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Integrated seismic risk analysis using simple weighting method: the case of residential Eskişehir, Turkey

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Abstract

A large part of the residential areas in Turkey are at risk for earthquakes. The main factors that threaten residential areas during an earthquake are poor quality building stock and soil problems. Liquefaction, loss of bearing capacity, amplification, slope failure, and landslide risks must be taken into account for residential areas that are close to the fault zones and covered with younger sediments. If these risks were separately analyzed and these analyses were combined, this would be more realistic than analyzing several hazard maps based a single parameter.

In this study, an integrated seismic hazard map of central Eskişehir was created based on two earthquake related parameters, liquefaction, and amplification, by using a simple weighting method. Other earthquake-related problems such as loss of bearing capacity, landslides, and slope failures are not significant for Eskişehir because of the geologic and the topographic conditions of the region. According to the integrated seismic hazard map of the Eskişehir residential area, the area is found to be generally at medium-high risk during a potential earthquake.

1 Introduction

Population growth accompanied by economic and social development triggers the growth of urban residential areas in particular. Therefore, this brings about the need for the design of new residential areas and the establishment of new city centers. While planning new residential areas, on the other hand, the protection of the existing and planned areas against potential disasters is of vital importance. When the location and the recent history of Turkey are taken into consideration, earthquakes come to the forefront among the disasters having the risk factor for the design of new residential areas.

The balance between human activity and the environment is often disturbed by the urbanization efforts (Mulder, 1996; Topal et al., 2003; Mulder and Pereira, 2009; Park

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et al., 2011; Erol and Topal, 2012). The decrease of this imbalance and its effects on the environment is possible through the multivariate urban planning (Erol and Topal, 2012; Bell, 1998; Bell et al., 1987). Geological and geotechnical data is also of great importance in terms of identification, control, vitiation, and prevention of geological hazards (Erol and Topal, 2012; Bell et al., 1987; Bell and Pettinga, 1985; Legget, 1987; Hake, 1987; Rau, 1994; Dai et al., 1994; Van Rooy and Stiff, 2001; Kılıç et al., 2006; Ulaş and Kılıç, 2008; Marker, 2009; Bell et al., 2009). In multivariate urban planning, multivariate soil risk analysis is also crucial for the prevention of potential impacts and for sound settlement.

On 20 February 1956, an earthquake of magnitude 6.4 took place in the Eskişehir city center. The earthquake heavily damaged 393 buildings in the city, rendering them unusable (Öcal, 1959). Furthermore, Eskişehir was classified as a second-degree seismic zone in the seismic hazard map according to the 1997 Bylaw on Buildings to be Constructed in Disaster Areas (DBYBHY, 1997).

During earthquakes, ground conditions of the residential areas are also the primary reason for damages, as well as the poor quality building stock. The damages caused by local ground conditions during an earthquake include the amplification impact of local conditions on seismic wave, loss of shear strength in a subsurface layer due to liquefaction, strong ground displacements resulting from slope failures and landslides, and foundation settlements driven by ground compaction (Beliceli, 2006). Since Eskişehir's residential area largely sits on level land, the risk of slope failure and landslide is much lower compared to the risk of earthquake. The reason for the variation of earthquake-induced damage across the region is soil liquefaction and amplification due to soil characteristics. Therefore, soil liquefaction analyses were conducted on 87 wells at a depth of 30 m for Eskişehir and its surroundings and an integrated hazard assessment of the soil structure during an earthquake was developed through site amplification characteristics derived from 23 seismic refractions again using 87 wells at a depth of 30 m.

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Within the scope of this study, the liquefaction index (LI) values acquired through the Standard Penetration Test (SPT) and the method proposed by Iwasaki et al. in 1978 and 1982 (Iwasaki et al., 1978, 1982) are classified based on the degrees of liquefaction potential proposed by Sönmez in 2003 (Sonmez, 2003).

The site amplification map, on the other hand, was developed by using V_{s30} values derived from seismic refraction measurements and empirical V_{s30} values derived from SPT values of the wells in the study area, using the methodology of Borchardt (1991) (Borchardt et al., 1991) within the context of another study carried out by Mutlu in 2012 (Mutlu, 2012). This study classifies the degree of seismic amplification potential of soil sites.

Study area

Eskişehir is a rapidly growing city located in northwestern Turkey, and a second-degree seismic zone under the risk of earthquakes (Fig. 1). The Porsuk Creek in the region flows through the city from the southwest, running through the city center and exiting from the east. Another important stream in the study area is the Sarisu Creek, a tributary of the Porsuk. Sarisu Creek, which runs from west to east, is effective in carrying and depositing alluvial sediments, which form the ground surface of the northwestern city center.

The damage and loss of life caused by earthquakes are more concentrated in residential areas underlain by soft soils (Borchardt, 1994). Earthquake-induced liquefaction appears on sandy soil whereas site amplification occurs on loose soils such as alluvial soils, including sands. Hence, the area to be analyzed should be assessed geologically. The geology of the study area, Eskişehir and its surroundings, consists of five geological formations from old to young, which are the Karkin Formation, Mamuca Formation, Porsuk Formation, Ilica Formation, and Akcay Formation (Fig. 2) (Tokay and Altunel, 2005). The city is underlain by the old Alluvial (Akcay) Formation of the Pleistocene age and the old New Alluvial (Porsuk) Formation of the Pliocene age, discordant to the underlying rock units and Middle-to-Upper Miocene deposits. The Akcay Formation is

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comprised of loosely consolidated clay, silt, sand, and gravels. The formation is in the form of terraces at the heights around the river basin. Porsuk Formation, on the other hand, is made up of the sediments carried and deposited by the Sarisu Creek and Porsuk Creek and its branches (Tosun et al., 2007). This unit overlays a large part of the Eskişehir city center (Fig. 2).

The study area was selected as the area covered by the old and new alluvial formations, taking the residential areas into consideration, and marked by a frame on the geological map (Fig. 2). While loose sand and low plasticity levels are found at the new alluvial unit, ground water levels are low because the city center is located along the banks of the Porsuk and Sarisu Creeks. Thus, areas with waterlogged loose sand and low plasticity levels pose a liquefaction risk (Bayrakçı et al., 2013).

There are several methodologies to assess the site amplification hazard. According to Abrahamson and Silva in 2008 (Abrahamson and Silva, 2008), the coefficient of site amplification is a function of the average shear wave velocity over the upper 30 m of soil. Another approach recommended by Borchardt (1994) (Borchardt, 1994) assumes that the soil sites having a wide range of shear wave velocity profile have typical behaviors that represent a certain site class. In this method, the empirical amplification factors are calculated by the potential acceleration spectrum at the bedrock level, features of the spectrum profile and the average shear wave velocity measured over the upper 30 m (Ansal, 2011). Site amplification hazard in the study area may also occur in the Old Alluvial (Akçay) formation in the central, western and northwestern parts of the city, as well as in the New Alluvial (Porsuk) formation.

2 Methodology

2.1 Site amplification

Site amplification means the increase in the amplitude of the earthquake-induced seismic waves while passing through the soft subsurface soil layers. It has been defined as

a function of the shear wave velocity for the soft layer of the upper 30 m of the surface (V_{S30}) by several researchers at different times (Borcherdt et al., 1991; Midorikawa, 1987; Joyner and Fumal, 1984).

Figure 3 shows that the site amplification formula based on shear wave velocity of Borcherdt (1991) (Borcherdt et al., 1991) gives a higher amplification value compared to the formulas of other researchers. This indicates that the site amplification calculation by using Borcherdt's (1991) formula provides more accurate risk assessment. Borcherdt's (1991) formula was used also in the site amplification analysis based on the shear wave velocity within the context of the study.

V_{S30} may be calculated empirically depending in different site categories by the standard penetration test values of the wells (SPT-N) (Jafari et al., 1997; İyisan, 1996; Kanai, 1996; Lee, 1990; Seed and Idriss, 1982; Ohta and Goto, 1978; Imai, 1977; Imai et al., 1975; Ohsaki and Iwassaki, 1973; Ohba and Toriumi, 1970) or directly by the seismic refraction method.

The soil with the V_{S30} velocity below 700 m s^{-1} is defined as the soft stratum. Formations with shear wave velocities above 700 m s^{-1} are considered as "engineering rock" (Beliceli, 2006). Site amplification risk is posed for the formations of which V_{S30} value is below 700 m s^{-1} .

Site amplification generated on areas underlain by young geological sediments by the earthquake-induced ground motions is correlated by the shear wave velocity. Based on this correlation, the NEHRP (National Earthquake Hazards Reduction Program) adopted a classification, also used in the 1997 UBC (Uniform Building Code), based on the average shear wave velocity for the upper 30 m. of the soil. The West and Central US State Geologists Earthquake Consortium (CUSEC) has also produced an amplification classification based on this classification generated based on the average shear wave velocity for unconsolidated sediments. This sample study carried out in Eskişehir's central residential area uses amplification values varying between 0–3.5. In weighting adjustments, the higher the site amplification values based on the site

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$$FS = \frac{(CRR)_{7.5}}{(CSR)} \cdot MDF. \quad (3)$$

CSR and CRR in the equation is given by the Eqs. (4) and (5).

$$CSR = 0.65 \cdot \frac{a_{\max}}{g} \cdot \frac{\sigma_{v0}}{\sigma'_{v0}} \cdot r_d [11] \quad (4)$$

In this equation, a_{\max} stands for the maximum horizontal acceleration on the ground surface, σ_{v0} for the total vertical stress, σ'_{v0} for the effective vertical stress, g for gravity acceleration, and r_d for the stress reduction factor based on the depth from the surface (Seed and Idriss, 1971).

The CRR value is calculated by Eq. (5) for magnitude 7.5 earthquakes (Mollamahmutoğlu and Babuçcu, 2006). Some corrections are needed for the raw SPT in order to determine the CRR based on the SPT. These corrections rely upon the analysis based on the corrected SPT-N (N_1)₆₀ proposed by Youd et al. (2001) and accepted worldwide.

$$CRR = \frac{1}{34 - (N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{(10(N_1)_{60} + 45)^2} - \frac{1}{200} \quad (5)$$

In accordance with the General Format for Soil and Ground Study Report issued by the Ministry of Public Works and Settlement in 2005, the drilling depth cannot be less than 20 m in First and Second Degree Earthquake Zones on account of liquefaction. Since Eskişehir lies in a second-degree earthquake zone, drilling used for the analyses were selected pursuant to this communique. All of the liquefaction analyses were done from the drilling that reached a depth of 20 m.

3 Data

The data of the 87 drillings in central Eskişehir were derived from two separate projects. The data of the 72 drillings were acquired within the context of the project titled “Micro

Zoning and Hazard Assessment Studies to Mitigate Disaster Damages”, supported by the Turkish Prime Ministry, while the other 15 were within the context of the Scientific Research Project No. 80200040 of the University of Anatolia. A total of 87 wells were assessed in terms of liquefaction analyses.

Amplification analyses were performed using 23 seismic refraction sections by Mutlu (2012) and 87 wells, which were also assessed within this study.

4 Findings

4.1 Site liquefaction analysis

LI values were acquired for the drilling in the region through the liquefaction analysis proposed by Iwasaki et al. (1978, 1982) (Table 3).

The LI values set forth were interpolated by the inverse distance weighting method (IDW) and a liquefaction potential map was created for the Eskişehir city center through the classification proposed by Sönmez (2003) (Fig. 4).

Regarding the liquefaction potential map, regions having mainly mid-high liquefaction risk were found in the central, western, and northwestern parts of the study area. The eastern part of the region has a relatively lower liquefaction risk (Fig. 4). A large part of the Porsuk Creek and its surrounding was found to have a moderate liquefaction risk. This part is where the thickness of the young alluvium is the greatest.

4.2 Site amplification analysis

Pursuant to the Borcherdt et al. (1991) methodology, amplification values calculated by shear velocities given by both the drilling and the seismic refractions were mapped using the IDW method (Fig. 5). Regarding the analysis, regions with high amplification having an amplification value of 1.5–1.7 according to Table 2 are located in the young alluvium close to the Porsuk Creek, which is at the center of the study area and in the

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insufficient. For instance, while the northwestern part of the city overlain by the old alluvial is not threatened by the liquefaction risk, it is at high amplification risk associated with a low shear velocity value. It is a crucial soil problem of the region that requires attention. The hazard map and the other maps should be used for an overall assessment in order to settle the residential area. Local drilling and comprehensive soil analyses should be performed for detailed studies.

The variables of the risk assessment studies should be increased based on developing technologies and information. This will enable the achievement of real life solutions and prevent potential problems.

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Table 1. Amplifier classification table.

NEHRP site class	Physical description (Borcherdt, 1994)	Expected site amplification (CUSEC)	Site amplification class
A	Hard Rock	0.8–1.0	None
B	Firm to Hard Rock	1.0–1.3	Low
C	Gravelly Soils and Soft Rock	1.3–1.7	Moderate
D	Stiff Clays and Sandy Soils	1.7–2.4	High
E1	Soft Soils (≤ 37 m thick)	2.4–3.5	Very High
E2	Soft Soils (> 37 m thick)	2.4–3.5	

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Table 2. Degrees of liquefaction potential (Sonmez, 2003).

Liquefaction potential index (LI)	Liquefaction potential
0	Non-liquefiable
$0 < LI \leq 2$	Low liquefiable
$2 < LI \leq 5$	Moderate liquefiable
$5 < LI \leq 15$	High liquefiable
$15 < LI$	Very high liquefiable

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Table 3. Liquefaction index values acquired across a 20 m depth.

Drilling	LI	Drilling	LI	Drilling	LI	Drilling	LI
SK-1	0	SK-23	7.232	SK-45	0	SK-67	0
SK-2	0.0244	SK-24	0.014	SK-46	2.252	SK-68	0
SK-3	0	SK-25	2.92	SK-47	0	SK-69	0.225
SK-4	0	SK-26	3.504	SK-48	1.575	SK-70	0
SK-5	1.595	SK-27	0	SK-49	0	SK-71	1.533
SK-6	0	SK-28	0.254	SK-50	2.558	SK-72	0.964
SK-7	0	SK-29	1.889	SK-51	0	SK-73	9.757
SK-8	0	SK-30	0.563	SK-52	0	SK-74	3.311
SK-9	0	SK-31	3.251	SK-53	0.02	SK-75	0.309
SK-10	0	SK-32	0.734	SK-54	7.303	SK-76	2.579
SK-11	0	SK-33	0	SK-55	15.918	SK-77	0.042
SK-12	0	SK-34	1.603	SK-56	9.195	SK-78	3.675
SK-13	0	SK-35	0	SK-57	0.037	SK-79	0.04
SK-14	0	SK-36	0	SK-58	0	SK-80	3.793
SK-15	0	SK-37	0	SK-59	0.065	SK-81	0
SK-16	0	SK-38	0	SK-60	1.392	SK-82	0
SK-17	0	SK-39	0	SK-61	12.109	SK-83	10.799
SK-18	0	SK-40	0	SK-62	0	SK-84	0.116
SK-19	0	SK-41	0	SK-63	0.014	SK-85	3.964
SK-20	0	SK-42	0	SK-64	0	SK-86	0
SK-21	0.083	SK-43	3.759	SK-65	0	SK-87	0.018
SK-22	0.449	SK-44	16.642	SK-66	9.971		

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Table 4. Classifications and simple weighting points used in the analyses.

Liquefaction potential class	score	Amplification potential class	score	Risk class	score
None	1	None	1	Very low	1
Low	2	Low	2	Low	2
Moderate	3	Moderate	3	Moderate	3
High	4	High	4	High	4
Very High	5	Very High	5	Very High	5

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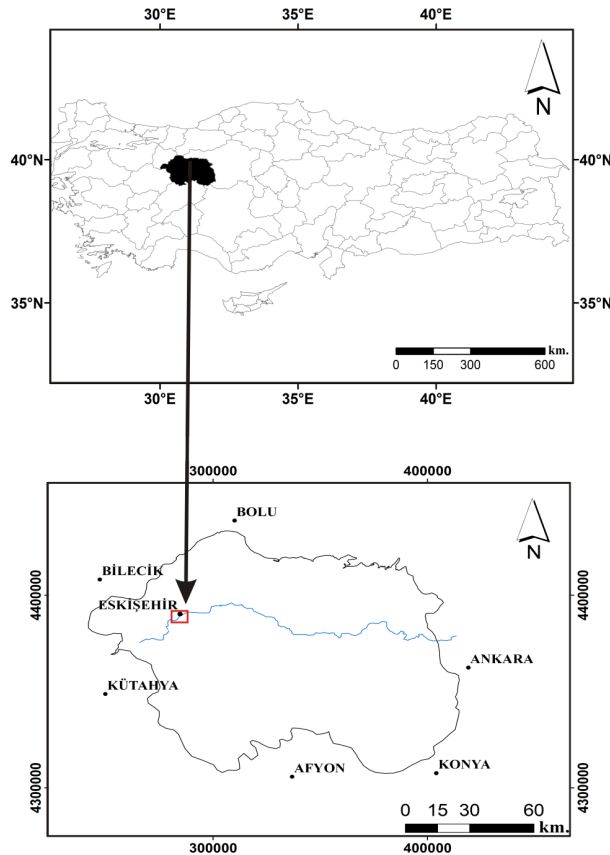


Figure 1. Site location map of the study area.

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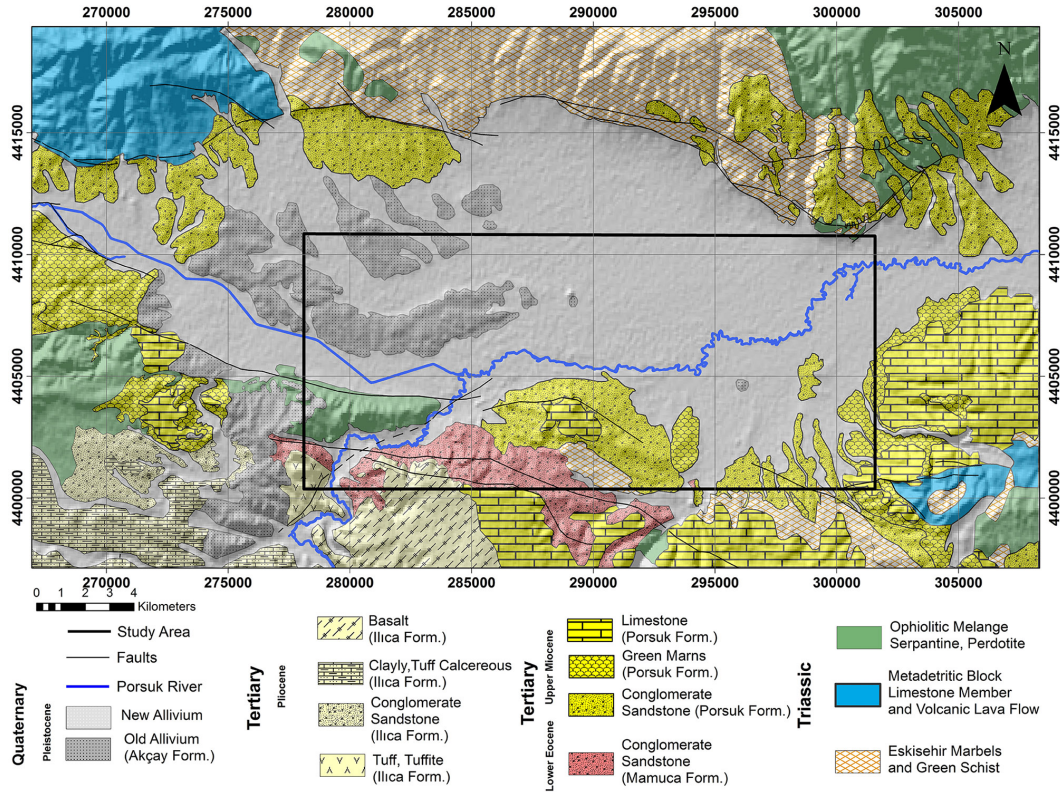


Figure 2. The geological map of Eskişehir (modified from Orhan et al., 2007).

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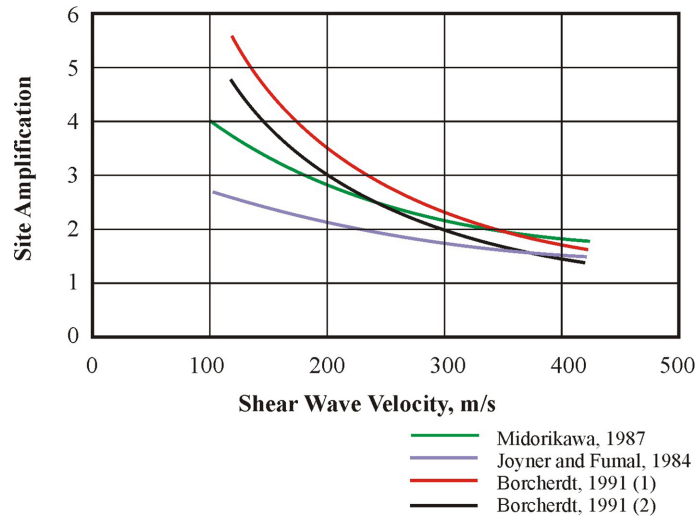


Figure 3. Modification of site amplification calculation based on shear wave velocity (Beliceli, 2006).

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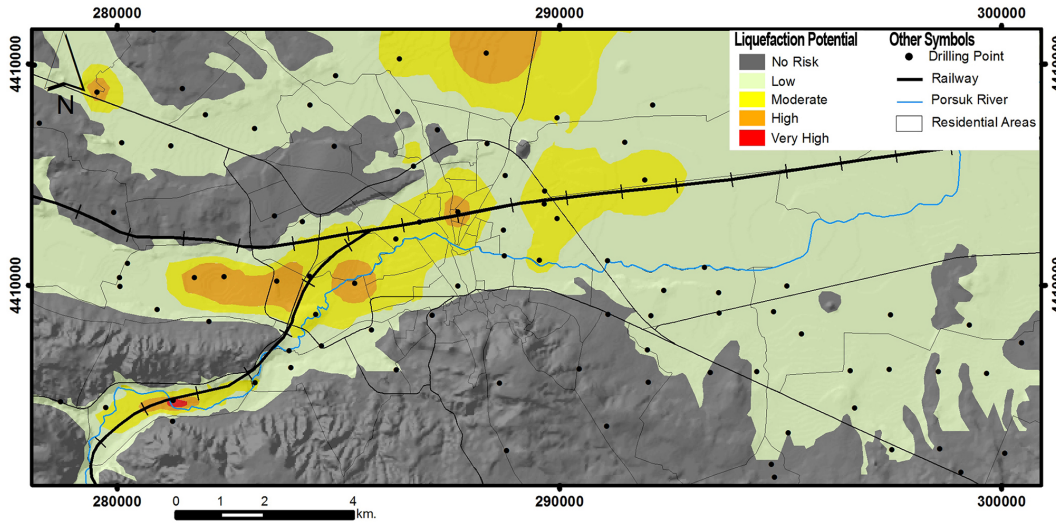


Figure 4. Liquefaction potential map acquired through the IDW method.

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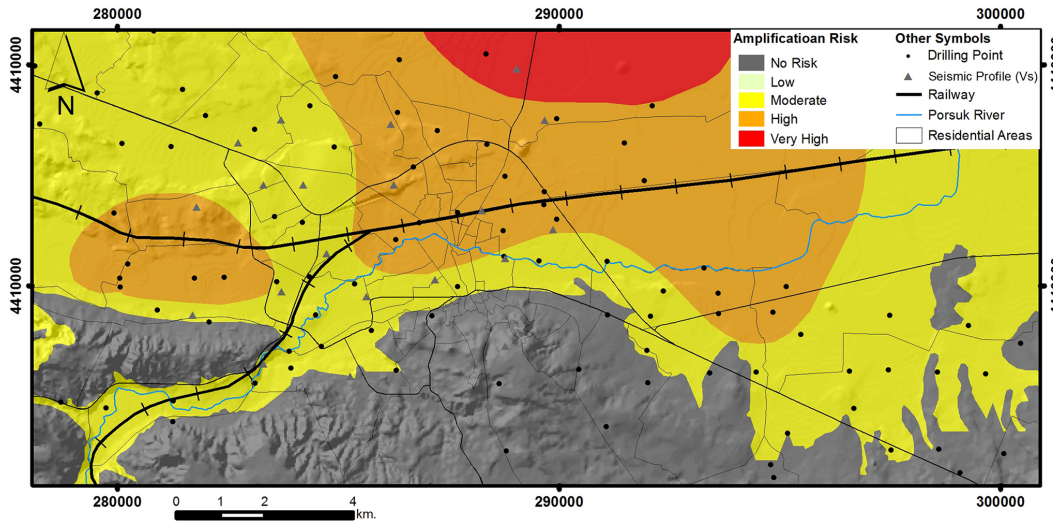


Figure 5. Amplification risk map acquired through the IDW method.

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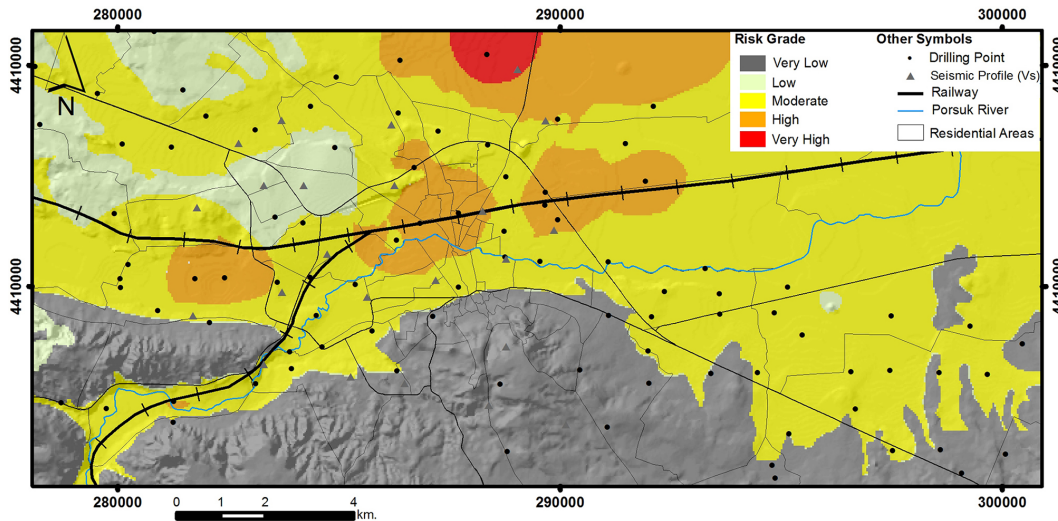


Figure 6. Hazard map produced through overlaying of liquefaction and amplification values on a given rate.

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