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Automatic 3D soil model generation for southern part of the European side of Istanbul based on GIS database

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Abstract. Automatic large scale soil model generation is very critical stage for earthquake hazard simulation of urban areas. Manual model development may cause some data losses and may not be effective when there are too many data from different soil observations in a wide area. Geographic information systems (GIS) for storing and analyzing spatial data help scientists to generate better models automatically. Although the original soil observations were limited to soil profile data, the recent developments in mapping technology, interpolation methods, and remote sensing have provided advanced soil model developments. Together with advanced computational technology, it is possible to handle much larger volumes of data. The scientists may solve difficult problems of describing the spatial variation of soil. In this study, an algorithm is proposed for automatic three dimensional soil and velocity model development of southern part of the European side of Istanbul next to Sea of Marmara based on GIS data. In the proposed algorithm, firstly bedrock surface is generated from integration of geological and geophysical measurements. Then, layer surface contacts are integrated with data gathered in vertical borings, and interpolations are interpreted on sections between the borings automatically. Three dimensional underground geology model is prepared using boring data, geologic cross sections and formation base contours drawn in the light of these data. During the preparation of the model, classification studies are made based on formation models. Then, 3D velocity models are developed by using geophysical measurements such as refraction–microtremor, array microtremor and PS logging. The soil and velocity models are integrated and final soil model is obtained. All stages of this algorithm are carried out automatically in the selected urban area. The system directly reads the GIS soil data in the selected part of urban area and 3D soil model is automatically developed for large scale earthquake hazard simulation studies.

Keywords: sea of Marmara; southern part of the European side of Istanbul; large scale soil model generation; 3D velocity model; automatic model generation; geographical information system

1. Introduction

Turkey is one of the most serious damage countries suffered by earthquake disaster in the

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world. In 1999, two destructive earthquakes hit Turkey, causing severe disasters in industrialized and densely populated urban areas. The earthquakes are generally destructive and sudden. They may cause serious casualties and may also leads to landslides, mudslides, ground cracks and other secondary disasters. A few miles away beneath the Marmara Sea, the North Anatolian Fault line is located. The 1999 Kocaeli earthquake with 7.4 magnitude represents the latest of a series of migrating main shocks towards Istanbul along this fault. Increasing are concerns on major earthquake which will attack the Istanbul-Marmara region directly, and a comprehensive plan for earthquake disaster mitigation must be made in view of the current and future state of the city. Istanbul forms one of the largest urban agglomerations in Europe. High probability of being exposed to an earthquake of M7 or larger in the next years worries authorities and researchers. It is imperative to provide reliable predictions of possible earthquake hazard and disaster to achieve a higher safety against a future earthquake. Simulation is being used as a tool of objectively predicting earthquake hazard and disaster. Larger scale numerical computation is possible due to progress of computer science, and enables scientists make out more detailed numerical simulation of higher resolution (Stokes *et al.* 2001, Ichimura and Hori 2004, Bielak *et al.* 2005, Ichimura *et al.* 2005a and 2005b, Yao *et al.* 2006, Hori *et al.* 2006, 2009, Hori and Ichimura 2008, Xu *et al.* 2008, Petropoulos and Fenves 2008, Tobita *et al.* 2009, Erdik *et al.* 2011, Roy and Sahu 2012, Shiuly *et al.* 2015).

In the general view of Istanbul, the Bosphorus links the Sea of Marmara to the Black Sea, and divides Istanbul into European and Asian sides. Istanbul, located on both Asia and Europe continents, is the most populated city of Turkey. Recent devastating earthquakes in Turkey show that Istanbul is under a threat of unruptured segments of North Anatolian Fault zone (Ozel *et al.* 2004).

The success of large scale simulation depends on realistic soil and city models. The theoretical hazard simulation strongly requires getting suitable three-dimensional soil and velocity models. The three-dimensional soil models consist of sedimentary soil layers and bedrock surface layer.

This paper aims to construct a basis to develop three-dimensional soil model of southern part of the European side of Istanbul next to Sea of Marmara. This basis consists of two main components, first one is a three-dimensional digital soil model and second one is a three-dimensional digital shear wave velocity model. Besides, this basis makes it very easy to derive shear wave velocity profiles and soil parameters at any point to comment on local soil classes.

The primary focus of this study is to propose an automatic soil and velocity model generation algorithm for southern part of the European side of Istanbul next to Sea of Marmara. The combination of geophysical surveys, geological site observations, and the field conditions in the observation area are evaluated numerically. The geographical information system database of Istanbul Metropolitan Municipality is used to develop models. The soil database for the related area was generated by OYO International Corporation and the soil data is obtained with geophysical measurements and geological works. The geophysical measurements include seismic refraction and ReMi (refraction microtremor), seismic reflection, PS Logging, array microtremor, electric resistivity. The geological works include normal drillings, deep drillings, drilling for liquefaction analysis, drilling for landslide analysis, extra drillings (for faults, alluvium, basement, etc.), CPT and trench works (OYO Int. Corp. 2007). In this study, an automation algorithm is developed to evaluate all geophysical and geological data for producing soil and velocity models automatically. Huge volume of the data of soil and rock properties are in GIS database and a system has been developed to get, evaluate, process and integrate these data. The system is developed by utilizing MATLAB which is an advanced the simulation and programing package.

MATLAB has advanced graphical and mathematical capabilities and widely used in system development for structural and earthquake engineering applications (Sahin 2015a, b).

2. General information about the study area

The proposed algorithm may be used for any selected urban area. In this study, southern part of the European side of Istanbul is selected as an application as shown in Fig. 1. The boundary coordinates of the study area Xstart=387250, Xend=415000, Ystart=4536400, Yend=4547400 (ITRF) as shown in Fig. 1.

There are 13 districts in the study area, while some of them are completely inside the study area, some of them are included partially. There is also a lake named as Küçükçekmece Lake inside the study area. The lake divides the study area into the west part and east-middle parts. At the south of the area, Sea of Marmara is located, and north-east boundary of the area is the Golden Horn bay.

The study area is selected due to the due to some important reasons. The Southern part of the European side of Istanbul is built on soft soil while the Northern European and the Asian side built on hard old rock. This side contains the most populated region in Istanbul located close to the Marmara Sea segment of the North Anatolian Fault Zone. This region contains the industrial and cultural centers of Istanbul. It can be said that this area is a hazardous region with proximity to the fault line and critical infrastructures located on soft soil.

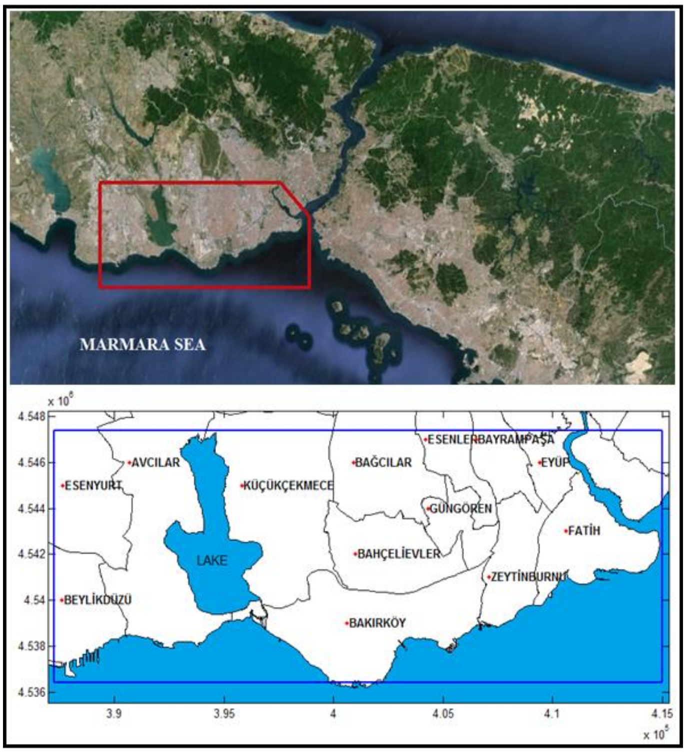

Fig. 1 The study area and boundary coordinates for automatic soil model generation

3. Geological information about study area

Formations and members in the study area was determined by OYO (2007) as follows:

•Trakya Formation (Palaeozoic, sandstone and others).

•Ceylan Formation (Eocene, Limestone and others).

•Gürpınar Member (belonging to Danışmen Formation) Oligocene - Miocene, sand, clay, clay stone, and others.

•Çukurçeşme Formation Miocene, Gravel and sand.

•Güngören Member (belonging to Çekmece Formation) Miocene, mainly clay.

•Bakırköy Member (belonging to Çekmece Formation) Miocene, limestone marl, and others.

•Alluvium Deposit and others Mainly Holocene, clay, sand, beach sand, top soil.

4. Data acquisition

During microzonation studies which resulted in 2007, 4365 borehole tests, 29 Microtremor tests, 201 PS Logging tests and 2630 Refraction Microtremor test were conducted (OYO Int. Corp. 2007). In this study, the observed data gathered from these tests are utilized.

5. Automatic soil model generation

In the proposed algorithm, firstly bedrock surface is generated from integration of geological and geophysical measurements. Then, layer surface contacts are integrated with data gathered in vertical borings, and interpolations are interpreted on sections between the borings automatically. Three-dimensional underground geology model is prepared using boring data, geologic cross sections and formation base contours drawn in the light of these data. During the preparation of the model, classification studies are made based on formation models. Then, 3D velocity models are developed by using geophysical measurements such as refraction microtremor (ReMi), array microtremor and PS logging. The soil and velocity models are integrated and final soil model is obtained. All stages of this procedure are carried out automatically in the selected area. The system directly reads the GIS soil data in the selected part of urban area and 3D soil model is automatically developed for large scale earthquake hazard simulation studies. The flow diagram for automatic three-dimensional soil and velocity model development is presented in Fig. 2. As shown in this Fig. 2, borehole, PS logging, microtremor and ReMi data is taken from the GIS database. Each data group is separated in 50 m×50 m spaced grid cells and their x, y and z coordinates are defined. The formation models are extracted from the borehole data and the bedrock surface model is automatically developed. It is observed that produced geophysical bedrock distribution map does not correspond to the geology bedrock distribution map which was produced by evaluating the borings. The geological and geophysical bedrock surface models are produced and integrated. Firstly, geology bedrock distribution map is produced by evaluating the borings from the GIS database. Then, the geophysical bedrock surface models are produced by using Microtremor, Refraction microtremor and borehole seismic (PS logging) data, respectively. The produced geological and geophysical models are integrated and a final bedrock model is automatically developed. Then, the surface layers determined from linear interpolation of borehole data are integrated and 3D soil model is obtained. The velocity distribution in the developed soil

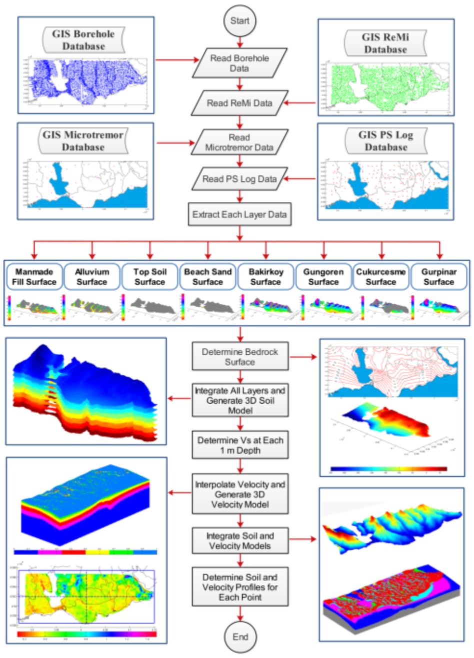

Fig. 2 Flow diagram for automatic soil and velocity model generation from GIS data

model is determined. The 3D velocity model is generated from linear interpolation of ReMi, microtremor and PS Logging data. The developed soil and velocity models are integrated and final soil model is obtained.

5.1 Determining bedrock surface

Trakya formation was mostly observed in the borehole logs from the eastern part of the study area while Ceylan formation was mostly observed in the borehole logs from the central part of the study area. But there was no sign of either Trakya formation or Ceylan formation in the borehole logs from the western part of the study area, particularly at the west of the Küçükçekmece Lake. To determine depth to bedrock in this part of the study area, the Refraction microtremor, Microtremor (MT) and PS Logging test results are utilized. In the literature, shear wave velocity at the engineering bedrock is assumed as 760 m/s. Instead of calculating only the depth at which shear wave velocity is 760 m/s, average shear wave velocities of both Trakya and Ceylan formations are considered, and the depth where shear wave velocity is 760 m/s, 870 m/s and 1200 m/s is determined. Although there are many borehole data at central and eastern parts of the study area, there are still some regions not reaching Ceylan and Trakya formations which are assumed as bedrock. The geophysical data are utilized in these parts to determine bedrock elevation. The bedrock surface model is obtained by combining geological and geophysical models as shown in Fig. 3.

5.2 Determining soil layer surfaces

As indicated before, there are eight different formations layered top to bottom in the stratigraphy as shown in Fig. 4. Beneath this regolith layers, the engineering bedrock appears as

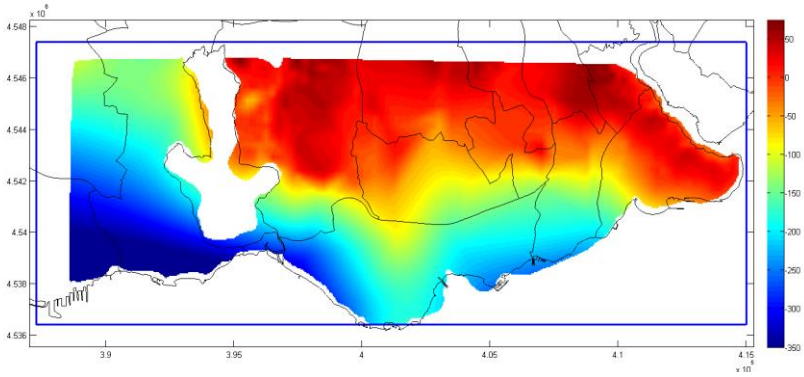

Fig. 3 Elevation of bedrock map for southern part of the European side of Istanbul

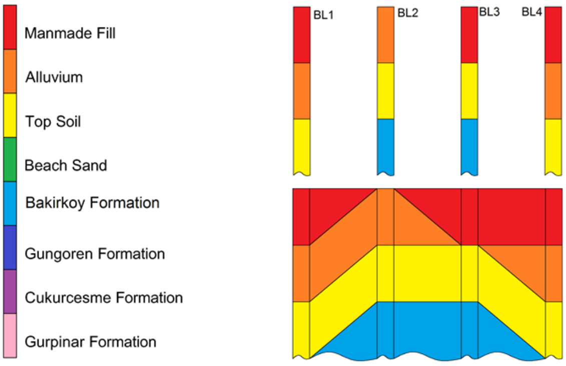

Fig. 4 Stratigraphy of the study area, and layer surface determination procedure

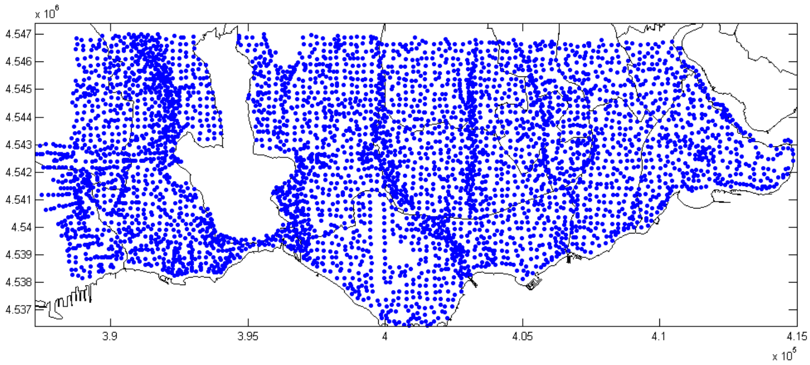

Fig. 5 Borehole test locations over the study area (OYO Int. Corp. 2007)

Ceylan Formation and Trakya Formation. A soil model generation system is developed to determine the formation top surfaces individually. The system is developed in MATLAB platform.

A brief explanation of proposed layer surface determination procedure is shown in Fig. 4. The upper and lower boundaries of the soil layers are combined. If any layer is not encountered in a borehole log, the following soil layer from the stratigraphy is assigned in place of it. These modifications mean that every formation exists in all borehole logs, but in some of them the nonexisting formations have zero thickness. For example, formation 2 has a thickness of zero in BL3, but still exists there to determine the layer boundary. Fig. 5 shows locations of borehole tests conducted in the study area.

5.2.1 Manmade fill surface

Starting with the topmost layer, Manmade Fill surface is determined. This surface is also the topography of the study area. The study area is divided into small cells and linear interpolation is applied between the borehole locations. A three-dimensional surface plot of the Manmade Fill formation is shown in Fig. 6. The color scheme indicates the elevation of layer surface. The colorbar shows the altitude of the Manmade Fill surface distribution through the study area. The cells where Manmade Fills are not observed are shown with gray colored patches.

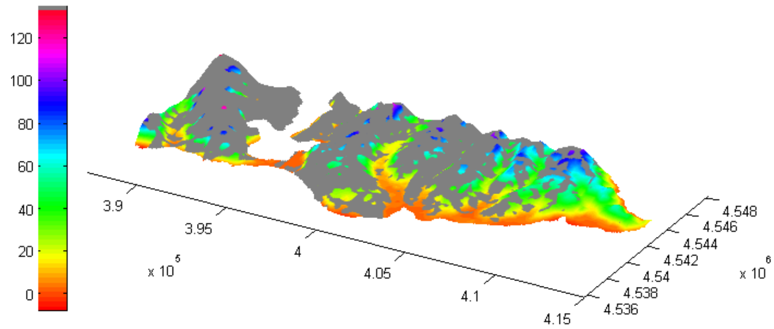

Fig. 6 3D plot of manmade fill surface

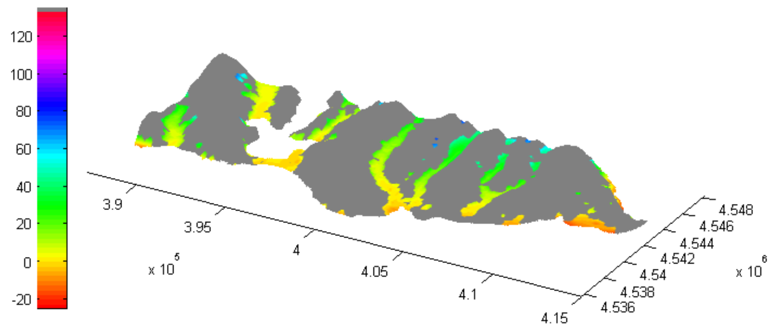

Fig. 7 3D plot of alluvium surface

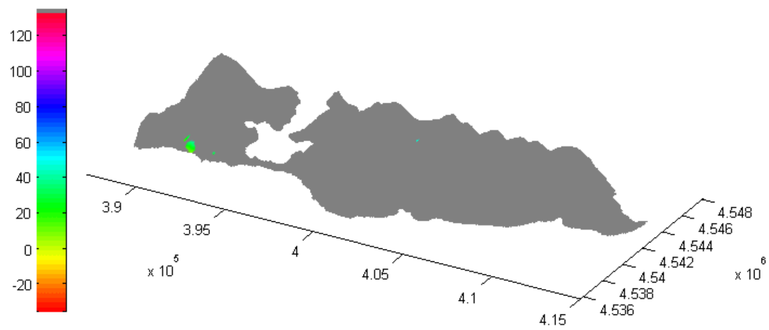

Fig. 8 3D plot of top soil surface

5.2.2 Alluvium surface

Secondly, Alluvium layer surface is determined as it is the second topmost layer in the stratigraphy. Following the same procedure, a three-dimensional surface plot of the Alluvium formation is obtained as shown in Fig. 7. Generally, valley beds are covered with Alluvium and gray colored cells mean that Alluvium formation is not observed there.

5.2.3 Top soil surface

Top Soil is the third layer in the stratigraphy. Three-dimensional surface plot of the Top Soil layer is obtained by applying the same procedure as shown in Fig. 8. It can be seen that Top Soil formation is observed only in an extremely small part of the study area and gray colored cells indicates that there is no sign of Top Soil formation.

5.2.4 Beach sand surface

Beach Sand is the fourth layer in the stratigraphy. Three-dimensional surface plot of the Beach Sand layer is obtained by following the same procedure as shown in Fig. 9. It can be seen from the Fig. that Beach Sand is located on very small areas on south coast of the study area.

5.2.5 Bakirkoy formation surface

Bakirkoy formation is the fifth topmost layer in the stratigraphy. It can be said that it is different from the upper four layers.While all of the upper four layers are observed generally at ground surface, Bakirkoy formation is observed generally under these upper four layers. Three-dimensional surface plot of the Bakirkoy formation is obtained by following the same procedure as shown in Fig. 10. The gray colored cells show that Bakirkoy formation is not observed there.

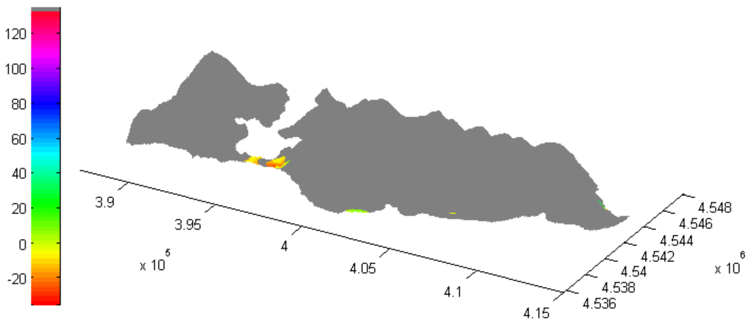

Fig. 9 3D plot of beach sand surface

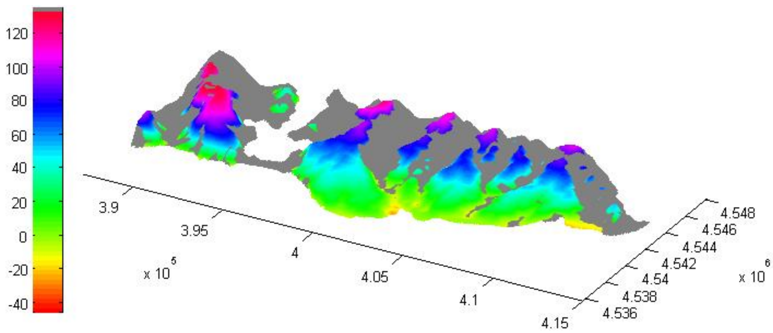

Fig. 10 3D plot of bakirkoy formation surface

5.2.6 Gungoren formation surface

Sixth layer in the stratigraphy is Gungoren formation. Three-dimensional surface plot of Gungoren formation is obtained by following the same procedure as shown in Fig. 11. Gungoren formation is observed at most of the study area. The gray colored cells indicate that there is no sign of Gungoren formation at those locations.

5.2.7 Cukurcesme formation surface

The last but one in the stratigraphy is Cukurcesme formation. Three-dimensional surface plot of Cukurcesme formation is obtained by following the same procedure as shown in Fig. 12. Cukurcesme formation is not observed in most part of the study area. Therefore, gray colored cells are dominant.

5.2.8 Gurpinar formation surface

Gurpinar formation is the last layer in the stratigraphy. Three-dimensional surface plot of Gurpinar formation is obtained by following the same procedure as shown in Fig. 13 Gurpinar formation is observed in most of the study area. The gray colored cells indicate that there is no sign of Gurpinar formation at those locations.

After obtaining bedrock surface and the regolith layer surfaces in the stratigraphy, the soil model is obtained.

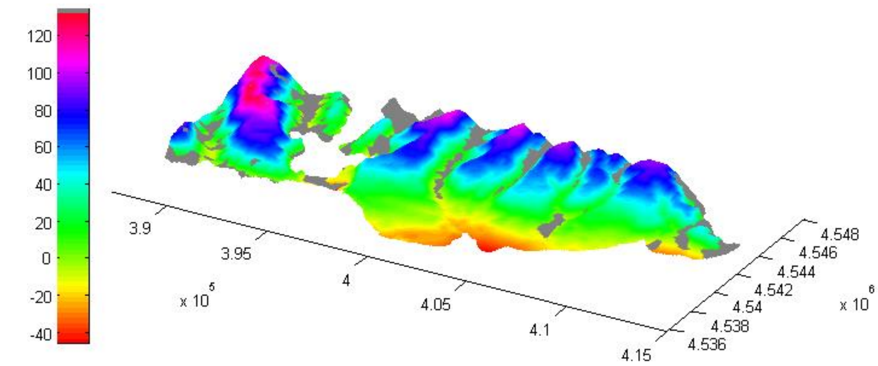

Fig. 11 3D plot of gungoren formation surface

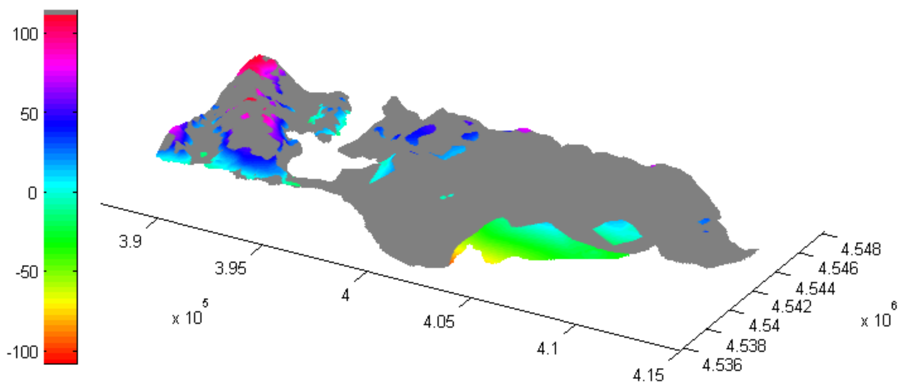

Fig. 12 3D plot of cukurcesme formation surface

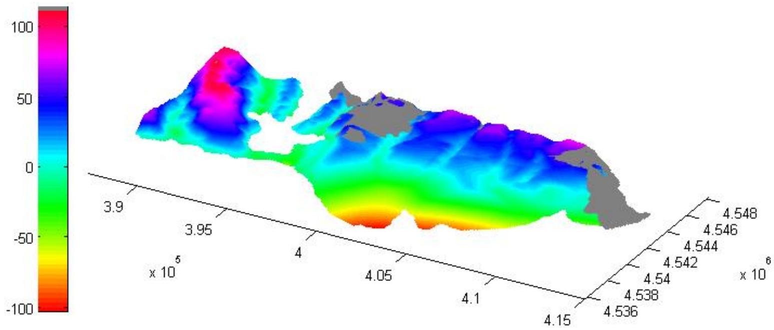

Fig. 13 3D plot of gurpinar formation surface

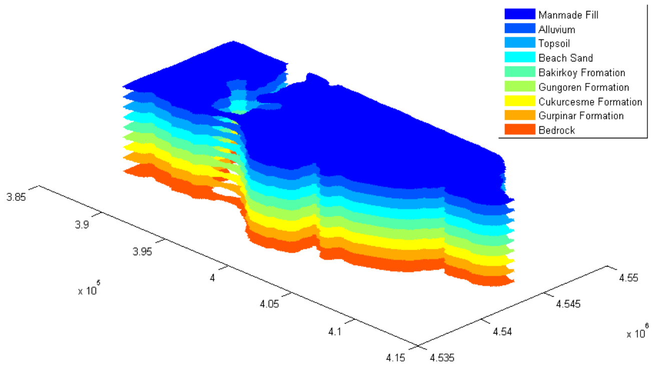

Fig. 14 3D digital soil model of the study area

5.3 Generating 3d digital soil model of southern part of the European side of Istanbul

The initial digital soil model is obtained by integrating the bedrock surface model and the regolith layer surfaces in the stratigraphy. The integration of bedrock surface and regolith surfaces is carried out by putting eight layers upon bedrock layer. The surface generation and integration process are carried out automatically. The interpolation and integration algorithms are coded and the soil model is automatically generated in study area as shown in Fig. 14. The layer thicknesses and layer depths at any point in the study area can be extracted from the developed initial soil model.

Different colors correspond to different layers in the stratigraphy from top to bottom, respectively from Manmade Fill layer to bedrock layer as it can be seen from Fig. 14.

6. Generating 3D velocity model

Refraction microtremor, microtremor and PS Logging test results gathered during microzonation studies by OYO (2007) are used to generate a three-dimensional digital velocity model. Firstly, the study area is divided into small cell and the data sets are combined by linear interpolation. The shear wave velocities at each 1 m depth for each observation stations are determined up to the maximum depth reached. Then, the velocity values over the study area for each 1 m depth are interpolated. This procedure successfully generates the three-dimensional digital velocity model.

The ReMi, microtremor and PS Logging test results show that shear wave velocities vary with depth at test location. This means that vertical shear wave velocity profile is known at each observation station. However, this data format makes it difficult to interpolate velocities directly over the study area. Therefore, each velocity profile is discretized into sub-profiles with 1 m thickness. After this discretization, each ReMi, Microtremor and PS Logging test results become usable for interpolation over the study area for each 1 m depth. The maximum depth reached in all ReMi, microtremor and ps log tests is nearly 335 meters. The produced velocity model will correspond to maximum depth of 273 meters. The difference occurs from the interpolation requirements in the proposed procedure. Figs. 15-17 show ReMi test locations, Microtremor test locations and PS Logging test locations, respectively.

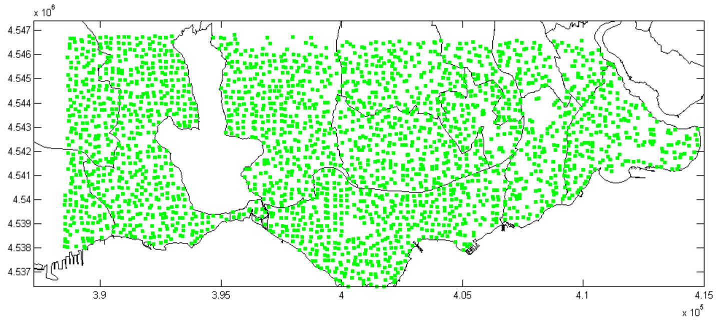

Fig. 15 ReMi test locations over the study area (OYO Int. Corp. 2007)

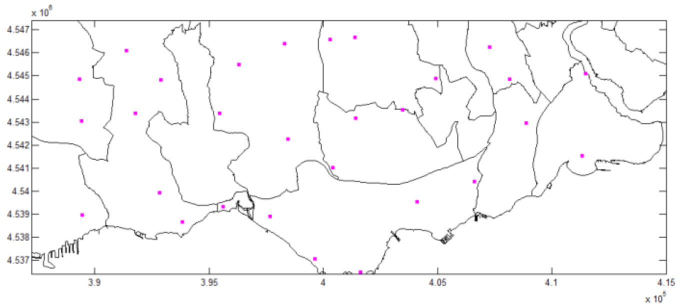

Fig. 16 Microtremor test locations over the study area (OYO Int. Corp. 2007)

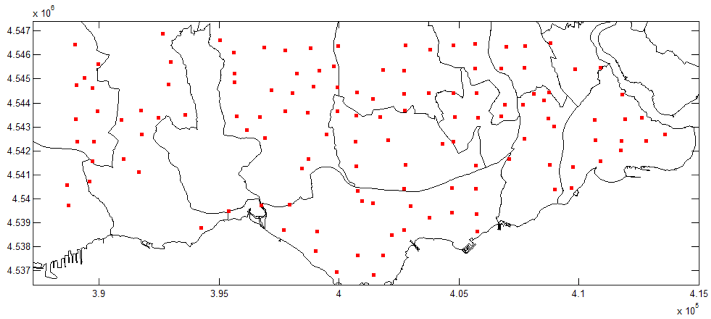

Fig. 17 PS Log test locations over the study area (OYO Int. Corp. 2007)

6.1 Digital velocity model

Three-dimensional digital velocity model includes a volumetric data whose elements correspond to shear wave velocity values at any depth up to 273 meters at any point in the study area as shown in Fig. 18. Dimensions of this volumetric data correspond to lateral dimensions of the study area and examined depth in the area.

The vertical shear wave velocity profile at any point in the study area can be obtained from this digital velocity model. The shear wave velocity profiles along any section may also be illustrated. These sections may be longitudinal X-X sections, latitudinal Y-Y sections or lateral Z-Z sections.

The shear wave velocity distribution at 30 meters depth is shown in Fig. 19. The dashed lines correspond to longitudinal and latitudinal sections passing from the center of the study area.

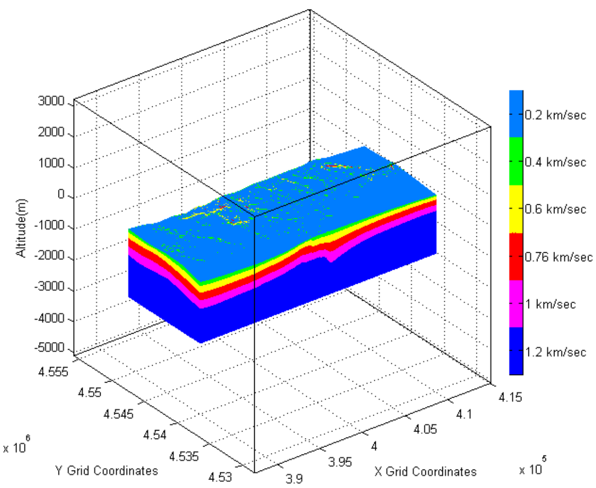

Fig. 18 3D digital velocity model of the study area

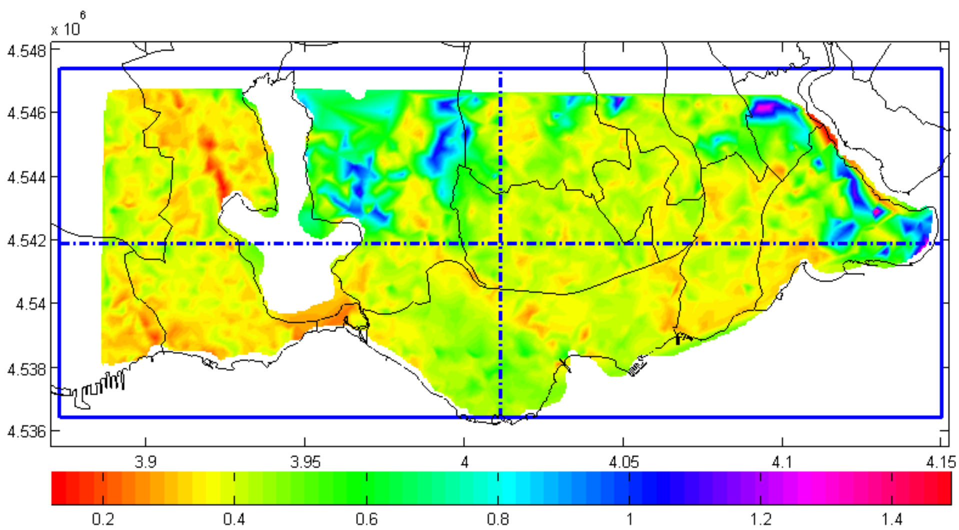

Fig. 19 Shear wave velocity distribution over the study area at 30 m depth

7. Conclusions

With the advances in computing technologies, it is nowadays possible to perform studies that access, interpolate and integrate large scale soil observation data and develop 3D digital models automatically. In this study, an algorithm is proposed for automatic three-dimensional soil and velocity model development of southern part of the European side of Istanbul next to Sea of Marmara based on geographical information system data. In the proposed algorithm, bedrock surface is generated from integration of geological and geophysical measurements. Layer surface contacts are integrated with data gathered in vertical borings, and interpolations are interpreted on sections between the borings automatically. Three-dimensional underground geology model is prepared using these boring data and 3D velocity models are developed by using geophysical measurements. The soil and velocity models are integrated and final soil model is obtained. All stages of this algorithm are carried out automatically. A simulation system with advanced graphical capabilities has been developed based on the proposed algorithm with MATLAB (Sahin *et al.* 2016). The soil and velocity models of southern part of the European side of Istanbul are obtained with the developed system. These models will be a valuable source for future earthquake hazard simulation studies.

Acknowledgments

The models are developed by using the data in Istanbul Metropolitan Municipality (IMM) servers depending on the protocol approved for the MarDiM project (Earthquake and Tsunami Disaster Mitigation in the Marmara Region and Disaster Education in Turkey). IMM is gratefully acknowledged for allowing us to use the database for developing models in this study.

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