling technique and sample quality are important in the determination of reliable soil parameters. Therefore, special attention was paid to drilling and sampling. Boreholes were drilled using hollow stem augers without using water flush. Continuous core sampling or in situ testing was carried out without leaving a blank zone. Undisturbed core samples were used for visual inspection and geotechnical testing. During the boring of these holes, the standard penetration test (SPT) was done with a split spoon sampler and safety hammer. The sampler is driven into the soil to a depth of 450 mm by means of a 63.5 kg hammer free-falling 760 mm with each blow. SPT test results are given in Figure 5. Cone Penetration Testing (CPT) In this study CPTU electrical cone penetration tests (piezocone) were carried out at 10 sites, following American Society for Testing and Materials (ASTM) procedures, and evaluated. At each location, a CPT probe penetrated to a depth of 6-22 m. The diameter of the cone was 35.7 mm and the tip angle 60° with a 150 cm² friction sleeve. The speed of penetration was 2 cm/s. Corrected point resistance (Qc) of CPT logs are shown in Figure 6.
Fig. 5—SPT test results

Fig. 6—CPT test results: corrected point resistance ($Q_t$) versus depth
Index properties of soils

Grain-size distribution, Atterberg limits and densities were determined according to ASTM standards. Index properties of soil samples are dependent on depositional environments. The plasticity index of the mud facies varies from 39% to 57% and most of the lagoonal muds are of the CL type. The water content is between 26% - 45%. The plasticity index of the marsh facies (peat) varies from 65% to 117% and the water content is between 226% - 405%. Dominant grain size in the area is sand. Sieve-analysis results of sands are given in Figure 7a. The sands are classified as “poorly graded with fines of 1–20%”, where the coefficient of uniformity Cu is less than 6 and the coefficient of curvature Cc is between 0.5 and 2.0 (Figure 7b) which implies dune origin.

Undrained shear strength of silty clays

The undrained-unconsolidated triaxial tests were carried out on undisturbed Shelby tube samples having 38 mm diameter and 76 mm heights. However, the results of the laboratory tests are usually subjected to uncertainties due to the inevitable sample disturbance, in this paper, conventional undrained-unconsolidated (UU) test method was chosen to determine undrained shear strength. Because the triaxial UU test is quick and easy it is a common test method, and comparison with other databases is possible. Due to sample heterogeneity and difficulties in obtaining samples, the multi-stage test method was preferred. In this method, axial load was applied under constant cell pressure until the specimen failed; the cell pressure was then raised and axial loading continued to obtain a new peak deviator stress. Test results show low internal-friction angles (<5°, with an average of 3°). These low internal-friction angles for undrained loading are due to the silty character of clays and the low sand contents. S_u values are 29-91 kPa.

Compressibility of silty clays

The void ratio (e)-log P curves for clay soils were obtained on the basis of the conventional oedometer test, done according to ASTM standards. The load-increment ratio is 1.0, and the duration of each load increment is 24 hours. Using (e)-log P curves, the pre-consolidation pressure and corresponding overconsolidation-ratio (OCR) values were determined, on the basis of the traditional Cassagrande construction. Some difficulties were encountered in applying the Cassagrande method to samples with low-pronounced yielding curvature. This situation is thought to be due to the silty nature of the samples, low overconsolidated condition, and sample disturbance. Compressibility index of clay samples are C_c=0.217-0.385 and OCR values range from 0.86 to 1.06. Compressibility index of peat samples range from 0.387 to 0.637.

Seismicity

Eastern Mediterranean region is tectonically complex and its structure is strongly related with the active subduction along the Hellenic and Cyprus Arcs. Present tectonics is driven by the collision of the African and Eurasian plates. Based on epicenter locations and bathymetry of the area, there are some studies suggesting the
presence of a subduction zone in this area. The distribution of seismicity as shown in Figure 8 is mainly concentrated along the Hellenic and the Cyprian arcs, with deeper earthquakes occurring along the subduction zones.

Fig. 8—The distribution of seismicity around the study area

True geometry of the Hellenic and Cyprian Arcs junction in the south of Antalya Bay is problematic. The cumulative distribution of earthquake hypocenters in cross section shows that evaluation of the earthquakes in two dimensions is not adequate and depth is a key property (Figure 9). Based on the depth distribution it is clear that earthquakes should be grouped into two; crustal earthquakes (D=0-50 km) and subduction zone earthquakes (50-140 km). Most of the subduction zone earthquakes are located in the Antalya Bay. Northernmost part of the subduction zone overlap with continent along Antalya coasts, however hypocenter depths are more than 90 km here. Maximum magnitude of these earthquakes is $M_{w}=6.0$.

Fig. 9—The cumulative distribution of earthquake hypocenters in cross section. Source: Bogaziçi University (Istanbul-Turkey) Kandilli Observatory and Earthquake Research Institute (KOERI).

Epicenters of crustal earthquakes are located all around the Antalya Bay as well as the continent. Maximum magnitude is $M_{w}=6.6$. Sources for these earthquakes are faults which are related with Isparta angle and Cyprus-Hellenic Arc tectonic regimes (Figure 10). One seismic source is located at the south of Finike. There is a debate about tectonic structure of the area between Finike and Anaximander Sea Mount and along 3064 m deep Finike trench. Even though fault geometry and mechanism is not clear, there is an intense seismic activity which creates earthquakes having magnitudes up to $M_{w}=6.5$. The distance between this activity and the study area is 100 km.

There is another seismic activity around the study area which is located along the line from Lake Eğirdir to Manavgat through Mediterranean Sea. This activity is thought to be related with eastern branch of Isparta Angle. The most important fault of East Isparta Angle is the Aksu Thrust. Even though this fault is not active today, big earthquakes ($M>5$) was recorded during last century on the Aksu Thrust. In the offshore area between Aksu and Finike
seismic source zones normal faults with N-S trend created graben topography. Two sets of earthquake epicenters with N-S trend should be related to these faults. East part of these normal faults produces earthquakes up to magnitude $M=5.6$ on the line from southern margin of the bay through Antalya coasts. On the western part of the Antalya bay, normal faulting continues in the continent, from Kemer to north of Antalya. Another earthquake activity is observed between Kemer-Korkuteli lineament, which produce up to $M=5.3$ earthquakes. There is also intense micro earthquake activity around the study area.

Fig. 10—Distribution of earthquake epicenters of crustal earthquakes. Source: Bogaziçi University (Istanbul-Turkey) Kandilli Observatory and Earthquake Research Institute (KOERI).

It can be concluded that the study area is prone to be affected by hazardous earthquakes ($M>5$). Another issue which should be considered is local site response of soils. The water table is close to surface and saturated soft clay, peat and loose sand can result in ground amplification. For some loose sand levels in the soil profile liquefaction potential must be considered.

**Flood**

Surface water resources of the area are: Aksu Stream, Kundu Stream and Kopak Stream. Kopak Stream is a short stream (3.5 km) which drain from Lake Yamansaz. Kundu Stream is also short stream (6 km) which drained from groundwater of the coastal plain and flow through the Mediterranean Sea. Aksu Stream drains from Lake Egirdir, flowing through 140 km and discharge to the sea. After reaching the coastal plain, Aksu Stream flows in its natural bed without any rehabilitation.

Antalya has a Mediterranean climate and after a dry summer a heavy rainfall comes during November and December. In 2001 Antalya received 1892 kg/m$^2$ rainfall, which is the second highest amount recorded during the next century, below the 1969 total of 1914 kg/m$^2$. Almost 75% of this high annual total rainfall occurs during the months of November and December. Daily maximum rain was recorded as 334.5 mm.

Very often flood occur in the 20,000 ha area causing to economic loss and death (Figure 11). In the past flood was more severe. Karacaoren Dam, which was constructed in 1990 at 50 km north from the coastline, resulted in some mitigation but not completely. In 2010 February Aksu Stream flooded with 920 m$^3$/sec discharge and 7500 ha land and property flooded. To save touristic property and people living in the area Aksu Stream bed should be rehabilitated. The rehabilitation project should be designed for discharge value for 500 years recurrence period and 6563 km$^2$ basin. Meandering river bed should be taken to short and deepened bed should be bordered by embankment. On the river mouth breakwaters should be constructed to prevent closure of the river mouth due to sediment accumulation.

**Total and differential settlement**

Some buildings constructed in the study area (especially peat dominated areas) suffer from foundation-settlement problems. Because immediate settlement is accommodated within the structure as it is built, settlement in this context refers to long-term consolidation settlement. Generally, settlement of buildings occurs shortly (within months) after the beginning of service life, however it may not be evident if there is no considerable tilt. Tilting or differential settlement in the study area occurs for a number of reasons. Local variation in soil compressibility is one reason. Varying environments of deposition and variation in the
Environmental geological aspects

Behind the western part of the Lara beach, 1 km width area is characterized by sand dunes. The Lara coast is influenced by two main monsoon wind regimes; NNW and S. Fine sands selected from the beach are transported by wind through north. Height of longitudinal dunes reaches to 10 m (Figure 12). Vegetation on dunes include pines (*Pinus Brutia*, *Pinus Pinea*), *Nerium Oleander* and *Pancratium*. These sand dunes are also spawning places for turtles (*Caretta Caretta*). Sand dunes are unique and nonrenewable resources, supporting a rich community of highly specialized plant and animal species. The dune ecosystem is not static; it is dynamic, and human impacts can readily change existing balances. Sand dunes are gift of geological past. Today our rivers are cut by dams, which prevent sediment transport to coasts. Moreover, sand and gravel quarries are decreasing sediment supply. Sand dunes will never grow up as they did before. Human impacts on the dunes include; pedestrian trampling, constructing footpaths, off road vehicle tracks, road construction, car parks, houses, the conversion of sand dunes to land for farming, waste disposal and sand dune mining. The major impact on sand dunes results from recreational use. However the dunes are lovely to visit or a nice place to live in, human lifestyle have to adapt to the dunes. The dunes cannot adapt to human unfortunately. In the last 30 years, mainly because of tourism, nearly 75% of the Mediterranean’s coastal dunes have been damaged or destroyed.

Eastern part of the study area between Kopakayi and Aksucayi was also sand dune ten years before. Today 25 five star hotels and resorts are covering almost all of the dunes. There are some proposals for remaining western dunes including amusement parks, theme parks, fair and exposition centers. In case of any
construction projects, Lara sand dunes will be lost due to above mentioned reasons.

Between sand dunes and tufa cliffs there is a wetland which is called Lake Yamansaz. The lake has about 15 km² surface area and 2.5 m depth. The temperature of the water in Lake Yamansaz begins to increase at the beginning of spring, reaching a maximum in July and then decreases in the middle of autumn (10°C in March to 27°C in July). Dissolved oxygen values are low during summer periods but it has been recorded as increasing during the spring and winter months (7.32 mg/l in March to 5.24 mg/l in July), pH values very between 7.22 and 7.78. 161 bird species belonging to 51 families, 4 amphibian and 19 reptilian species are living in the lake and these organisms are adversely affected by reed burning, illegal hunting and building activities. The covered area was larger before 1950's. Canals were dug to shorten and deepen the drainage path and therefore lake level was reduced to the sea level. There were other water ponds in the study area, but now they are completely disappeared or squeezed. For example former Lake Acı was squeezed and now it is a drainage canal which is known as Kopakçayı Stream. Former lake bottom areas first became fields and later land parcels for buildings. Drainage increased the water velocity in the lake and this caused to change in water chemistry and lake bottom morphology, thus causing habitat alterations.

Conclusions

Based on the geological and geotechnical investigations carried out, the following conclusions are drawn:

Soils of the Lara coastal strip are of dune and lagoon origin. After Holocene sea level rise, granular material carried by Aksu Stream was deposited as barrier beach. Behind the barrier beach, the area became a lagoon and in the shallow environment of the lagoon, peat developed. Between beach barrier and swamp area sand dunes developed.

Dominant grain size in the area is sand. Almost all of the sands are poorly graded (well sorted) implying dune origin. Fine grains and peats are rare. The plasticity index of the clays varies from 39 % to 57 % and most of the
lagoonal muds are of the CL type. The water content is between 26% - 45%. The plasticity index of the marsh facies (peat) varies from 65% to 117% and the water content is between 226% - 405%. Test results show low internal-friction angles (<5, with an average of 3). S6 values are 29-91 kPa. Compressibility index of clay samples are \( C_{c} = 0.217 - 0.385 \) and OCR values range from 0.86 to 1.06. Compressibility index of peat samples range from 0.387 to 0.637.

The earthquake distribution around the study area is mainly concentrated along the Hellenic and the Cyprian arc, with deeper earthquakes occurring along the subduction zones. Most of the subduction zone earthquakes are located in the Antalya Bay. Northernmost part of the subduction zone overlap with continent along Antalya coasts, however hypocenter depths are more than 90 km here. Maximum magnitude of these earthquakes is \( M_{w} = 6.0 \). Epicenters of crustal earthquakes are located all around the Antalya Bay as well as the continent. Maximum magnitude is \( M_{w} = 6.6 \).

It can be concluded that the study area is prone to be affected by hazardous earthquakes (\( M > 5 \)). Another issue which should be considered is local site responses. The ground water level is high and the acceleration of the saturated soft clay, peat and loose sand could be amplified. Some loose sand levels indicate liquefaction potential.

Antalya has a Mediterranean climate and after a dry summer a heavy rainfall comes during November and December. Very often flood occur in the 20,000 ha area causes to economic loss and death. To save touristic property and people living in the area Aksu Stream bed should be rehabilitated.

Some buildings constructed in the study area suffer from foundation settlement problems. Tilting or differential settlement in the study area occurs for a number of reasons. Local variation in soil compressibility is one reason. Varying environments of deposition and variation in the thickness of compressible soil also contribute to tilting.

Regarding impacts of urbanization on the geological environment, and vice versa, it can be argued that dense urbanization and touristic facilities bring threat for geological environment of Lara Coastal Plain. Geotechnical problems and natural hazards are the disadvantages of the area for city development. Therefore city plan of the area should be revised according to geotechnical aspects and environmental geological aspects as well.

Acknowledgements

This study was supported by the Akdeniz University Research Fund (Antalya, Turkey). Author expresses his gratitude to Pelin Ozsoy, Murat Karatas, Bulent Cangir and Cagdas Gurbuz for their assistance during laboratory and in situ tests.

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