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Delineation of the Seawater-Freshwater Interface from the Coastal Alluvium of Kaleköy-Gökçeada, NW Turkey

[1]Yunus Levent Ekinci, [1]Alper Demirci and [2]Can Ertekin
[1]Department of Geophysical Engineering,
[2]Department of Geological Engineering, Çanakkale Onsekiz Mart University, Turkey

Abstract: In this study, combined geophysical methods were performed to determine layered seawater-freshwater interface which is under natural conditions through a semipervious layer in a coastal alluvium of Gökçeada-Turkey. The surveyed area named Kaleköy is located in the northeastern part of Gökçeada. Electrical resistivity tomography technique with using dipole-dipole electrode configuration was performed over two profiles. The interpretation of the two-dimensional inversion of the acquired resistivity data delineated the seawater-freshwater interface successfully. Additionally to the resistivity data, two-dimensional seismic refraction tomography survey was also conducted to characterize the alluvium properties in terms of saturation conditions. It was determined that the soil is characterized with unconsolidated sediments. This study yielded useful information about the geometry of seawater body under the freshwater. The interface was determined at the depth of 7-8 m approximately and presents an undulated surface. Moreover, it was observed that seawater intruded far distant than the length of the survey area (>150 m).

Key words: Seawater-freshwater interface, geophysics, resistivity, seismic refraction, Gökçeada-Turkey

INTRODUCTION

Coastal aquifers are known with developing of seawater-freshwater interface. In detail, providing that groundwater is withdrawn or pumped from a coastal aquifer, it causes rearranging of natural balance. That is, seawater-freshwater interface intrudes into the coastal aquifer or even to usable parts of it. This phenomenon is called seawater intrusion, encroachment or encroachment of seawater (Bear, 1979; Domenico and Schwartz, 1990). Under natural conditions (without pumping or withdraw), the flow of freshwater can limit landward encroachment of seawater. By pumping water upwards of replenishment from a coastal aquifer, phreatic surface lowers in vicinity of the coast, hence a new seawater–freshwater interface develops. For instance, hydrogeology at many coastal locations is characterized by a layer of freshwater that is replenished from rain and which overlies a deeper seawater layer intruding from the ocean and sea (Unsworth *et al*., 2007). One of factors controlling geometry or layering of seawater and freshwaters is aquifer media. Related to the media, some modals are shown in Fig. 1. Left hand side section in Fig. 1 shows intruding seawater and its equilibrium with freshwater by replenishment in natural conditions. In case of extending an impervious layer (e.g., clay rich zone) into land, it

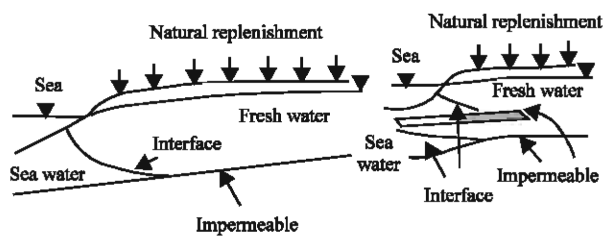

Fig. 1: Some modals of seawater-freshwater interface (modified after Bear, 1979)

affects developing a new interface and equilibrium between seawater and freshwater (right hand side in Fig. 1).

Surveying existence of seawater-freshwater interface can be possible via wells, geophysical methods or both of them. One of the geophysical survey methods to determine the interface is DC resistivity. This method was conducted to determine layered seawater-freshwater interface which is under natural conditions through a semipervious layer in a coastal alluvium of Kaleköy-Gökçeada, Northwestern Turkey by using two-dimensional Electrical Resistivity Tomography (ERT) technique. ERT is one of the most commonly applied geophysical technique for groundwater exploration, seawater intrusion and also capable of determining the

Corresponding Author: Yunus Levent Ekinci, Department of Geophysical Engineering, Faculty of Engineering and Architecture, Çanakkale Onsekiz Mart University, Terzioğlu Campus, 17020 Çanakkale, Turkey
Tel: +90 286 218 00 18/2166 Fax: +90 286 218 05 41

quality of groundwater whether groundwater is saline, brackish, fresh or contaminated (Barker, 1980; Nassir *et al*., 2000; Sumanovac and Weisser, 2001; Bauer *et al*., 2006; Sherif *et al*., 2006; Sumanovac, 2006; Casas *et al*., 2008). The method has become an increasingly efficient tool to investigate the resistivity distribution of the subsurface. Furthermore, the high technological developments of computer controlled multi-electrode survey systems and the developments of two- and three-dimensional resistivity inversion software packages have let more effective surveys and reliable resistivity representations of the subsurface with high resolution (Dahlin, 2001; Drahor *et al*., 2007). The aim of the ERT technique is to survey the subsurface along the survey line repeatedly by a selected electrode array. By this way, the line of electrodes is scanned quickly to obtain the apparent resistivity pseudosections from the first electrode to the last electrode with the usage of an automatic electronic system. The advantage of this technique is to observe quickly the pseudosections of the investigation line during the field observation (Drahor, 2006). Additionally to the ERT technique, Seismic Refraction Tomography (SRT) technique was also conducted in order to determine whether the media is unconsolidated or not. It is clearly known that water saturation is a key point for liquefaction analysis in coastal regions. The shallower the water level is the higher the liquefaction risk is. Present results show that the soil in survey area is characterized with unconsolidated sediments due to very low S-wave velocities (result not presented because of the noisy data). The boundary between the seawater and freshwater was found at the depth of ~7-8 m, according to the ERT results. Due to the geological conditions, it presents an undulated interface. On the contrary to expectations, the seawater intruded far distant than the length of the survey area (>150 m). These results confirm that the area has also a high liquefaction risk because of the high water level and unconsolidated alluvium.

DESCRIPTION AND SURFACE GEOLOGY OF THE SITE

Gökçeada is the largest island of Turkey, comprises 289.5 km^2 and has a population of ~9000. This island is in an active tectonic region and locates between latitudes 40° 05' 12" N, 40°14' 18" N and longitude 25°40' 06" E, 26°01' 05" E. The whole surface geology of Gökçeada is represented by a thick sedimentary sequence, volcanic rock and alluvium. The depositional period of sedimentary sequence is Early Eocene to Late Oligocene (Temel and Çiftçi, 2002). This sequence consists of conglomera, sandstone, shale, siltstone, limestone and intercalated coal seams. This sedimentary sequence is defined with different formation names and four tectono-stratigrafic packages by unconformity surfaces (Temel and Çiftçi, 2002). From bottom to top, these conformity surfaces are Early-Middle Eocene including Karaağaç and Fıçıtepe Formations; Middle Eocene-Late Oligocene consisting of Soğucak, Ceylan, Mezardere, Osmancık, Armutburnu Formations; Early-Middle Eocene with Ayvacık Volcanics; Late Miocene-Pliocene including Gazhanedere and Kirazlı formations. The last sedimentation period is also marked by alluvium. Regarding of the survey site, western and eastern parts of it in which Mezardere Formation outcrops are hilly and the formation consists of sandstone-shale sequence. The plain is also represented by alluvium (Fig. 2). Hill slope allows rapid surface runoff wherefore infiltration occurs easily into alluvium.

Engineering based studies are of importance in terms of liquefaction risk of settlement areas and natural hydrogeological conditions. The site is also appropriate to investigate seawater-freshwater interface shape due to the fact that freshwater resulting from surface runoff limits seawater beneath itself, natural hydrogeological conditions and liquefaction potential. This study is the

Fig. 2: The location map of site and the surveyed profiles (not to scale)

first in literary meaning in the island because attempts of studies are constrained by researches about volcanology, petroleum geology and paleontology of the island.

THE METHOD AND RESULTS OF THE FIELD APPLICATIONS

Because of the fact that there is no data from wells in this site, geophysical methods were applied to evaluate ground conditions in terms of water table and the shape of the seawater-freshwater interface in the aquifer presented by alluvium and sandstone-shale sequence in vicinity of the site (Ekinci *et al*., 2007). ERT technique was performed using dipole-dipole electrode configuration with Iris Syscal-R1^{+} resistivity meter. The measurements were carried out over 2 profiles. Electrode spacing of 4 m was selected for the profile ERT1 and 10 m for ERT2 (Fig. 2). Since it is usually not advisable to use n values of greater than 6 or 7 for dipole-dipole electrode configuration (Loke, 2000) the measurements were conducted using a maximum dipole separation of 7 electrodes spacing. The schematic representation of the dipole-dipole electrode configuration is shown in Fig. 3. In order to improve the quality of the data, the standard deviation of stacks of each data point was taken into account. The resistivity meter performed a stack of a minimum of three for each data point. When the standard deviation between the measurements reached 3%, a maximum of five measurements were performed for each data point during the investigation. The standard deviations were generally below 2%. Readings were stored in the data logger of the resistivity meter and transferred to the computer by means of a RS232 connection cable. The processing and interpretation of the measured data were performed using the two-dimensional inversion algorithm of Loke and Barker (1996). For this purpose, RES2DINV software was used. This algorithm is based on the smoothness-constrained least squares and produces a geoelectrical section for a profile data. The optimization adjusts the two-dimensional resistivity model by reducing the difference between the calculated and measured apparent resistivity values in the iterations. There was not a high random noise in the investigation area so the maximum number of iteration was set to be 5 for two profiles. The inversion process produced a fit with an rms error of 7.6% for ERT1 and 5.2% for ERT2. It was thought that the obtained results provided a realistic true resistivity distribution of the subsurface depending on the rms errors.

Additionally to ERT profiles, SRT technique was also applied with a Geometrics ES-300, 12-channel seismic recorder. SRT profile was surveyed with a total length of

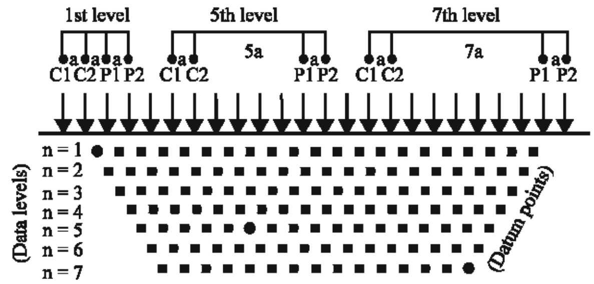

Fig. 3: The schematic representation of dipole-dipole electrode configuration, the locations of the datum points and the data levels

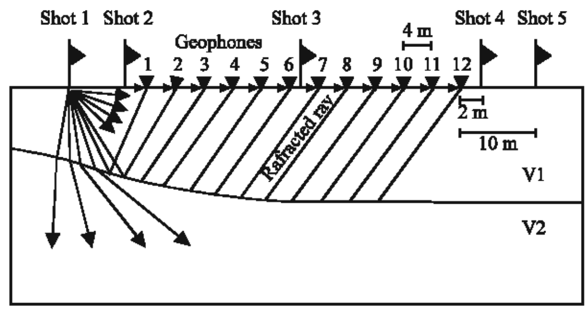

Fig. 4: The schematic representation of seismic refraction tomography survey (Only the rays from the shot 1 point are illustrated)

64 m and with a geophone spacing of 4 m. Five shot points were selected: one in the middle, two close to first and last geophone and two far offsets. The schematic representation of seismic refraction tomography survey is shown in Fig. 4. First arrivals picked and the travel time curves were used in the calculation of the model velocities and depths to the interfaces with the package of PLOTREFA 2.67. The inversion method used starts with a user selected initial velocity model and iteratively traces rays through the model with the goal of minimizing the rms error between the observed and calculated travel times. The inversion process produced a fit with an rms error of 1.6% for P-waves. The S-wave survey did not produce good result since the data quality was very low. First arrivals could hardly be picked in noisy data. It also indicates unconsolidated nature of the survey area.

The geoelectrical sections were obtained up to penetration depth of ~9 m for ERT1 and ~22 m for ERT2 (Fig. 5). The zone from the surface to the depth of approximately 7 m corresponds to alluvium composed of gravel-sand-silt-clay. The resistivity values vary from 15 to 35 ohm-m in the zone. This low resistivity value for this kind of alluvium may be attributed two main factors: either high clay ratio or the water saturation in the

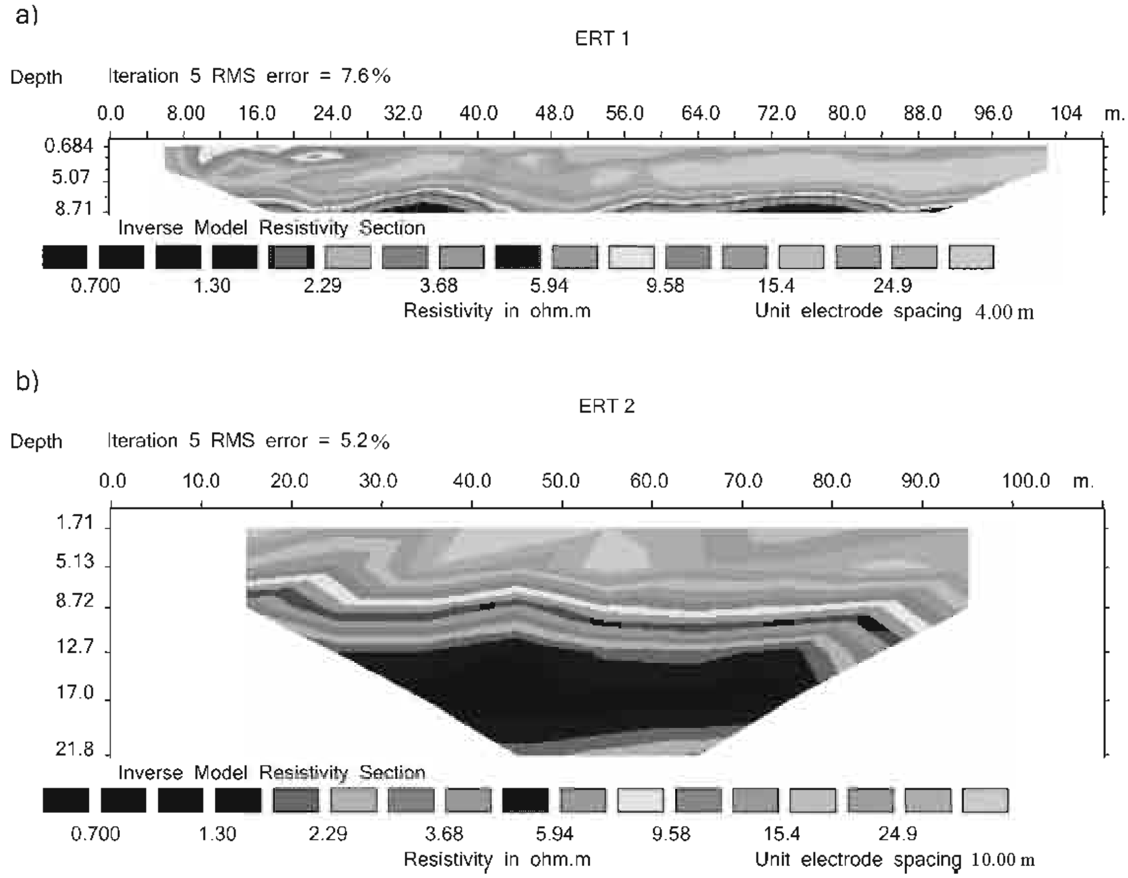

Fig. 5: The inverse model resistivity sections of the profiles, (a) ERT1 and (b) ERT2

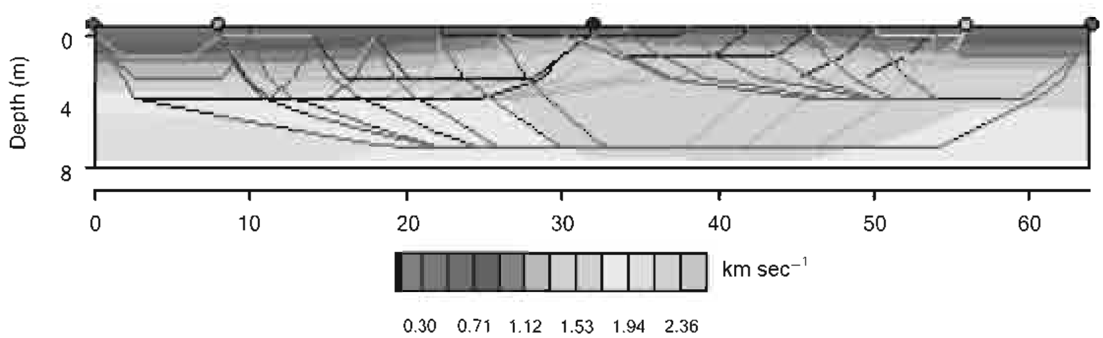

Fig. 6: The seismic tomography section for the profile SRT with ray traces

alluvium. The existence of water saturation in this zone is suggested due to both hydrogeological conditions (shallow water level, rapid surface runoff) and the high P-wave velocity in the alluvium. It can be clearly seen that the velocities of P-waves are ~1.45-1.7 km sec^{-1} in that zone between the depths of 2-7 m (Fig. 6). The bottom zone characterized by very low resistivity values ranging from 0.7-3 ohm-m in both profiles and this corresponds to seawater (Fig. 5). Because of the high resolution depending on small electrode spacing on ERT1 in comparison to ERT2, the intrusion of the seawater can be observed from ERT1 precisely and it indicates below the depth of ~7-8 m. At the bottom part of the very low resistivity zone observed on the profile ERT2 (>20 m), resistivity values increase with depth (Fig. 5). This may be interpreted to be decreasing porosity in response to increasing compaction and this compaction may indicate Mezardere formation represented by sandstone-shale sequence.

CONCLUSION

In this study, combined geophysical studies which were performed to determine the seawater-freshwater interface at the coastal alluvium in Kaleköy-Gökçeada, have been demonstrated. In order to identify the layered seawater-freshwater interface, ERT technique was applied over two profiles. Two different electrode spacings were selected for the survey to investigate both the interface of the seawater-freshwater and downward extension of seawater. The conducted ERT survey identified successfully the goals. The interpretation of resistivity sections with the combination of SRT section provided a meaningful existence of freshwater. It was observed that the freshwater exists over the denser seawater and the interface presents an undulated surface. The reason of this layered seawater-freshwater situation depends on rapid surface runoff related to hilly topography of the vicinity of the site. Surface runoff also means rapid infiltration into the alluvium. As a result of this study, the seawater-freshwater interface was observed below the depth of ~7-8 m and the base level of seawater extends more than 20 m. Additionally, the increase of resistivity values below than 20 m may trace the existence of Mezardere formation.

Due to the active tectonic of the region, shallow water table level and the existence of sand zones in the coastal areas of Gökçeada, it is thought that there is a potentially liquefaction risk in the coastal area of the Kaleköy. Owing to the extension of urbanization towards the coastal sites in the island, preventive measures should be considered against liquefaction risks in construction of engineering structures by local authorities.

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