Site Specific Ground Motion Modeling and Seismic Response Analysis for Microzonation of Baku, Azerbaijan

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A b s t r a c t

We investigated ground response for Baku (Azerbaijan) from two earthquakes of magnitude $M6.3$ occurred in Caspian Sea (characterized as a near event) and $M7.5$ in Shamakhi (characterized as a remote extreme event). S -wave velocity with the average shear wave velocity over the topmost 30 m of soil is obtained by experimental method from the V_p values measured for the soils. The downtown part of Baku city is characterized by low V_{s30} values (< 250 m/s), related to sand, water-saturated sand, gravel-pebble, and limestone with clay. High surface PGA of 240 gal for the $M7.5$ event and of about 190 gal for the $M6.3$ event, and hence a high ground motion amplification, is observed in the shoreline area, through downtown, in the north-west, and in the east parts of Baku city with soft clays, loamy sands, gravel, sediments.

Key words: Baku, Azerbaijan, peak ground acceleration, site amplification, strong ground motion.

1. INTRODUCTION

Densely populated cities situated in seismic areas characterized by the occurrence of earthquakes with moderate intensity always raise big issues in terms of seismic hazard and risk, making the earthquake disaster preparedness really challenging for decision makers. This is the reason why seismic microzonation has been becoming a widely used methodology for predicting the seismic hazard of an area in order to mitigate the earthquake disaster and assess the seismic risk. One recent example is given by Shiuly *et al.* (2014), who computed the ground motion amplification scenario of sedimentary deposits for the seismic microzonation of Kolkata Megacity (India), located on the world's largest delta island with very soft soil deposit.

Baku is the capital of Azerbaijan, and is one of the fastest growing cities of the country. It lies in one of the seismic zones of Azerbaijan, Absheron peninsula, which is situated on the NW part of the South Caspian region (Babayev *et al.* 2010). Recently, Telesca *et al.* (2012) performed a detailed study of temporal properties of its historical and instrumental seismic catalogue. Although earthquakes of very low intensity from its own focal zone occurred in the peninsula, a potential seismic hazard can arise from the active focal zones of the Caspian Sea and Shamakhi-Gobustan (Fig. 1). We can identify two sources of earthquake activity in the area: the subduction zone (Jackson *et al.* 2002) and shallow crustal faults.

Baku is situated in the trough representing a fan-shaped depression, as a result of the presence of north-western dislocations which occur from the western and eastern fault systems (Shikhalibeyli 1996, Babayev *et al.* 2010), and the whole Absheron zone with Baku city is mostly compressed with the thrust and reverse faults (Babayev *et al.* 2010). The shallow substrate of the city is mainly represented by deposits of Quaternary age composed by sands, gravel-pebble, and limestone with clay and intercalated layers of sand and rubble and water-saturated sand (Babayev *et al.* 2010). Since soft sediments, responsible for the great amplification of seismic waves, represent a very large fraction of the soil, it is crucial to investigate their site effects on the region (Subhadra *et al.* 2015). Furthermore, Baku city (the investigated area is indicated by the black rectangle in Fig. 2) is subjected to a continuous increase of urbanization that should be taken into account along with the large seismic potential of the region around, struck by rather intense earthquakes during 1842 (M_s5), 1902 ($M_s7.5$), 1910 ($M_s4.9$), 1922 (M_s5), 1935 ($M_s3.5$), 1937 (M_s5), 1946 ($M_s5.1$), 1958 ($M_s2.9$), 1971-1973 ($M_s5.1-5.6$), 1979 ($M_s4.4$), 1983 (M_s5), 1992 ($M_s4.5$) (Babayev 2010, Babayev *et al.* 2010, Babayev and Telesca 2014, Gasanov 2003). In this study, for the earthquake scenario we use macroseismic parameters of 1902 Shamakhi earthquake ($M_s7.5$) and those of the South Caspian 2000 earthquake ($M_s6.3$), because

Fig. 1. Absheron peninsula with earthquakes' distribution for the period 1842-2014 (Babayev and Telesca 2014).

Fig. 2. Map of the Absheron peninsula. The investigated area is indicated by the black rectangle.

Absheron peninsula experienced these earthquakes with intensity effects of V-VI (1902 Shamakhi earthquake) and of VI-VII (2000 Caspian earthquake) on its area, and because of the regional fault system. In particular, during the strong 2000 Caspian earthquake 35 people were killed and more than one thousand buildings were severely damaged (Babayev *et al.* 2010). So, there is a high possibility that these earthquakes might re-occur in the future with a similar or higher magnitude level.

The city of Shamakhi (situated about 110 km west of Baku, Fig. 3) was struck by strong seismic events in the past: in 1191, 1667, and 1859 (Veber 1904). On 13 February 1902, a catastrophic earthquake (Shamakhi earthquake) occurred in the region (intensity = $X_{\text{(Rossi-Forel scale)}}$) (Boghdanovitch 1904). The event destroyed completely all the buildings located around the epicenter, and several rockfalls, landslides and eruptions of mud volcanoes occurred; also moderate ground shaking was felt in Baku city. Its surface magnitude was estimated as 6.9 ± 0.2 (Kondorskaya and Shebalin 1982); however, considering that the ground shaking lasted for approximately 30-40 s and the ruptured area was about 80 km long, its magnitude could be estimated as 7.5 (Levitski 1902, Boghdanovitch 1904, Babayev *et al.* 2010).

Fig. 3. Topographic map of South Caspian Region. The white lines indicate the main Quaternary faults of the area. The map shows the epicenters of the two seismic events that occurred in 2000 (yellow stars). The red stars indicate the epicenters of other large events that struck Absheron peninsula in 1191, 1667, 1859, and 1902. The marked box indicates the investigated area (tectonics modified after Jackson *et al.* 2002, Babayev *et al.* 2010, 2014).

Thus, even though Baku city, Absheron peninsula, and adjacent Caspian Sea are characterized by moderate seismicity, with intensity of VIII on the MSK-64 scale, the region is considered to be at a high seismic risk due to infrastructures' high vulnerability.

Subsurface ground conditions can be considered as being mainly responsible for the effects of potential earthquakes (Subhadra *et al.* 2015). Secondary wave velocity with the average thickness of 30 m of soil (V_{S30}) is a parameter that significantly influences the amplification factor of the site and the level of ground shaking. The values of the near-surface S -wave velocity are generally used to assess seismic hazard of the site. On the basis of many earthquake scenarios it is well known that it is the amplification of ground motion, especially that generated by soft soil layers, that is mainly responsible for the damage on buildings and structures, as it was observed from earthquakes that occurred in Mexico, Japan, USA, and Turkey (Subhadra *et al.* 2015). Therefore, it is highly recommended to estimate the site effects and understand the soil performances during strong shaking, in order to mitigate the level of earthquake disaster. In this research, we calculated the S -wave velocity, performed the site response assessment, and calculated the Peak Ground Acceleration (PGA) for scenarios of two earthquakes which were felt in Baku city and we analyzed their distribution through the city both at bedrock and surface ground levels. Furthermore, we used the software SHAKE2000 (Ordonez 2010) to carry out the 1-D response of the site at depths ranging between 20 and 50 m below ground level. We determined the amplification factor and calculated the accelerograms in a subsurface layer.

2. METHODOLOGY

2.1 Modeling parameters for earthquake scenarios

The determination of acceleration of the surface motion in the investigated area was based on the analysis of local site effects, geological settings of the surface, amplification factor, and the seismic response of subsurface soil. In our models, the areal extension of the examined area was 2800×2000 , so it was gridded into 28×20 square cells (with side size of 100 m) (Fig. 2).

Since the seismic data are few and the strong earthquakes are generally associated with local irregularities, we employed a scenario-based deterministic approach (Babayev and Telesca 2014). For this strong motion simulation, we select near-field and remote (extreme) target earthquake scenarios. We selected the target earthquakes taking into account their distance from Baku, their magnitude, their effects on the investigated area, the event location in relation to the regional fault system, and their re-occurrence within a certain time interval (Babayev *et al.* 2010). We consider the Caspian earth-

quake occurred in 2000 (with magnitude 6.3 and epicenter at about 35 km from Baku) as a near event (Fig. 3, indicated by yellow star), and a hypothetical event of $M7.5$ occurred in Shamakhi (at about 110 km from Baku) as an extreme (remote) event (Fig. 3, indicated by red stars). The disaster caused by the recent $M7$ Haiti earthquake that occurred on 12 January 2010, is a clear example of the need to consider historical extreme events in this type of studies. In fact, the probabilistic seismic hazard model that was built for Haiti's area did not consider historical large seismic events; therefore, the surface PGA was absolutely underestimated (USGS 2010). In this study we modeled ground motion for each cell of the city in terms of PGA both at bedrock and surface ground levels using the parameters of the above-mentioned two target earthquakes. To estimate the expected PGA at bedrock, we used the following relationship (Aptikayev and Kopnichev 1979):

$$\log A = \begin{cases} 0.28M - 0.8 \log R + 1.7, & A > 160 \text{ gal} \quad (\text{for near-field events}) \\ 0.28M - 2.3 \log R + 0.8, & A < 160 \text{ gal} \quad (\text{for far-field events}) \end{cases} \quad (1)$$

where A is measured in gal and the hypocentral distance R in km. This relationship can be adapted to a wide range of bedrocks from soft to hard, as Baku city is characterized. Comparing Eq. 1 with the following relationship empirically obtained for Japanese intra-plate earthquakes (*e.g.*, Tonouchi and Kaneko 1984)

Fig. 4. Comparison of acceleration formula depending on the distance calculated for $M6.3$ (near event) and $M7.5$ (remote event) earthquakes. The curves labeled 1 and 2 indicate the “near” and “remote” earthquakes from Baku, respectively, and are obtained applying relationship 1. The curves labeled as 3 and 4 indicate the Japanese intra-plate earthquakes occurred at the depths of 35 and 55 km, respectively, obtained using Eq. 2.

$$\log A = 0.5M + 0.0043H - \log(R + 0.0055 \times 10^{0.5M}) - 0.003R + 0.83, \quad (2)$$

where H is the focal depth, we find a good agreement between the attenuation curves (Fig. 4), thus providing a sound ground for using the relationship 1 (Babayev *et al.* 2010).

2.2 Shear wave velocity distribution for Baku city

Site effects (or the soil seismic response) analysis examines the vertical propagation of shear waves within a one-dimensional soil deposit and calculates the expected response at the surface (Kirtas *et al.* 2016). The soil deposit is considered to consist of homogeneous and isotropic horizontal layers with different elastic properties, laterally extended to infinity (Kirtas *et al.* 2016).

We modeled the subsurface structure down to the seismic bedrock by a horizontally multi-layered structure, with depth-dependent shear-wave velocity, density and thickness (Babayev *et al.* 2010). Using the P -wave velocity values measured in several boreholes, we developed, for each cell of the grid in which Baku city was divided, the subsurface ground model and we identified the type and thickness of sediments, along with the variation of the underlying rock layers. P -wave velocity test was performed in the laboratory (Kuliyev 1986), on-site and on the samples retrieved from the boreholes. The rock samples collected from several stone quarries situated in Absheron peninsula were checked in order to be used as standard testing specimens without macroscopic defects, altered or fractured zones. By means of ultrasonic nondestructive tester that measures the time of propagation of ultrasound pulses, the V_P was measured in the samples.

Figure 5 shows the map of Baku city with the locations of the drilled boreholes, while Fig. 6 shows the calculated accelerograms for the typical subsurface models. The synthesized accelerogram of maximum possible effect on the reference ground in Baku city was calculated on the basis of site effects, geological surface conditions, amplification factor and subsurface soil seismic response (Babayev *et al.* 2010).

The time duration of the strong motion of all models involved is less than 5 s and the whole signal lasts 55 s. The peak value of acceleration of model A1 is around 1 m/s^2 . Compared to the other models involved in the current research, the peak value of acceleration of model A1 is smaller. Subsurface thickness of the site of model A1 is not large and soil structure consists of two layers. Although subsurface layers consist of sands and clays (soft sediments), the additional presence of sandstones and tuffs (hard rocks) in the basement does not allow the amplitude to increase and attenuate the waves. Model D4, three layers of which contain strata of soft sediments, has a larger peak value of acceleration, of around 3 m/s^2 of N-S component of

Fig. 5. Map of Baku city; the red dots indicate the sites of drilled boreholes.

Fig. 6. The calculated accelerograms for typical subsurface models A1, C1, C2, and D4 throughout the area (see Table 1 for the subsurface model description).

Table 1

Subsurface models of soil and sediments for Baku

Model	Thickness of a layer [m]	Lithology
A1	5	sands, clays, sandstones
	1010	tuff, breccia, shale
C1	4	sands, gravel-pebble
	5	clays and clayey sands
	20	clays
	3800	clays, clayey sandstone, clayey limestone
C2	7	sands, water-saturated sands
	7	clays, pebble, soft-weathered limestone
	23	clays
	3200	organic clays, clayey sandstone
D4	7	limestone, sands
	20	sands, clays, limestone
	1390	conglomerate, tuff, sandstone, breccia, shale

synthesized accelerogram. However, the basement of the model consists of hard rock components, such as limestone, conglomerate, tuff, sandstone, and breccia, which also attenuate the wave. The soil structure of models C1 and C2 are assumed to be the four-strata structure, with three subsurface layers with soft sediments. The peak values of acceleration for C1 and C2 are the largest: 4 m/s^2 for C1 and higher than 3 m/s^2 for C2. The strata are inclined to cause a significant amplification of wave amplitude consisting of water-saturated sediments, soft-weathered limestone, organic clay and sands.

Table 1 shows the subsurface models assigned to the model cells. Shear wave velocity V_S [m s^{-1}] averaged over the top 30 m of the soil are estimated from the following empirical relationship

$$V_S = V_P / (4.34 - 0.49 V_P). \quad (3)$$

The V_P value was measured for the specific soils by experimental method (Seed *et al.* 1969). The S -wave velocity averaged over the upper 30 m of the soil column and obtained by Eq. 3 was mapped on the city (Fig. 7).

For hard sedimentary rocks, the amplification factor within a layer was calculated by using the following relationship 4 (Midorikawa *et al.* 1992):

$$\log A_{\text{PGA}} = 1.11 - 0.42 \log V_S, \quad (4)$$

where A_{PGA} is the amplification factor of PGA between target layer and the layer with $V_S = 440 \text{ m/s}$. Shear wave velocity (V_S) has the advantage of reflecting the stiffness of soils. Consequently, V_S is an important parameter in

Fig. 7. Spatial distribution of average S -wave velocity V_{s30} [m/s] for Baku estimated by empirical calculations.

subsoil exploration. Shear wave velocity (V_s) by itself is a useful parameter for seismic classification of soils. A widely used seismic soil profile (Dobry *et al.* 2000, Sabetta and Bommer 2002) criteria considers the average V_s in the upper 30 m (V_{s30}). The reference site condition for which the current research is done equals 440 m/s which is represented by dense soil, soft rock (Dobry *et al.* 2000), typical for subsoils in Absheron peninsula. For soft sedimentary rocks and soils, the amplification factor and the relevant accelerogram in a subsurface layer have been determined from shear-wave velocities, density, and thickness of the layer using the SHAKE software (Ordenez 2010). The measured and calculated values of seismic wave velocity and density, and the calculated values of the amplification factor for the principal subsurface units of the model are those used by Babayev *et al.* (2010) (the reader is referred to Table 3 in Babayev *et al.* 2010).

Figure 7 shows the average S -wave velocity (V_{s30}) distribution in the investigated area.

The high V_{s30} values (450–500 m/s) are found in a large part of the city, towards the west-northwest and east-northeast parts of the study area, including some parts of the downtown area. S -wave velocity of >500 m/s is found in 40% of the Baku city area. Some shoreline areas, central part of the city and small spots of the city are featured by comparatively low V_{s30} values (<200 m/s) that could be correlated with eolian-delluvial, water-saturated deposits, soils consisted of clay with inserted layers of sand, pebble and

gravel. In general, the decrease of VS_{30} is observed when the ground motion increases (Subhadra *et al.* 2015).

The determination of the site features for estimating seismic hazard is generally performed on the basis of the near-surface S -wave velocity that with the average of over 30 m thickness of soil (V_{S30}) represents one of the site parameters widely utilized for site classification and prediction in terms of the seismic shaking amplification.

2.3 One dimensional (1-D) ground response analysis

The amplification factor for soft soils was obtained by means of SHAKE2000 software (Ordonez 2010), whose basic assumptions are that the soil succession extends infinitely in the horizontal direction and the soil responses are responsible for upward propagation of S -waves from the underlying rocks. By means of stress-dependent soil properties, SHAKE2000 performs simulations of the non-linear dynamics of the subsurface soil and sediments, requiring as input of the values of the S -wave velocity, density, thickness, shear modulus and damping factor of each layer of the subsurface model. We calculated the 1-D response of a soil column, consisting of a number of horizontal layers, with infinite horizontal extension. The bottom layer is the half-space. For each layer we imposed the condition of homogeneity and isotropy with characteristic of input values. Since the analysis

Fig. 8. Map of amplification factor for Baku city for the highest near M 6.3 target event.

Table 2

Dynamic soil and rock layer properties

Era	Period	Epoch	Lithology	Charac- teristics	Max. thickness [m]	V_s [m/s]	Density [g/cm ³]	G/G_0
Cenozoic	Tertiary	Paleogene	Paleocene- Eocene	Rock Rock Rock	1500	1.15	2.13	N/A
			Marlstone					
			Oligocene	Sandstone				
		Neogene	Miocene	Sandstone Tuff, breccia Shale, tuff, sandstone Conglomerate	1200	0.99	2.04	N/A
		Pliocene	Clayey limestone	Rock	3800	0.59	1.95	N/A
			Clayey sandstone	Rock				
	Quaternary	Pleistocene	Clay, sand- stone, tuff	Rock	2000	0.5	1.89	N/A
			Sand & gravel	Stiff soil	23	0.6	2.1	N/A
			Clayey soil	Medium soil	20	0.25	1.8	C*
		Pleistocene- Holocene	Sandy soil	Stiff soil	7	0.5	2.0	N/A
			Clayey soil	Soft soil	5	0.1	1.6	C
			Organic sands	Soft soil	15	0.12	1.7	S*
		Holocene	Clayey soil	Medium soil	7	0.15	1.7	C
			Sandy soil, gravel	Medium soil	4	0.35	1.9	G*

*)C implies clay, S implies sand, G implies gravel;

G/G_0 – relation of shear modulus ratio *versus* shear strain and the strain dependent damping. Initial shear or low amplitude shear modulus is denoted by G_0 .

takes into account the non-linearity of the soils using an iterative procedure, an important role is played by dynamic soil properties. For each soil and rock layer we compiled a table with dynamic properties and the properties have been assigned to each cell, respectively (Table 2).

In this analysis, the necessary input data were the dynamic soil properties and the soil profile. The soil profile is given by the number of layers with the corresponding input values.

This method has been proved to provide well-constrained results and is widely used to perform 1D dynamic soil response analyses (Kirtas *et al.* 2016, Theodoulidis *et al.* 2014). The modification of the soil elastic properties is based on an effective rather than the peak shear strain time-history value (Kirtas *et al.* 2016). The latter refers to a single occurrence with a limited effect on the soil column response during the entire strong ground motion (Theodoulidis *et al.* 2014).

The amplification factor for Baku varies from 0.7 to 1.7 for the highest near target *M*6.3 earthquake (Fig. 8).

3. DISCUSSION

Using all dynamic parameters of subsurface soil, amplification factor and the values of the PGA at bedrock for the two events as seismic input motion parameters of the model, the surface PGA for both target earthquakes was determined (Figs. 9 and 10).

The PGA map for both the bedrock and the ground surface level for the *M*7.5 target earthquake (remote extreme Shamakhi earthquake, 13 February 1902) is shown in Fig. 9. The PGA values vary from 120 gal (0.120 g) to 122 gal (0.122 g) for bedrock level (Fig. 9a) and 80 gal (0.08 g) to 240 gal (0.24 g) for surface level (Fig. 9b).

The PGA values for soft soils derived from SHAKE2000 were used to spatially map the PGA at both the ground surface (Fig. 10a) and the bedrock level (Fig. 10b), with the *M*6.3 earthquake (near event, the Caspian earthquake of 25 November 2000) as the most vulnerable source. The PGA values range from 70 gal (0.07 g) to 120 gal (0.12 g) at the bedrock and 40 gal (0.04 g) to 190 gal (0.19 g) at the surface (Fig. 10). The E-NE sectors of Baku and downtown show PGA values at the surface of about 170-190 gal and at the bedrock of about 120 gal for the *M*6.3 target earthquake, indicating large damage (Fig. 10). The PGA strongly varies at the surface in the eastern section of the city (Fig. 10b).

In Fig. 11, the 5% damped site specific response spectrum at the surface for the *M*6.3 scenario earthquake is plotted. Two peaks, of 0.7 and 0.88 g, are clearly visible in the spectral acceleration, indicating an enhanced amplification for the mesh with clayey sands and sandy clays (areas with C1 typical subsurface model; see Table 1 for description and Fig. 7) with very low V_{S30} value (<200 m/s).

The PGA values for the *M*7.5 earthquake are larger than those for the *M*6.3 earthquake along the shoreline, in downtown area, and northern, eastern and north-eastern parts, which may be caused by the wave propagation through the crust to the top of bedrock underneath the investigated site and ground conditions (Subhadra *et al.* 2015).

Fig. 9. Distribution of PGA at (a) bedrock level, and (b) surface for the largest $M7.5$ target earthquake (Shamakhi earthquake, 13 February 1902).

Fig. 10. Distribution of PGA at (a) bedrock level, and (b) surface for the largest $M6.3$ target earthquake (Caspian earthquake, 25 November 2000).

Fig. 11. The 5% damped response spectrum at the surface for $M6.3$ earthquake scenario in Baku.

Also, for both target earthquakes, the calculated PGA values are higher at the surface than at the bedrock level (Figs. 9 and 10); this could be due to shallow overburden between surface and rock that has amplified ground motion. As observed in Subhadra *et al.* (2015), the level of site amplification changes with site characteristics, type, thickness, stiffness and impedance contrast with the underlying bedrock. The PGA variations are maybe due to the typical characteristics of the material. For instance, seismic waves amplify or de-amplify, depending, respectively, on the low or high values of the S -wave velocity (V_{S30}) (Subhadra *et al.* 2015). A low S -wave velocity (V_{S30}) is in relationship with a high PGA (indicating larger potential damage to buildings) (see Figs. 9 and 10, especially throughout shoreline of the city). Amplification factors become larger in those sections of the city, characterized by lower S -wave velocity V_{S30} and higher seismic hazard. Therefore, a better estimation of the high seismic vulnerability of an area is a consequence of a better estimation of the susceptibility to higher ground motion amplification at the surface (Subhadra *et al.* 2015).

Although a quantitative assessment of surface PGA for the same near and remote events was performed for Baku city in 2010 by Babayev *et al.* (2010); in this current research we used more realistic values for the ground conditions, estimating the dynamic soil and rock layer properties of the study area considering also the relationship of shear modulus ratio *versus* both shear strain and strain-dependent damping, and the initial shear modulus. Besides, we used additional typical subsurface model (A1) to see if the surface PGA distribution was different from that obtained by Babayev *et al.* (2010). As a result, we verify that ground condition and additional subsurface model information do not influence significantly the overall results of surface PGA.

Additionally, in this study we calculated also bedrock PGA with the parameters of the same target scenario earthquakes which are important for the investigated area, but without considering amplification factor of the layers to the surface, in order to see the distribution of the bedrock seismic shaking caused by those two events. Such approach allowed us to estimate PGA at bedrock level to reveal the probable trace of the seismogenetic fault in order not to underestimate the peak ground acceleration near the fault at the surface, and consequently the intensity level. According to Fig. 10a, we observe the fault traces with intersection at the bedrock level, as it is revealed by the near event. This might drive to further investigations of the area in order to bring the results of tectonic researches, to investigate the seismic catalogue specifically for those cells where traces and intersection are, and to see the focal mechanism solutions of the events to estimate the fault types. Additionally, a number of models should be compiled for that area to characterize the surface layer on the fault area, to estimate how the maximum acceleration of strong ground motions is affected by the attenuation relationship between the peak acceleration and the distance.

4. CONCLUSION

The capability to build adequate emergency responses in case of strong earthquake occurrence or to draft suitable seismic disaster prevention plans closely rely to the availability of estimates of site effects due to earthquake ground motion. In this context, in the present paper we modeled the site specific ground motion and analysed the seismic response for the city of Baku, situated in Absheron peninsula. We used two earthquake scenarios related to $M6.3$ Caspian Sea earthquake (characterized as near event) and $M7.5$ Shamakhi earthquake (characterized as remote extreme event). We performed 1-D nonlinear analysis in order to understand more clearly the soil succession. We applied an amplification function which can explain nonlinear effect of soil and connect average S -wave velocity with the function in order to apply to the area where borehole data are provided to high density. In this study,

we showed that the prediction of site amplification depends mainly on the average *S*-wave velocity at the surface. The proposed model enables to spatially map the ground motion of the urban city with boring database. The maps would furnish a solid basis to reinforce the structures in the area, to mitigate the consequences that possible seismic events with similar intensity could produce and, thus, to diminish significantly the probable loss.

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References

- Aptikayev, F., and Y. Kopnichev (1979), Considering focal earthquake mechanism at the prediction of strong motion parameters, *Doklady/Trans. USSR Acad. Sci.* **247**, 822-825 (in Russian).
- Babayev, G. (2010), About some aspects of probabilistic seismic hazard assessment of Absheron peninsula. **In:** *Catalogue of Seismoforecasting Research Carried Out in Azerbaijan Territory in 2009*, Republican Seismic Survey Center of Azerbaijan National Academy of Sciences, “Teknur”, Baku, 59-64 (in Russian).
- Babayev, G., and L. Telesca (2014), Strong motion scenario of 25th November 2000 earthquake for Absheron peninsula (Azerbaijan), *Nat. Hazards* **73**, 1647-1661, DOI: 10.1007/s11069-014-1159-7.
- Babayev, G., A. Ismail-Zadeh, and J.-L. Le Moüel (2010), Scenario-based earthquake hazard and risk assessment for Baku (Azerbaijan), *Nat. Hazards Earth Syst. Sci.* **10**, 2697-2712, DOI: 10.5194/nhess-10-2697-2010.
- Babayev, G., A. Tibaldi, F.L. Bonali, and F. Kadirov (2014), Evaluation of earthquake-induced strain in promoting mud eruptions: the case of Shamakhi–Gobustan–Absheron areas, Azerbaijan, *Nat. Hazards* **72**, 789-808, DOI: 10.1007/s11069-014-1035-5.
- Boghdanovitch, G. (1904), Remarques sur le tremblement de terre a chemakha le 31 janvier 1902. **In:** *Comptes Rendue des Seances*, Tome I, Academie Imperiale des Sciences, St.-Petersbourg, Russia, 282-291 (in French).
- Dobry, R., R.D. Borcherdt, C.B. Crouse, I.M. Idriss, W.B. Joyner, G.R. Martin, M.S. Power, E.E. Rinne, and R.B. Seed (2000), New site coefficients and

- site classification system used in recent building seismic code provisions, *Earthq. Spectra* **16**, 41-67, DOI: 10.1193/1.1586082.
- Gasánov, A. (2003), Earthquakes of Azerbaijan for 1983-2002, Elm, Baku (in Russian).
- Jackson, J., K. Priestley, M. Allen, and M. Berberian (2002), Active tectonics of the South Caspian Basin, *Geophys. J. Int.* **148**, 214-245, DOI: 10.1046/j.1365-246X.2002.01588.x.
- Kirtas, E., P. Koliopoulos, G. Panagopoulos, E. Mouratidis, I. Sous, A. Kappos, N. Theodoulidis, A. Savvaidis, B. Margaritis, and E. Rovithis (2016), Identification of earthquake ground motion using site effects analysis in the case of Serres city, Greece, *Int. J. Civil Eng. Architect.* **2**, 20-27.
- Kondorskaya, N.V., and N.V. Shebalin (eds.) (1982), New catalog of strong earthquakes in the USSR from ancient times through 1977, World Data Center for Solid Earth Geophysics, Report SE-31, Boulder, Colorado, 608 pp.
- Kuliyev, F.T. (1986), Otchet o seysmicheskoy mikrorayonirovaniy territoriy Bolshogo Baku, Baku, Fond Instituta Geologii AN Azerb. SSR., 56 pp. (in Russian).
- Levitski, G. (1902), Bulletin de la Commission Centrale Sismique Permanente (Annee 1902, Janvier-Juin), Academie Imperiale des Sciences, St.-Petersbourg, Russia, 62 pp.
- Midorikawa, S., M. Matsuoka, and K. Sakugawa (1992), Evaluation of site effects on peak ground acceleration and velocity observed during the 1987 Chiba-ken-Toho-Oki earthquake, *J. Struct. Constr. Eng. Architect. Inst. Jap.* **442**, 71-78 (in Japanese with English abstract).
- Ordóñez, G.A. (2010), SHAKE2000: A computer program for the 1-D analysis of geotechnical earthquake engineering problems, User's Manual, GeoMotions, LLC, Lacey, Wash, 262 pp.
- Sabetta, F., and J. Bommer (2002), Modification of the spectral shapes and subsoil conditions in Eurocode 8. In: *12th Europ. Conf. on Earthquake Engineering*, paper ref. 518.
- Seed, H.B., I.M. Idriss, and F.W. Kiefer (1969), Characteristics of rock motions during earthquakes, *J. Soil Mech. Found. Div.* **95**, SM5, 1199-1218.
- Shikhaliyev, E. (1996), *Some Aspects of Geological Structures and Tectonics of Azerbaijan*, Elm, Baku (in Russian).
- Shiuly, A., V. Kumar, and J.P. Narayan (2014), Computation of ground motion amplification in Kolkata Megacity (India) using finite-difference method for seismic microzonation, *Acta Geophys.* **62**, 3, 425-450, DOI: 10.2478/s11600-013-0169-2.
- Subhadra, N., P. Simanchal, P. Prabhakara Prasad, and T. Seshunarayana (2015), Site-specific ground motion simulation and seismic response analysis for microzonation of Nanded City, India, *Nat. Hazards* **78**, 915-938, DOI: 10.1007/s11069-015-1749-z.

- Telesca, L., G. Babayev, and F. Kadirov (2012), Temporal clustering of the seismicity of the Absheron-Prebalkhan region in the Caspian Sea area, *Nat. Hazards Earth Syst. Sci.* **12**, 3279-3285, DOI: 10.5194/nhess-12-3279-2012.
- Theodoulidis, N., C. Karakostas, V. Lekidis, K. Makra, B. Margaris, K. Morfidis, C. Papaioannou, E. Rovithis, T. Salonikios, and A. Savvaidis (2014), The Cephalonia (Greece) earthquakes of January 26 and February 3, 2014: Effects on soil and built environment. **In:** *2nd Europ. Conf. on Earthquake Engineering and Seismology (2ECEES), 25-29 August 2014, Istanbul, Turkey*, Paper No. 3008.
- Tonouchi, K., and F. Kaneko (1984), Methods of evaluating seismic motion at base layer. OYO Tech. Rep. No. 6, Japan, 12-14.
- USGS (2010), U.S. Geological Survey Earthquake Hazards Program: Seismic Hazard Map for Haiti Region, available from: http://neic.usgs.gov/neis/eqdepot/2010/eq100112rja6/neic_rja6w.html (accessed: 1 June 2010).
- Veber, M.V. (1904), Recherches preliminaries sur le tremblement de terre a Chamakha. **In:** *Comptes Rendue des Seances*, Tome I, Academie Imperiale des Sciences, St.-Petersbourg, Russia, 238-241 (in French).

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