Research Article

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GIS based approach to analyze soil liquefaction and amplification: A case study in Eskisehir, Turkey

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Abstract: This study involves gathering the geological and geotechnical data and processing them in 3D structural model for the assessment of the likelihood of liquefaction hazard. A total of 467 borehole logs up to 30 m of depth were analyzed. Based on engineering characteristics of the soil formation, Geographical Information System based subsurface model maps and liquefaction hazard maps were prepared. Also microtremor measurements have been taken on different locations to assess the amplification of the alluvial formation. By obtaining amplification spectrum between the soil layers and response spectra at the top of the bedrock and at ground surface, a thematic map on amplification factor is produced. It is believed such kind of visual models will help engineers and designers on all aspects of future development of the cities especially transportation, infrastructure, and land uses against possible earthquake hazards.

Keywords: Earthquake hazard mitigation, Voxel Analyst, Geographic Information System, Liquefaction, Soil Amplification

1 Introduction

Structural failures during seismic events are mostly attributed to insufficient or incorrect site investigations. To minimize the risk in the computations, a number of geological and geotechnical investigations may be needed [1]. However, several studies have shown that in most cases geotechnical investigations are inadequate as very few resources are committed to the investigation. Geotechnical investigation expenses vary significantly between 0.025%

and 0.3% of the total project cost. Inadequate data on soil properties result in large uncertainties, and large uncertainties result in large construction costs for unknown conditions [2, 18].

Various instrumental field observations have been obtained during recent earthquakes, reflecting the effects of geotechnical site conditions. During earthquakes, soil layers are subjected to multidirectional cyclic stresses with different amplitudes and frequencies that lead to cyclic deformations and changes in stress–strain and strength properties. Earthquake characteristics on the ground surface are mostly affected by the soil layer properties. Numerous strong motion records obtained within relatively short distances from each other have shown that ground motion characteristics differ significantly between nearby locations due to differences in the interactions between the earthquake source, its path and the geological site conditions. Thus, modeling the ground conditions appropriately can control for vulnerability during a seismic event [3].

There have been a number of studies assessing the deterministic and probabilistic seismic hazard risks for the city of Eskisehir of Turkey [4]. An investigation on the hydrogeological and seismotectonic features has been performed and the liquefaction potential map is prepared for the city center of Eskisehir by [5]. To estimate the vulnerability of the building stock, the average acceleration response spectra obtained from site response analyses was used to determine the spectral accelerations for short (0.2 s) and long (1 s) periods. In addition, the risks posed by future seismic events in the area of concern using a probabilistic seismic loss estimation methodology with 13 main and 4 background source zones were evaluated. It's found that peak ground acceleration and MSK intensity were 0.26 g and 7.5, respectively, with a 10% probability of 50 exceedance over 50 years [6].

Geographical Information System (GIS) is a tool that is widely used to plan the proper management of all geographically referenced information [7]. With the development of GIS engineering tools, it is possible to integrate and compare any data with spatial components, re-

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Figure 1: Location of the study area.

regardless of the data's source [8]. Previous studies have attempted to propose 3D models to characterize the site response of various basins [9, 10]. The aim of the present study was to assess liquefaction susceptibility of the city of Eskisehir, which is located on alluvial deposits, in conjunction with amplification phenomena and to develop 2D and 3D model of the sedimentary sequence using GIS methodology. The proposed 3D model describes the geometry and dynamic characteristics of the basin. Ultimately, the findings should provide data for further urban planning studies for the city.

2 Methodology

2.1 Geological setting

We selected a study zone that covered a number of populated districts in the city of Eskisehir, which is located in midwestern Turkey (Figure 1). The Porsuk River divides the city into two parts, and the study area (shaded in yellow in Figure 1) is located in the north of the river. The city's topographic and municipal borders are shown as yellow

lines in Figure 2. The city's altitude ranges from 790-1,010 m; the Porsuk River has an average altitude of 795 m, and the city's highest altitude (1,010 m) is in its northern and northwestern areas.

The geology is formed of loose sedimentary rocks 70 scattered across the plain. The basin's basement consists of Mesozoic gabbro and marble, Eocene and Miocene conglomerates, sandstone conglomerate, claystone marn and limestone. Both younger and older alluvial sequences cover large areas, describing the Quaternary deposits. Pleistocene conglomerates, sands and gravels intercalated with mudstone and caliches have a maximum exposed thickness of about 200 m, and overlie the Miocene and pre-Neocene formations. Uppermost Pleistocene sediments are overlain by 10–90 m thick Holocene alluvium that is comprised of the loose sand and gravel of the Porsuk River [11]. These materials are composed of mixtures of Eocene conglomerates, consisting of gravels embedded in clay soil, and behave like a stiff soil. The upper part of the basin was deposited on a weathered soft Miocene, with the exception of the limestone, which is rather silicified. The old alluvium sequence crops out at a high topographic scarp of the plain; when compared to the young alluvium,

Figure 2: Topographic map of city of Eskisehir.

it is significantly stiffer and seldom involves carbonate-cemented conglomerate layers. The more recent alluvium generally consists of loose sediments and its thickness ranges from 30–40 m at the basin margins and extends up to 90 m toward the center of the basin. Generally, sand containing higher amounts of silt formation is located in the upper layers, between 5–10 m. Sand, including sand containing silt layers, can be encountered as far the lower layers. The fraction of sand increases toward the lower levels, where a gravelly sand layer begins to form [12].

The Inonu, Eskisehir and Alpu basins are confined by faults in the south and north of the study area, which consists of alluvial plains with a total surface area of 639 km² (Figure 3). Two main oblique faults exist throughout the city. The main tectonic fault system of basin trends NW-SE and exhibits normal faulting characteristics with slight lateral components. They form the Eskisehir plain and have inclinations between 60° and 80°. The Eskisehir-Inonu Fault Zone (EIFZ) is the most important fault zone. It is divided into branches and extends as a zone 1–4 km wide, running toward the north. According to current knowledge of the morphological evidence, the position of the ophiolitic rocks and the distribution of the earthquake epicenters, this fault can be classified as an active fault and is assumed to be the seismic source for future earthquakes in the city of Eskisehir [13].

Even though the activity of the faults surrounding the Eskisehir plain is limited and some of its parts are buried by unconsolidated Miocene formations, it is possible that there exists a restricted extensional regime by the NE-SW striking dominant tectonic effect. Prior to the Neotectonic period, the NW-SE trending dextral strike-slip system was transformed into an extensional regime by the effects of the North Anatolian Fault Zone during the Plio-Quaternary; it has been stated that this buried fault acted as a pure strike-slip fault before the Neotectonic period.

2.2 Approach used

We used Voxel Analyst (VA) software for 2D and 3D analysis of the gathered data. VA is specifically designed for volume modeling, analysis of spatial relationships with heterogeneous data volumes, and visualization [14]. It provides tools for loading, modeling, analyzing, manipulating and plotting 3D scientific data. Data can be imported from external 2D and 3D modeling packages in standard ASCII format, and sparse data can be loaded and numerically modeled using several algorithms. Graphic components such as cross-sections, cutting planes, chair displays, iso-surfaces and isosolids can be generated and edited interactively. VA's multithreading capability allows for graphic displays and computations to be done simultaneously. VA

Figure 3: Fault segments in the Eskişehir Fault Zone (Altunel and Barka 1998).

runs as a stand-alone program and it can also import or export data in AutoCAD. VA has geological and geotechnical engineering modeling and analysis capabilities, and more specifically it can evaluate alluvial deposits (gravel, sand, silt and clay). It is also possible to create 3D distributions and calculate the volume of the deposits. The area of the pilot zone is approximately 5.2 km² and covers 18 districts (Figure 4).

3 Results and discussions

3.1 Geological and geotechnical investigation

We split the 5.2 km² study area into 537 grid cells (Figure 5) for the ground modeling; each cell had an area of 0.10 km² (100 × 100 m). Based on a detailed assessment of available geotechnical data, including a total of 467 borehole logs up to 30 m deep, we created representative soil profiles for each cell where one or more borehole data were available, using the most appropriate borehole for each cell. Standard penetration tests (SPT) were performed for every 1.5 m. throughout the entire length of each bore hole [19]. For cells with no borehole data present, we estimated their soil profiles based on those of its neighboring cells by using the inverse distance interpolation method. The ground's top layers, up to a depth of 4–5 m, consisted of fine-grained soils that can be classified as low plasticity

clay-silt, CL-ML according to the unified soil classification system. The sandy layer after this stratum consisted of fine-grained silt grading to coarse-grained sand and gravel in the lower part of the section. The sandy part can be classified as silty sand, SM, where the coefficient of uniformity (C_u) ranged from 4–8, and mean particle diameter (D_{50}) was 0.06–0.5 mm. The thickness of this soil profile ranged from 3–15 m. The depth of the groundwater fluctuated between 3–5 m. The groundwater level is taken 3 m. for the computations (Figure 6).

We performed one-dimensional seismic ground response analysis using “Shake 2000” software to determine the elastic acceleration response spectra on the ground surface [25]. Correlation by [15] was used to correlate the standard penetration resistance with shear wave velocity as:

$$V_s = 51.5N^{0.516} \quad (1)$$

where N represents the uncorrected standard penetration blow counts. We established shear wave velocity values down to the engineering bedrock, with an estimated shear wave velocity of 760 m/s. We also determined that equivalent shear wave velocities for the topmost 30 m ranged from 160–450 m/s. We then compared these calculated shear wave velocity profiles to shear wave velocity data from microtremor array results and modified our profiles if necessary. Representative soil profiles are shown in Figure 6. For each soil layer in the soil profiles, we calculated the total unit weight and shear wave velocity. For

Figure 4: Study area.

Table 1: List of earthquake accelerations used in the study.

Earthquake	Station	Magnitude	Component	PGA (g)
Duzce 11/12/99	531Lamont	7.1	1059E	0.133
Kocaeli 17/09/99	Cekmece	7.4	CNA000	0.18

all types of soil, we used the generic $G/G_{\max}$ and damping curves proposed by [24]. For input motion 1999 Kocaeli and 1999 Duzce earthquake databases were used (Figure 7). The recorded PGA values are given in Table 1. We used these for the rock outcrop motion inputs and scaled the acceleration time history inputs for all cells with respect to the peak accelerations obtained by [20–22].

An assessment of the conditions that will trigger liquefaction is one of the most important steps in any seismic risk project. Over the years, different approaches have been developed to evaluate the liquefaction potential of soil deposits, such as the stress-strain or energy-based methods. Most of these assessment methods were developed based on laboratory and in-situ tests. One of the most popular techniques is a deterministic method termed the

“cyclic stress method” or “simplified procedure;” this calculates both seismic loading and soil liquefaction resistance in terms of cyclic stress. It is a procedure developed by [16] after the devastating 1964 earthquakes in Alaska and Niigata, Japan, uses empirical estimations of filed observations and laboratory investigations. This method compares seismic induced loading, defined in terms of cyclic shear stress, to the liquefaction resistance (cyclic resistance ratio) of the soil. A safety factor of < 1 indicates that potential demand exceeds resistance and that liquefaction is expected to be triggered. This procedure has since been modified and is now a widely accepted method for estimating liquefaction risk [17]. In this study SPT based method was used.

3.2 Liquefaction analysis and mapping

The liquefaction potential index (P_L) is a weighted integration of the liquefaction resistance safety factor within the uppermost 30 m of sediment beneath the site [26, 27]. This method is especially well suited for GIS applications used to evaluate the probability of liquefaction at a given site. The method estimates liquefaction susceptibility based on the penetration resistance of SPT depth measurements,

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN
17																B1														
18												B2	B3	B4	B5	B6	B7			B8	B9	B10								
19														B11	B12	B13	B14	B15	B16	B17	B18	B19	B20	B21	B22	B23	B24	B25	B26	
20														B27	B28	B29	B30	B31	B32	B33	B34	B35	B36	B37	B38	B39	B40	B41		
21															B42	B43	B44	B45	B46	B47	B48	B49	B50	B51	B52	B53	B54	B55		
22															B56	B57	B58	B59	B60	B61	B62	B63	B64	B65	B66	B67	B68	B69		
23															B70	B71	B72	B73	B74	B75	B76	B77	B78	B79	B80	B81	B82			
24															B83	B84	B85	B86	B87	B88	B89	B90	B91	B92	B93	B94	B95			
25															B96	B97	B98	B99	B100	B101	B102	B103	B104	B105	B106	B107				
26									B108	B109					B110	B111	B112	B113	B114	B115	B116	B117	B118	B119	B120	B121				
27					B122				B123	B124	B125					B126	B127	B128	B129	B130	B131	B132	B133	B134	B135	B136				
28						B137	B138	B139	B140	B141	B142	B143				B144	B145	B146	B147	B148	B149	B150	B151	B152	B153	B154				
29					B155	B156	B157	B158	B159	B160	B161	B162	B163	B164	B165	B166	B167	B168	B169	B170	B171	B172	B173	B174	B175					
30		B176	B177	B178	B179	B180	B181	B182	B183	B184	B185	B186	B187	B188	B189	B190	B191	B192	B193	B194	B195	B196	B197	B198	B199					
31	B200	B201	B202	B203	B204	B205	B206	B207	B208	B209	B210	B211	B212	B213	B214	B215	B216	B217	B218	B219	B220	B221	B222	B223	B224					
32		B225	B226	B227	B228	B229	B230	B231	B232	B233	B234	B235	B236	B237	B238	B239	B240	B241	B242	B243	B244	B245	B246	B247						
33		B248	B249	B250	B251	B252	B253	B254	B255	B256	B257	B258	B259	B260	B261	B262	B263	B264	B265	B266	B267	B268	B269	B270						
34			B249	B250	B251	B252	B253	B254	B255	B256	B257	B258	B259	B260	B261	B262	B263	B264	B265	B266	B267	B268	B269	B270						
35				B271	B272	B273	B274	B275	B276	B277	B278	B279	B280	B281	B282	B283	B284	B285	B286	B287	B288	B289	B290							
36				B291	B292	B293	B294	B295	B296	B297	B298	B299	B300	B301	B302	B303	B304	B305	B306	B307	B308	B309								
37							B310	B311	B312	B313	B314	B315	B316	B317	B318	B319	B320	B321	B322	B323	B324	B325								
38							B326	B327	B328	B329	B330	B331	B332	B333	B334	B335	B336	B337	B338	B339	B340	B341								
39										B342	B343	B344	B345	B346	B347	B348	B349	B350	B351	B352	B353	B354								
40										B343	B344	B345	B346	B347	B348	B349	B350	B351	B352	B353	B354	B355	B356							
41											B357	B358	B359	B360	B361	B362	B363	B364	B365	B366	B367	B368	B369	B370						
42										B371	B372	B373	B374	B375	B376	B377	B378	B379	B380	B381	B382	B383	B384	B385	B386					
43										B387	B388	B389	B390	B391	B392	B393	B394	B395	B396	B397	B398	B399	B400	B401	B402	B403	B404			
44								B405	B406	B407	B408	B409	B410	B411	B412	B413	B414	B415	B416	B417	B418	B419	B420	B421	B422	B423	B424			
45									B425	B426	B427	B428	B429	B430	B431	B432	B433	B434	B435	B436	B437	B438	B439	B440	B441	B442	B443	B444		
46									B445	B446	B447	B448	B449	B450	B451	B452	B453	B454	B455	B456	B457	B458	B459	B460	B461	B462	B463	B464	B465	
47										B467	B468	B469	B470			B471	B472	B473	B474	B475	B476	B477	B478	B479	B480	B481	B482			
48										B483	B484					B485	B486	B487	B488	B489	B490	B491	B492	B493	B494	B495				
49										B496	B497					B498	B499	B500	B501	B502	B503	B504	B505	B506	B507	B508				
50									B509							B510	B511	B512	B513	B514	B515	B516	B517	B518	B519	B520				
51																B521	B522	B523	B524	B525	B526		B527	B528	B2529					
52																		B530	B531	B532	B533				B534					
53																				B535	B536									
54																				B537										
	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	

Figure 5: Cell locations and borings. The pink colored cells indicates that the data for this boring selected from neighbouring cells. The yellow colour cells shows the boring is located in the same cell.

and determines the index related to that site on the ground surface. The calculations was based on the procedure formerly proposed by [28] using the variation of the safety factors with depth. The liquefaction potential index, P_L , defined as

$$P_L = \int F(z) w(z) dz \quad (2)$$

where z is the below the ground water surface, measured in meters; $F(z)$ is a function of the liquefaction resistance factor, F_L , where $F(z) = 1 - F_L$ but if $F_L > 1.0$, $F(z) = 0$; and $w(z) = 10 - 0.5z$. Eq. (2) gives values of P_L ranging from 0 to 100. F_L is the factor of safety against liquefaction.

The liquefaction susceptibility criteria based on liquefaction potential index is presented in Table 2. The site may then be spatially located by determining the geographic coordinates, and together with all of the boring informa-

tion, the P_L then becomes an additional feature connected to the spatial element. The index value characterizes the site at the ground surface since the weighting function used by the P_L has its maximum value at the ground surface, giving more weight to $(1 - F_L)$ values at shallow depths.

We mapped the distribution of the likelihood of liquefaction at any given location in the form of P_L contours, which we produced using the results of the SPT measurements as discrete values. These P_L contours thus divide areas that are anticipated to experience different degrees of liquefaction. In addition, once a P_L contour map is generated, other useful GIS-based spatial analysis operations may be performed, such as overlays with other GIS coverage containing the geospatial locations and attribute

Figure 6: Variation of soil profile and shear wave velocity.

Table 2: Liquefaction susceptibility classification developed by [28].

Liquefaction potential index (I_L)	Susceptibility
$I_L = 0$	Very low
$0 < I_L \leq 5$	Low
$5 < I_L \leq 15$	High
$15 < I_L$	Very high

databases of civil engineering facilities, lifelines or populations at risk [23].

We performed the liquefaction susceptibility assessment for the uppermost 30 m of submerged silty sand and sandy sediments. We found that the existence of a shallow groundwater table in the alluvial layers along with shallow-seated silty sand levels showed a high potential for liquefaction. Our analyses also revealed that some parts of the study area close to the Porsuk River on the west were sensitive to liquefaction. In the case of a peak ground

acceleration close to $a_{\max} = 0.40$ g, a much larger area would also be affected by liquefaction.

We evaluated the amplification factor (i.e., the ratio of the peak horizontal acceleration at the ground surface to the peak horizontal acceleration at the bedrock) for each borehole. Microtremor array measurements conducted at six different points had different soil profiles, ranging from soft soil to soft rock. Figure 8 shows that the peak horizontal acceleration (PGA) values at the bedrock level were amplified at various locations; the amplification factors ranged from 2.5–4 and the spectral accelerations at 0.1 s ranged from 0.49–0.51. We then divided the study area into three zones based on the liquefaction susceptibility and range of amplification 209 factors assigned to each zone.

Figure 9 shows the liquefaction potential index parameters for predicting the occurrence of liquefaction in a 2D map. Figure 10 shows the liquefaction-prone zones, as evaluated using a the safety factor method in a 3D map. Because the degree of damage due to liquefaction is significantly affected by the severity of liquefaction at differ-

Figure 7: Acceleration time histories and their respective acceleration response spectra used as input motion in the site response analysis.

Figure 8: Settlement suitability map and amplification factors.

ent soil layers, the liquefaction potential index (which is proportional to the thickness and depth of the liquefiable layer), along with the safety factor, provide an estimate of the continuous volume of liquefiable soil deposit and an estimate of the interpolation confidence. The grids selected showed very low to very high degrees of liquefaction susceptibility in the city of Eskisehir. Zones with a

high liquefaction susceptibility were found in some northern and western parts of the studied area. However, the 3D map makes it is easy to see the depth and thickness of the liquefiable layers. By identifying the thickness of the potentially liquefiable layer, it is thus easy to anticipate the liquefaction-induced settlement on the ground surface. This 3D information visualization data can help de-

Figure 9: 2D Liquefaction susceptibility map.

Figure 10: 3D map of liquefaction prone zones.

signers, engineers and even policymakers to understand the safety precautions necessary to minimize risk in case of a seismic event.

4 Conclusion

The purpose of this study was to better understand the city of Eskisehir's geotechnical soil conditions in order to evaluate their vulnerability in case of an earthquake. This pilot study is the first phase of a project that will consider both geotechnical conditions and a liquefaction hazard assessment. By using datasets in a 3D environment, 233 we found that it was possible to capture and interpret 3D subsoil conditions that allowed for spatial analyses of geological architectures and processes at a range of scales. The 3D subsoil conditions can also help engineers during infrastructure construction projects, thereby allowing them to take necessary precautions. This evaluation of subsurface condition uncertainties was much easier than using other 2D techniques. The zone maps that we produced in this study are based on currently available data, knowledge and practice. They can be changed or modified at any time as new data or methods are presented. However, these maps can be useful for defining the steps that are needed to improve existing building codes and to develop new codes, as well as to raise awareness about earthquake hazards among the public, policymakers, land-use planners and local governments.

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