ORIGINAL STUDY

3D geological model and geotechnical data for Bucharest: necessary input for assessing local seismic hazard of a densely populated area

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Abstract

Especially after the March 4, 1977 disastrous Vrancea earthquake (Mw 7.4), the necessity for a detailed local seismic hazard map for Bucharest, the capital city of Romania, was recognized. The distribution of earthquake effects as well as subsequent earthquake recordings throughout the city revealed a high variability of seismic ground motion, not only due to source effects but also due to local site effects. The geophysical methods employed in recent years allowed only limited results, so that there are no general geological models of the city applicable to a city-wide analysis. By using a recently compiled geological database, which relies mostly on several hundreds of borehole measurements performed for the subway in Bucharest and a recent DEM for the area, this study establishes the positions of the main seven Quaternary layers beneath the city. A 3D geological model is obtained by interpolation using the GIS kriging method. The 3D geologic model covers most of the city area, reflecting the confidence boundaries. This study also discusses geotechnical data availability and the influence of hydrogeology on the analysis of microzonation of the Bucharest city area.

Keywords Geological model database · Local seismic hazard in Bucharest · Vrancea earthquakes · Microzonation maps

1 Introduction

Bucharest, the capital city of Romania, with more than 2,5 million inhabitants and working people in transit in the city, is considered as a hotspot for natural disasters by a global study of the World Bank and the Columbia University (Dilley et al. 2005). Bucharest is mentioned as one of the most endangered capitals in Europe due to seismic risk in the study of Crowley et al. (2021).

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Most major cities in Romania are situated in valleys or plains, being crossed or near important rivers—this criterion being fundamental for urban development. Where there are rivers, typically there are also thick layers of weakly consolidated sediments in the underground. When subjected to strong motion due to earthquakes, these layers might contribute to significant amplification factors, which can lead to important variability in the distribution of ground motion parameters at surface. This increase in the amplification factors in some areas might lead to disastrous damage of heritage buildings of the city, most old and inadequately designed in respect to earthquakes. That is why the understanding of local site conditions in areas with major cities is extremely important for engineering seismology (Marmureanu et al. 2010; Yilmaz 2015). Geological and geophysical characteristics of the shallow layers together with real strong motion recordings at surface and in boreholes are fundamental for modeling as well as for validation and corrections of the microzonation models.

The variability of ground motion parameters in Bucharest was highlighted during major intermediate-depth Vrancea earthquakes such as the ones on March 4, 1977 (Mw 7.4, 94 km depth), August 30, 1986 (Mw 7.1, 131 km depth) and May 30, 1990 (Mw 6.9, 91 km depth). Given that 90% of the casualties due to the 1977 earthquake were recorded in Bucharest (mainly due to the collapse of 32 moderate or high-rise buildings) and currently there is still a significant number of vulnerable buildings as well as a constantly increasing seismic risk exposure, microzonation studies are highly important to determine which city zones might be potentially subjected to strong damage. There is still a significant number (several hundreds of buildings) of vulnerable structures in Bucharest seriously shaken by past earthquakes and being continuously exposed to the relatively high ground acceleration induced by Vrancea earthquakes with magnitudes $Mw \geq 6$ (4 in the last 50 years) and having by consequence a constantly increasing of seismic risk exposure.

2 State of the art

The influence of the geological models beneath Bucharest upon the propagation of seismic waves was first investigated by Grecu et al. (2003) and Cioflan et al. (2004), but they present geological formations in simple models which do not benefit of the in situ recorded geological dataset in Bucharest.

Following a number of Romanian research projects and benefitting of a decade of close co-operation with German specialists from Karlsruhe University, some models of local seismic effects in Bucharest emerged and can be found in the studies of Bala et al. (2006), Cioflan et al. (2006), Kienzle et al. (2006). Other studies followed with improved results on the amplification of seismic waves on their path to the surface through shallow Quaternary layers (Bala et al. 2009; Marmureanu et al. 2010; Bala 2014), but to this day there is no consensus regarding the distribution of local seismic hazard in and around Bucharest city, mainly because different authors adopted at the time different geological models in Bucharest as well as different seismic velocity values attributed to the shallow sedimentary layers, which came mainly from other descriptions, rather from in situ data measured in the underground of Bucharest.

The reflection and refraction profile recorded in 2005 by Prospectiuni S.A. in eastern Bucharest was interpreted by Bala et al. (2005) and it resulted that P-wave and S-wave arrival times for the same interface vary by just a few miliseconds due to the near horizontal layers (depth changes are not greater than 1–2 m for the same layer). However the

amplitude variations for the same reflected wave along the profile suggest that the acoustic impedance is variable along the same layer due to lithological changes. There were also minor faults and fractures especially in the central part of the seismic profile, which interrupted the upper sedimentary layers down to 50 m depth.

Several years after the destructive earthquake of March 4, 1977 it was a general belief that what cause the high degree of destruction in Bucharest, damaging especially the constructions of 8 levels or more, was the single peak in the spectral acceleration value at periods greater around 1.5 s, as the sole recording of the 1977 earthquake, in central and eastern Bucharest, showed. Limited number of instrumental data was one of the issues. At the next great earthquake from 1986 (Mw7.1) the spectral acceleration values recorded 3 peaks and the last one around 1,6 s, but no tall building collapsed in Bucharest, although it was considered a strong earthquake.

Real recordings of the 1986 and 1990 Vrancea earthquakes have clearly showed that peak ground acceleration values, as well as spectral acceleration values at different periods, can be significantly different throughout the city for one earthquake (Marmureanu et al. 2016). There is also significant variability of the spectral acceleration values in Bucharest from one Vrancea earthquake to the other (Bala et al. 2015a, b; Pavel 2021), even at the earthquakes characterized by very close magnitudes.

In time a real database of strong motions from earthquakes recorded in Bucharest have been created and is increasing each day, beginning with the records from URS network of accelerometers established in Bucharest in 2004–2005 (Ritter et al. 2005). The strong motion database is continuing in the present which the recordings obtained in Romanian Seismic network managed by National Institute for Earth Physics (NIEP), Romania.

The observations of Bala et al. (2005) show that there are important variations in local geology and lithology, therefore we must have a local network with measuring points of 0.5 km, in order to have a good approximation of the near-surface geology throughout the city.

At this point the real challenging task is to obtain a 3D geological model in Bucharest, accompanied by improved geophysical characteristics of each shallow layer, which are the basis of this task, in order to be able to obtain in a second step a quantitative set of spectral amplification values compute at surface, capable of describing a sustainable model of microzonation throughout the city.

3 Geographical setting and geomorphological features of Bucharest area

Considering the main geographical landmarks of Romania, Bucharest is located in the southern part of the country, ca. 65 km north of the Danube River, 100 km south of Carpathians, and 250 km west of the Black Sea.

The capital city of Romania lies in the central area of the Romanian Plain, more precisely in the Bucharest Plain, a division of the Vlăsiei Plain.

3.1 Geomorphology

The topographic altitudes in Bucharest vary between 50 and 60 m in the south-eastern part and 95–110 m in the north-western part, reflecting a relief slightly inclined toward south-east, influenced also by the erosion of the two rivers crossing the city from

north-west to south-east: Dâmbovița and Colentina. These two rivers are dividing the city area into three main geomorphologic units: the Dâmbovița-Colentina inter-fluvial domain (between the two rivers), the North Field, or Băneasa-Pantelimon plain, situated north of the Colentina River and the South Field, or Cotroceni-Văcărești plain south of the Dâmbovița River (Fig. 1b).

Dâmbovița river has a large floodplain, widening from NW to SE, as a consequence of the river's sharp meandering. Due to the swamps and frequent floods, the relief of the Dâmbovița floodplain was strongly modified by the anthropogenic changes of the river, starting in 1880.

The Dâmbovița channel anthropogenic changes in time are described by Stanciu et al. (2022).

The Colentina River, although very meandering, maintains a general straight line on NW–SE direction and has an almost identical morphology as the Dâmbovița: the right bank is high and steep, and the left one has two terraces (Enciu et al. 2008).

4 Geotectonic framework and geological setting

From a geotectonic point of view, Bucharest city is situated within the geological unit of the western Moesian Platform (Wallachian sector), some distance to the west from Intramoesian fault and close to the southern part of the Carpathian foredeep, after Visa-rion et al. (1988).

The Moesian Platform represents a major tectonic unit of the Carpathians and Bal-kans foreland, considered with an Epi-hercynian folded basement and thick, slightly deformed, Palaeozoic, Mesozoic and Tertiary sedimentary deposits. It forms a W-E elongated, fault-delineated structural unit, which prolongs into the Black Sea down to the continental slope (Săndulescu 1974).
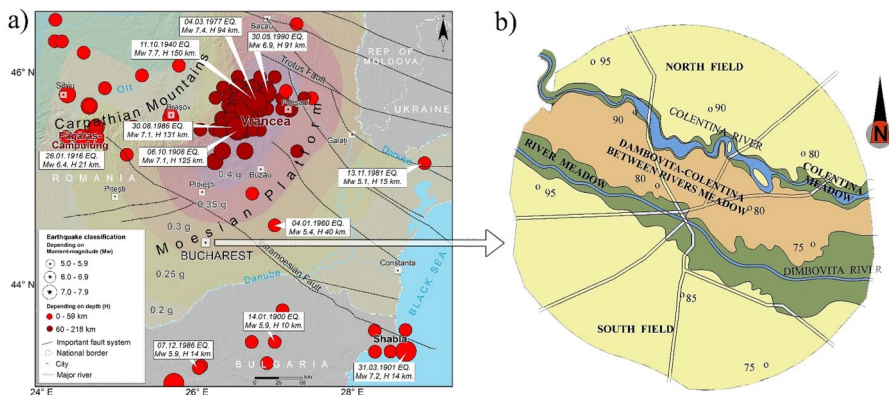

Fig. 1 a Earthquakes in the last 500 years close to Bucharest (according to the Romplus Catalogue, Popa et al. (2022), supplemented by the EPICA and SHEEC Catalogues), important fault systems (according to Săndulescu 1974) and peak ground acceleration values according to the zonation map of the official P100-1/2013 seismic design code (for a mean return period of 225 years); **b** geomorphological map of the Bucha-rest area

4.1 Geology of Bucharest area

4.1.1 Sedimentary cover

The first reliable information regarding the upper crustal structure of the Moesian Platform has been provided by refraction and reflection seismic surveys deployed for oil and gas prospecting (Paraschiv 1979).

In 1999–2000 researches on crustal structure continued by deep refraction seismic profiling (eg. Vrancea'99) and studies reaching Moho depths begin to describe the crustal structure of the platform (Hauser et al. 2001; Raileanu et al. 2005, 2012).

The Carpathian foredeep in front of Eastern Carpathians arc Bend suffered an active subsidence during the Upper Tertiary and Quaternary and, as a result, an asymmetric sedimentary basin resulted. Bucharest is situated in the southern part of this southward thinning basin according to Mutihac (1990). The thickness of the Tertiary and Quaternary sediments, reaching near the Eastern Carpathians Arc Bend a depth of 8–10 km, appears to be reduced in the area of Bucharest to about 500–1500 m depth (Ciugudean and Ștefănescu 2006). The Quaternary alluvial and lacustrine deposits lying beneath Bucharest area present a continuous dipping thickness from south (Măgurele) to the north (Otopeni) according to Liteanu (1952) and Enciu et al. (2008). On the top of the Quaternary deposits there are Holocene loess-like sediments, recent alluvial material and anthropogenic backfill, which are thicker near the center of the city.

4.2 Classification of the Quaternary deposits

A first classification on the geological and lithological composition of the Quaternary deposits in Bucharest area was made by Liteanu (1952). The study of Liteanu (1952) was used as geotechnical database in other studies in order to assess the physical and dynamic properties of the sedimentary layers in and around Bucharest, such as Lungu et al. (1999), Mandrescu et al. (2004) and Bala et al. (2005). The classification of Quaternary deposits in Bucharest was substantially improved by Ciugudean-Toma and Stefanescu (2006), based on the analysis of hundreds of boreholes drilled along the principal subway lines beneath Bucharest. A comparison between the classification of Quaternary complexes after Liteanu (1952) and the one proposed by Ciugudean-Toma and Stefanescu (2006) is given in Table 1.

After 2006, the stratigraphic classification of Quaternary layers in Bucharest established by Ciugudean-Toma and Stefanescu (2006) was gradually and generally adopted, in studies such as Hannich et al. (2006), Kienzle et al. (2006), Bala et al. (2011, 2014). By adopting and working with the same classification of shallow sedimentary layers, researchers can make their respective results more prone to be directly compared. This is one of the reasons for using the geologic classification in this study, along to the fact that our borehole database was structured in this way.

The classification of the 7 principal layers (geologic complexes) with the general characteristics given in Table 1, after Ciugudean-Toma and Stefanescu (2006), which are illustrated in Fig. 2, are used in subsequent figures and text of the present study.

A more advanced work about the shallow geology of Bucharest was published by Enciu et al. (2008), on the ground of numerous discoveries in the field work and in the quarries in the city surroundings during the years. In this paper, the subdivisions of Quaternary layers

Table 1 Definition of Quaternary complexes in Bucharest after Liteanu (1952) and Ciugudean-Toma and Ştefanescu (2006)

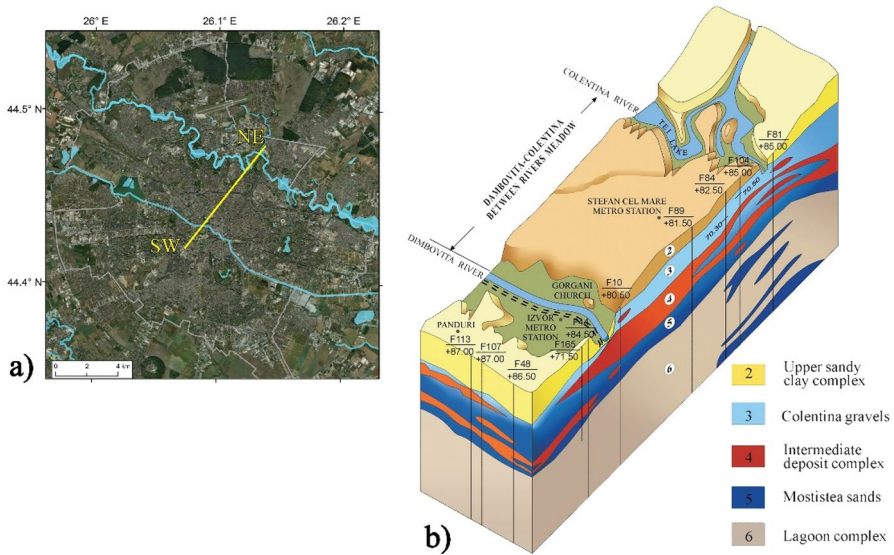|	Definition of sedimentary complexes after Liteanu (1952)			Definition of sedimentary complexes after Ciugudean-Toma and Ştefanescu (2006)			
No	Thickness	Composition	Complex	Thickness	Composition	Complex	Layer no.
		Loess deposits	The horizon of the upper deposits	3–10 m	Loessoid deposits with anthropogenic fillings	The anthropogenic layer and backup filling	1
				2–5 m la 10–16 m	Loess, sands alternating with clays and sands	The upper sandy-marly complex	2
2		Upper bank of sand with pebbles		1–20 m	Sands and pebbles	Colentina Complex	3
3		Deposits of intermediate clays		1–23 m	Consolidated clays and calcareous concretions, with thin sand layers	Complex of intermediate clays	4
		Thick bank of sands		10–15 m	Medium to fine sands with the Mostiştea aquifer	The Mostiştea sands complex	5
5	50–100 m	Marl in alternation with sands	Marl Complex	10–60 m	Sandy clays and clays	Lacustrian Complex	6
6	100–170 m	Layer A	Lower horizon of sands with gravels	10–40 m gravel, intercalations of 5 –40 m marls/clays	Gravels and sands with intercalations of marls and clays	Complex of Frăteşti layers	A 7.A
		layer B					B 7B
		layer C					C 7C

Fig. 2 a Surface projection of next image on Bucharest map; **b** cross-sectional model showing the distribution of the first 6 layers in Bucharest underground (after Ciugudean-Toma et al. 2004; Ciugudean-Toma and Ştefănescu 2006)

are thoroughly described and some of them changed as names, others changed the absolute age, but the whole geological classification remains basically the same, especially for the geotechnical applications. One important feature of the geology of Bucharest (after Enciu et al. 2008) is that a series of local faults and fractures are presented in the bedrock in Bucharest zone, established at the upper part of Cretaceous, where solid rocks (limestones) characterized by higher seismic velocities are documented.

4.3 Discussion on the geologic layers and their geotechnical characteristics

The Quaternary deposits beneath Bucharest have some geotechnical properties which are relevant in the modeling process of the site effects.

- *Layer 1* Comprised originally of vegetal soil and backfill. Because the central part of the city was occupied at least in the last 500 years, this layer was replaced with successive layers of garbage and buildings demolition, with thickness around 0.5–5 m, which might be thicker locally.
- *Layer 2* Display two types of deposits: field deposits and meadow deposits, which differ by thickness, structure and possibly by origin. There are two lithological types of deposits: typical loess and loess-loam.
- *Layer 3* The transition from layer 2 to layer 3 stratum is sometimes possible through clayey or sandy silt layers, yellow and with grey spots.
- *Layer 4* is present through all types of cohesive soils from clayey sands to grease clays but leading clays. The preponderant color for these clays is yellow or brown and the presence of limestone inclusions as disseminations and limestone parts. Layer 6 could

be characterized as being marly, very consolidated with fine clayey sands and very cemented sands (after Ciugudean-Toma and Stefanescu 2006).

Geometrical characteristics of the first 6 layers, as well as the natural unit weight of each layer, are presented in Table 2.

Loess is corresponding to a silty clay, with 20% of clay fraction and about 50% of silt fraction. As granularity, the loam deposits have a clay fraction larger than silt fraction and their distribution is uneven over the Bucharest area.

The types described above appear only over the fields on the meadows of Colentina and Dâmbovița rivers, as well as in the terrain between the two rivers (Fig. 1). Their origin as deposits of the eolian conditions and lacustrine forms are generally accepted.

As a conclusion, drillings performed on both plains, from the South and North of Dambovita river, indicate the same layers succession. The difference appears at the south-west area, where the loams package is around 20 m and made of two, sometimes three layers B and C, while in inter-fluvium area it has a thickness of maximum 5 m and is made of a single layer B and C.

5 Hidrogeology in Bucharest area

From a hydrogeological point of view, the seismic behavior of the subsoil of Bucharest especially the Quaternary alluvial succession is of importance, out of which the three most important sand-gravel layers, some of which are channel-shaped.

The main aquifers in Bucharest's subsoil form: 1. the "Colentina" aquifer (app. 5 m depth); 2. the "Mostistea" aquifer (from approx. 15 m depth); 3. the "Fratesti" aquifer, from approx. 150 m to depth.

The Fratesti aquifer is the thickest aquifer in the Quaternary strata of Bucharest. Due to its great thickness as well as due to its regional continuity throughout southern Romania, as well as in the Bucharest underground, this aquifer acts in particular as a reflection or refraction limit in the earthquake wave propagation and plays an important role.

The second deep aquifer, the Mostistea aquifer, is quasi-horizontal but has numerous interruptions (sand lenses) and thickness variations. Due to its location close to the surface, the grain size distribution (medium to fine sand) and the water content, this aquifer is assumed to have a significant liquefaction and drainage potential in the event of strong earthquakes due to its location.

The near-surface Colentina aquifer has variable thickness (2–20 m) and is not found in the entire Bucharest subsoil. Due to its depth in the immediate vicinity of the Earth's surface, and through the formation of a free groundwater table, this aquifer plays also an important role from the point of view of liquefaction and drainage to be induced in case of strong earthquakes. The lateral inhomogeneities of this aquifer as well as the seasonal and anthropogenic-induced fluctuations in the groundwater level (due to groundwater extraction) are in favor of an increased liquefaction and drainage potential that needs to be investigated.

Figure 3 clearly shows the inclination of the surface of Layer 7A interface (Table 1), and the water table is marked in 3 places along the profile with a small triangle. The first 7 drillings from south to north show the same behavior, also for Layer 7 B and C interfaces, which are continuing to the north with layer 7A; they are also intercepted in the Pipera borehole with an increased thickness toward the north part of profile.

Table 2 Main attributes of the first 6 geological layers beneath Bucharest: depth to upper limit, thickness and natural unit weight (γ). After Cugudean-Toma and Stefanescu, 2006

Geologic zone in Bucharest (Fig. 1)	Geologic layer no	1. Backfill soil	2. Upper Sandy Clayey complex	3. Colentina Gravel complex	4. Intermediate Clay Layer	5. Mostistea sandy layer	6. Lacustrine Layer
	Depth to upper limit (m)	0	0.5–5	5–12	10–20	15–35	35—50
Baneasa plain (NE plain)	γ (kN/m³)	16.9 -17.4	Loam B 17.6–20.1 Loam C 16.2–19.6		15–23	10–15	10–60
	Thickness (m)	0.5–4 (max.15)	9–20	1.5–20			
Văcărești plain (SW plain)	γ (kN/m³)	16.9 -17.4	Loam B 18–20.3 Loam C 16.6–19.8				
	Thickness (m)	0.5–4 (max.15)	9–20	1.5–20	0–5	3–8	
Interfluvium	γ (kN/m³)		Loam B 18.5–21 Loam C 17.5–20	20	18.5–20.5	19.5–21	19–21
	Thickness (m)	0.5–3 (max.7)	0.5–3	10–15		15–20	10–60

Table 2 (continued)

Geologic zone in Bucharest (Fig. 1) Geologic layer no	1. Backfill soil	2. Upper Sandy Clayey complex	3. Colentina Gravel complex	4 Intermediate Clay Layer	5. Mostistea sandy layer	6 Lacustrine Layer
Depth to upper limit (m)	0	0.5–5	5–12	10–20	15–35	35–50
Meadow						
γ (kN/m^3)		Silty- clayey 15.4–21 Sandy-silty 17.7–19.5				
Thickness (m)	0.5–3.5	7–9	10–15			

$^*\gamma$—is the natural unit weight in (kN/m^3)
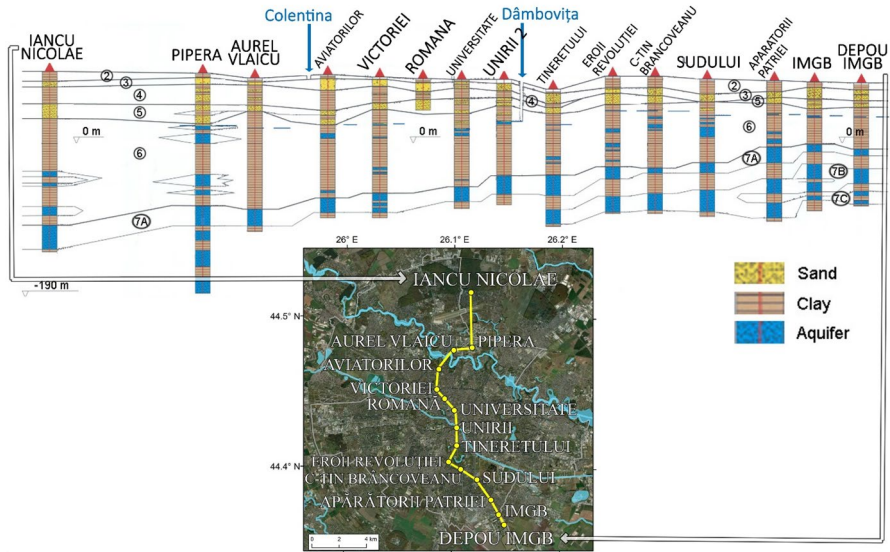
Fig. 3 North–south geologic profile for Bucharest, constructed on the base of lithologic column of individual boreholes, with their location presented in the map; altitude is exaggerated 5:1. Layers from 2 to 7 are presented

In general, these hydraulic connections determined in Bucharest small differences between both aquifers' levels. Thus, the hydrostatic level is one of a unique layer and it is considered the phreatic water table in Bucharest underground. The difference between the maximum and minimum values of hydrostatic level is ± 1 m considering the natural conditions without artificial influence.

5.1 The influence of local hydrogeology on site-effects occuring during strong earthquakes in Bucharest

Several authors describe the influence of the water level during earthquakes in Bucharest. For example, Ehret et al. (2010), on the ground of two geologic profiles of 2 drillings in Bucharest, have modelled the water pressure during a strong motion and concluded that groundwater level changes strongly influence the ground response and cannot be neglected for site effect analyses. In the presence of confined aquifers, liquefaction can take place in the subsurface, depending on the intensity of the earthquake. The liquefaction may result in attenuation of shear wave propagation and can reduce duration and amplitude of ground shaking. As a consequence, ground water level (changes) should be considered for further seismic microzonation studies.

Hannich et al. (2006) analyzed the variation of shear wave velocities, in parallel with detailed geological/geotechnical disposition of the penetrated soil layers by CPT, at one location in Bucharest. At this site, the water table was recorded at 8.5 m depth. However, after their results if the water table is increasing and is placed between 5 and 8.5 m depth, the probability of liquefaction during a strong Vrancea earthquake can become greater than 35%.

The conclusion is that the SCPTU-techniques, used for the investigation of share waves velocity in the upper layers of surface geology, as well as hydrogeology conditions in Bucharest, provide a reliable method to determine in-situ state parameters and dynamic characteristics, useful for the application of linear and non-linear modeling of the ground motion (Bala and Hannich 2021a).

6 Digital geological model of the 7 principal Quaternary complexes in Bucharest

6.1 Available data

The first step in the generation of the 3D geological model (3DGM) was the acquisition and the digital processing of pre-existing geological and geotechnical data. These data consisted of analogue maps at various scales that displayed the location of the drillings, geological cross sections and borehole logs. The primary data provider was S.C. METROUL S.A., a Romanian subway construction company which was involved in the geological and geotechnical mapping of the main metro lines performed in Bucharest, beginning with the 1980's.

In the present study we have benefitted of all the data acquired in the last years by METROUL S.A. such as the drillings presented in Fig. 3. Most of the drillings reached a depth of 30—70 m, only few being deeper and reaching 150—200 m depth. Also, in our 3DGM we included data from the NATO-SfPProject 981,882 (Bala et al. 2010), for 10 drillings down to 50 m depth in the city center. When needed, maps were scanned, georeferenced and digitized in order to determine the precise location of the measurement point. Data for 45 locations were added in such way.

All available data points, with depth data for the first 6 layers, are displayed in Fig. 4. For the base of the 7th layer, further investigations are needed for a representative interpolation.

In total, we used an amount of:

- 969 point values for Layer 1;
- 349 point values for Layer 2;
- 340 point values for Layer 3;
- 331 point values for Layer 4;
- 274 point values for Layer 5;
- 59 point values for Layer 6;
- 47 point values for Layer 7 (divided between the different interfaces: A, B and C).

The Digital Elevation Model (DEM) used as a reference for the 3DGM (given that most of the times the profile altitude wasn't given) was the one recently published by the Romanian National Agency for Cadaster and Land Registration (ANCPI) in 2022. This DEM is freely available on the ANCPI Geoportal (), under an Open Government License (OGL ROU 1.0). The DEM has a cell size of 2 by 2 m and is qualitatively superior to previous DEM's such as the European Digital Elevation Model (EU-DEM) or the one used in Kienzle et al. (2006)—better reflecting the topographical altitude in areas with forests, buildings or near rivers and lakes. Some differences (up to 1 m) can be present in some
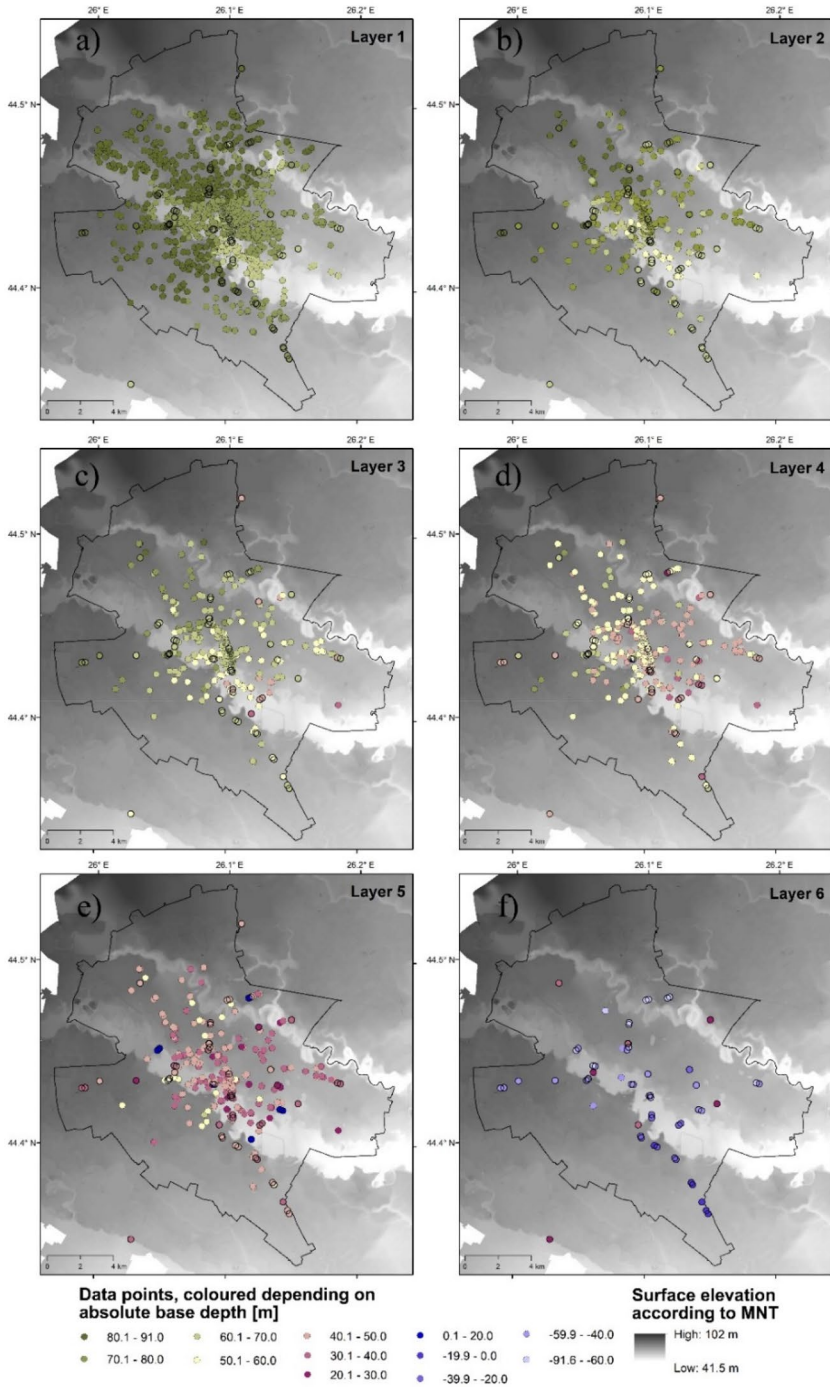
Fig. 4 Available drilling points in the database for the first 6 layers, overlayed on the Bucharest elevation map

locations—given the time evolutions between the moment the boreholes were performed and nowadays, but for now it is almost impossible to identify them.

6.2 Modeling method

Data points with absolute depth values were used to generate the 3DGM, using the kriging interpolation method applied individually for the first 6 layers. Kriging is considered as one of the most appropriate interpolation methods for our purpose, as shown by comparative results in Chesnaux et al. (2017), Bamisaiye (2018), Wellmann and Caumon (2018) and Igaz et al. (2021). Besides, we chose it in order to have consistency with the study of Kienzle et al. (2006) for Bucharest. By using kriging, we were able to have a quantification of the interpolation errors and potential errors in our data. We used ESRI ArcMap 10.6 as software, with the following parameters:

- Simple kriging with Normal Score transformation type. De-clustering before transformation was selected, given that in some areas, our data points are very dense. The order of trend removal was chosen as constant. The model was optimized.
- For cell delustering, cells were rotated 45°, to match the trend also highlighted by Enciu et al. (2008), revealed also by elevation at the surface (Fig. 4);
- A student version of the ESRI ArcMap 10.6 as software was used, with a number of bins of at least 10 (depending on each layer), in order to better account for abrupt elevation changes;
- For Neighborhood Search, we preferred to use 4 Sectors with 45° offsets and a minimum number of neighbors of 3 and a maximum of 5. This allowed to limit the contribution of distant points especially in the outskirts of the city.

After interpolation, we checked for data conflicts: bottom layers piercing through upper layers. Given that is expected that bottom layers disappear, we replaced the values of the bottom layer with the same values as the top layer, for the selected area (resulting in 0 thickness). This was performed for limited areas of Layers 1 to 4.

In order to show areas where there is high confidence in our 3DGM, we computed also prediction error values, following recommendations in Liang et al. (2021). In Figs. 5 and 6 we map the limits where these errors are lower than 10% of the difference between maximum and minimum values of a specific layers—describing this limit as "area with values of high confidence". Typically, geological models are not clipped, but one can view in such way the areas where the model has a lower confidence, such as south-west and north-east of Bucharest, where input data is sparse.

6.3 Resulting maps

Figure 5 shows the resulted values for Layers 1–6, in terms of absolute depth at the base of each layer, with a similar legend in order to enable comparison between them. Figure 6 shows the thickness values. All data for Layers 1–6 can be downloaded as raster from the Mendeley Data repository (Toma-Danila et al. 2022). Figure 7 shows a 3D representation of data in Fig. 5, clipped according to values of high confidence areas.

For the layers 1, 3 and 5 the area of high confidence is covering almost all the city limits (Fig. 5a, c and e). For the other maps one can observe that areas with confidence
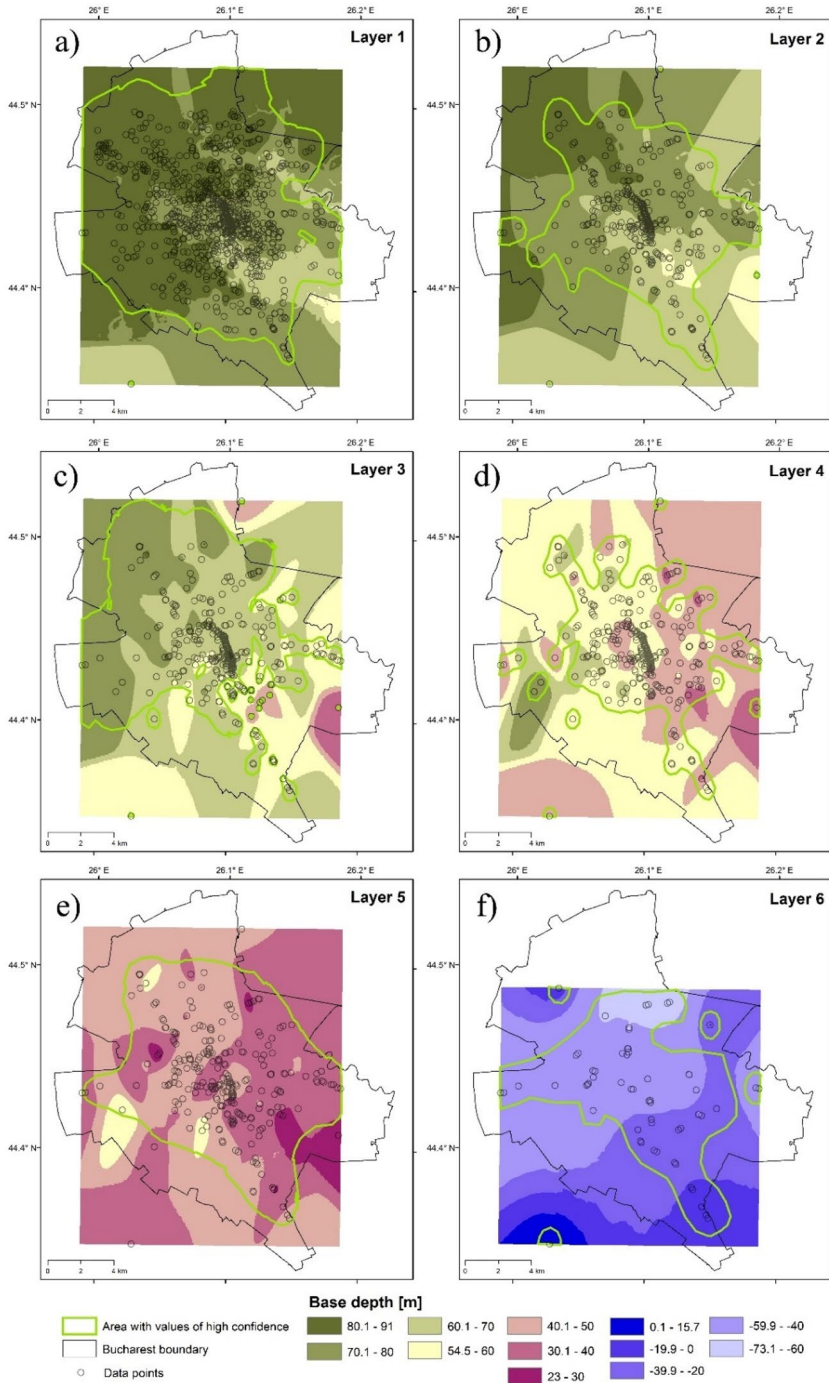
Fig. 5 Map with interpolated values for layer relative depths, for layers 1–6 in the Bucharest area: **a** Layer 1; **b** Layer 2; **c** Layer 3; **d** Layer 4; **e** Layer 5; **f** Layer 6
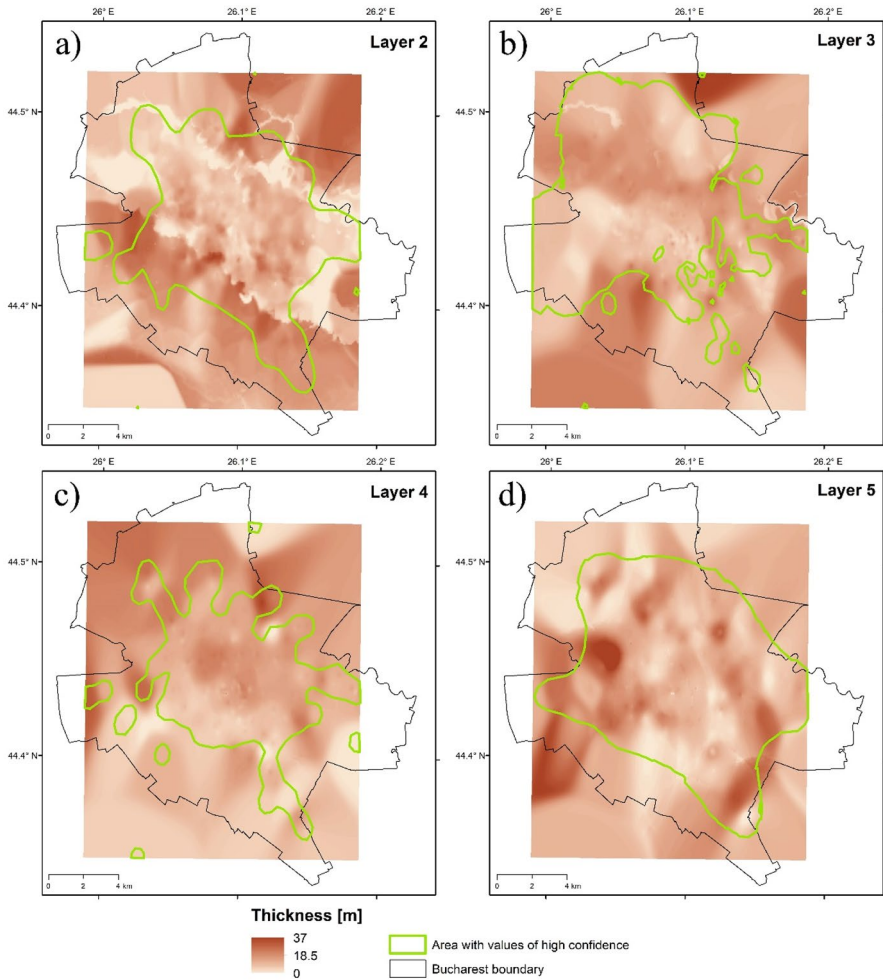
Fig. 6 Thickness values for layer 2–5, mapped using a similar legend

of 75—80% are also important for the interpretation and also for subsequently using the database for other methods of deriving the site effects in the area.

The results from Fig. 6 are showing that the thickness values are changing rapidly across the city, at least for the layers 1–5, and only such a model would permit the retrieving of the values at 100 m interval, required for the microzonation studies.

The thickness of layer 6 is much larger according to Fig. 8a and for the layer 7 the thickness is not yet determined, because the boreholes which are available in the database were designed mainly for exploration and water extraction and therefore they are only piercing the layer 7A, which is the main aquifer underneath Bucharest (Frătești layer A).
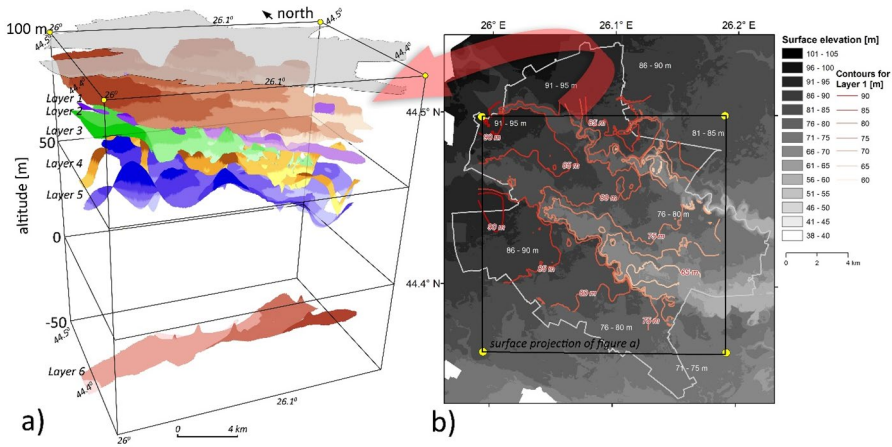
Fig. 7 **a** A 3D representation of the Bucharest 3DGM, showing the base altitudes of the first 6 layers (altitude is highly exaggerated in order to enable the differentiation of the layers); **b** the extent of the 3D model at surface, superimposed on the Bucharest elevation map

7 Discussion of the results

For layer 5, in the north-western part of the city there is an area were the depth and the thickness has greater values than surroundings. Its implications will need to be evaluated when modeling seismic hazard, but also additional boreholes seem to be necessary for a greater confidence. Layer 6 has a smaller area of high confidence, compared to the layers above; some isolated borehole data were not considered in our approach as relevant for a contiguous more certain representation. Nevertheless, the north-west to south-east trend is a clear feature. This time, values on this axis are closer to the surface toward south-east, opposed to the trend showed by layers 1–5.

Figures 7a and 8a show that the slope of first 6 layers is generally oriented from north-west to south-east, with lower depths in north-west, following more or less the topography (Fig. 8a).

The Digital elevation model used enabled a better 3D modeling compared to older studies, due to poor DEM resolution available at the time and it is extended on an area which almost covers the entire area of Bucharest city, as it is in Fig. 7b. The aria of the model presented by Kienzle et al. (2006), is a square of 7×7 km in the Bucharest center (Fig. 8b), while the present model is a square of 15×15 km.

The layer 7a is dipping from SE to NW in Fig. 8a., but also from south to north as the profile in Fig. 3 (for 7A, 7B and 7C).

The structural map described by Enciu et al. (2008) is also describing a sinking from south to north for the layers 7A, B and C, with the observation that his model does not have information in the eastern and western sides of Bucharest area.

The same observation were made by Burcea et al. (1966) about the interface of Tertiary/Cretaceous under Bucharest. Although it was established that the inclination is generally from south to north (see also Enciu et al. 2008), it was also noticed that the line of greatest slope is from SE (about 600 m depth) to NW (1400 m depth) after Burcea et al. (1966) in their study of interpreting different seismic profiles.
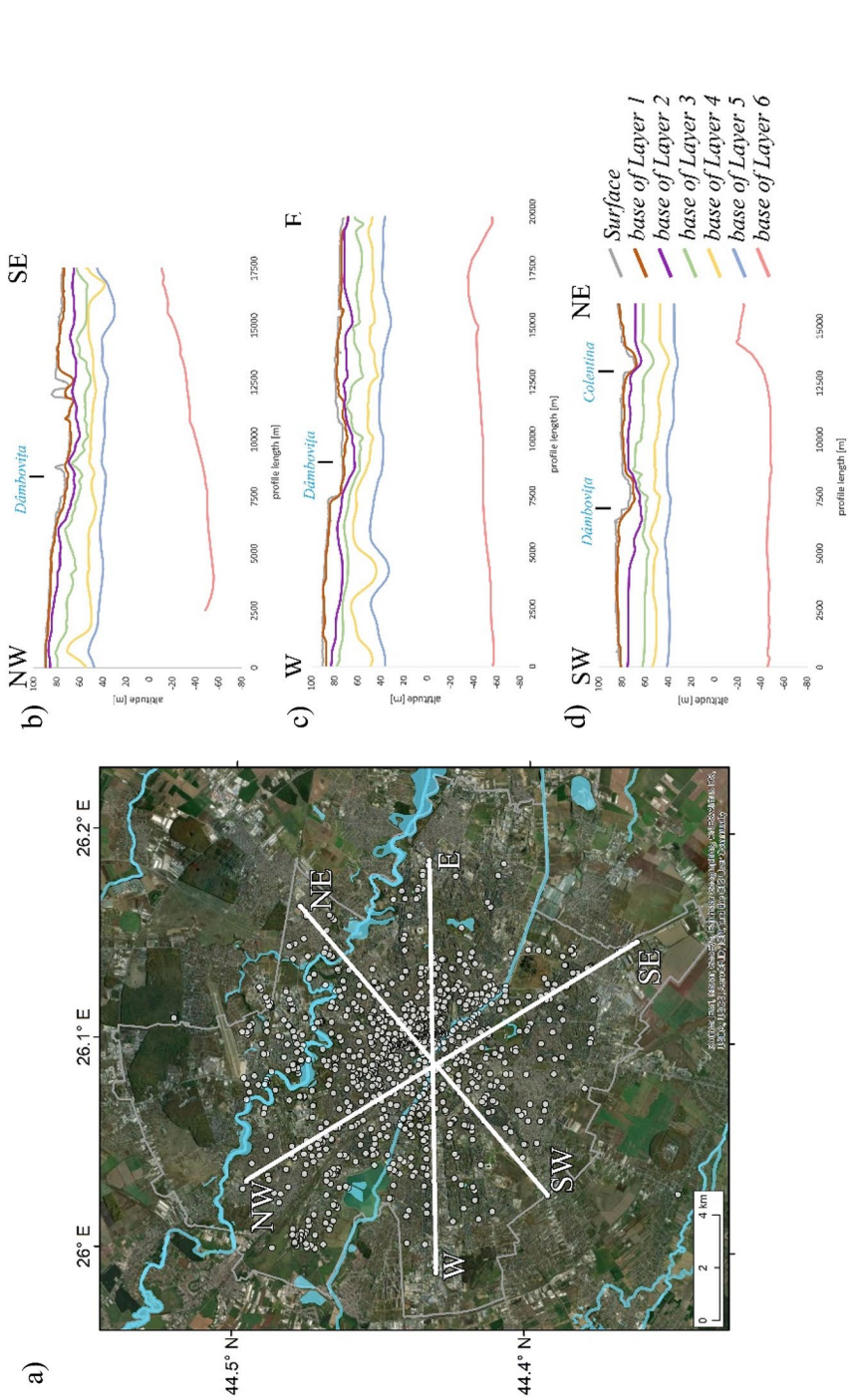
Fig. 8 a The location of three profiles obtained based on the 3DGM (white lines), oriented: **b** north-west (NW)—south-east (SE); **c** west (W)—east (E); **d** south-west (SW)—north-east (NE)

The shallow geology of Quaternary layers in Bucharest city is rapidly changing from one point to another in only a few hundreds of meters not only in the thickness of the layers, but also in the geotechnical properties of each layer.

8 Conclusions

Several 3D geological models for Bucharest were elaborated and published (e.g. Kienzle et al. 2006; Serpescu et al. 2013), but their extent as well as the number of data points used to design the geological layers were limited—especially for deeper layers. In the present study a detailed set of data was available, which enabled the development of a city-wide 3D geological model relevant for integration in local seismic hazard assessment. By using GIS and the kriging interpolation method, and taking into account the uncertainties, we ensure that the developed geological model is representative and is also publicly available (Toma-Danila et al. 2022). Besides geology, we also present in this paper representative geotechnical data, laying the foundation for further studies of local seismic hazard.

Because the shallow Quaternary layers in Bucharest present relative great laterally changes in thickness and partly in lithology, in-situ measurements in boreholes or by special methods on the surface are highly necessary for microzonation purposes. Our study uses a detailed geological database of borehole measurements, which enables a refined interpolation and development of a 3DGM. This now sets good premises for further studies aiming to compute different spectral amplification factors throughout the city and different distribution of ground motion parameters at surface, due to various Vrancea earthquakes.

The 3DGM shows the base depth and thickness of the 7 Quaternary layers beneath Bucharest and is consistent with previous studies and profiles, having also a greater extent (even though the areas with low confidence need to be taken into consideration, being showed on the maps). By using GIS, specific values can be easily extracted and 2D profiles can be generated (as the ones in Fig. 8). The 3DGM shows that layers 1–6 are slightly inclined from north-west to south-east. The interface of layer 7 is the only one which is inclined from SE to NW, but also from south to north.

The 3DGM represents one of the base input data for local deterministic seismic hazard studies, which require the computing of the spectral amplification of the seismic signal, from depths relevant for Bucharest area, given its geological 3D structure and basic geotechnical characteristics from the bedrock to the surface. In this effort, recently published data regarding shear-wave velocity values in Bucharest area are inscribed (Bala and Toma-Dănilă 2021b; Toma-Danila et al. 2021). Both the databases are determinant for the local hazard studies in an area threatened by relatively high values of seismic hazard and risk due to large magnitude Vrancea earthquakes.

The slope of first 6 layers is generally oriented from north-west to south-east (Figs. 7a and 8a), with lower depths in north-west, following more or less the topography (Fig. 8a). The same observation is made by Bala et al. (2021b) in their study of the share-wave velocity near surface, but the velocity values are increasing from the north-west towards south-east, with some local variations. It seems that these values are influenced by the topographic surface and more or less by the inclination of layers from 1 to 6.

The same pattern was observed by Sudhaus and Ritter (2009) in their study about the variation of peak amplitudes of P and S waves in the Bucharest underground from teleseismic events and Vrancea earthquakes.

These observations prove that a simple glance on the 3D geological model, coupled with analyses of other geophysical and seismological models in Bucharest, might be able to have important consequences on the distribution of local seismic microzonation.

Data availability Digital Elevation Model (DEM) is recently published by the Romanian National Agency for Cadaster and Land Registration (ANCPI) in 2022. This DEM, titled NTM (numerical terrain model) is freely available on the ANCPI Geoportal (https://geoportal.ancpi.ro/portal/home/), under an Open Government License (OGL ROU 1.0). The dataset contains raster of the 3D geological model for Bucharest, elaborated by Toma-Danila et al. (2022), within the framework the present paper. Data contains raster for the base depth and thickness of layers 1–6 (presented in Figs. 5 and 6), as well as data regarding the availability of measurement at each layer, for original data points (presented in Fig. 4). Due to restrictions imposed by the data provider, open access to the original geological input data cannot be granted.

Declarations

Conflict of interest The authors of this paper have no interests that are directly or indirectly related to the work submitted for publication, except for the scientific purpose.

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