Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake, and Associated Seismic Sequence

Chapter 3: Geology, Geomorphology, and Soil Characteristics

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3.1 Geology and Geomorphology

A wide zone of convergence between Eurasian and African plates during Late Cretaceous and Cenozoic time occurred in the overall compression setting, in which extensional basins have developed since Oligocene in association with subduction zones, thus consuming oceanic and attenuating subduction zones. The Pannonian or Carpathian Basin, which is located in the SE part of Central Europe, is an integral part of the Alpine orogenic system. The basin is of Miocene through Quaternary age, and it is surrounded by the Carpathian, Alpine, and Dinaric mountains (**Figure 3.1**). The basin is of extensional origin, and its formation was accompanied by intensive magmatism during the Middle Miocene rifting climax within its Croatian part.

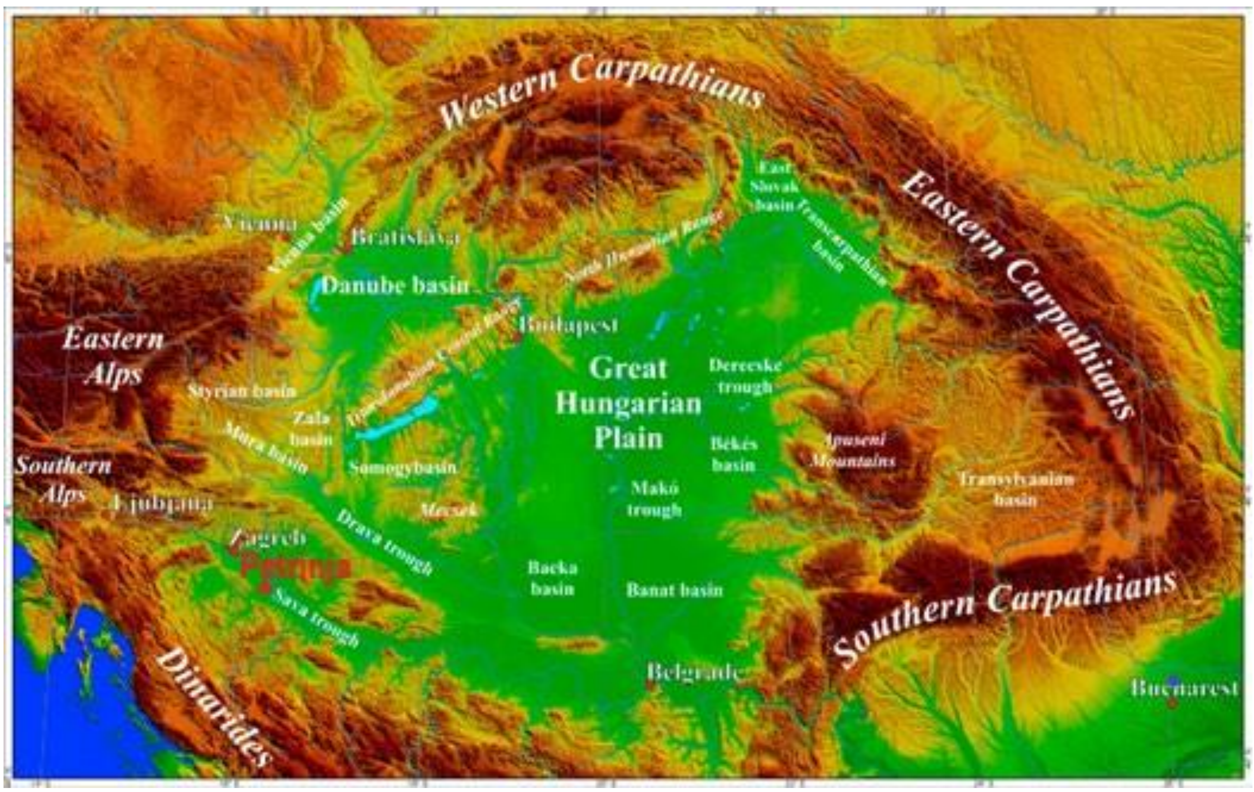

Figure 3.1 Digital terrain model of the Pannonian basin (adapted from Horváth et al., 2015).

The geomorphological term Pannonian Plain is more widely used to denote roughly the region of the Pannonian basin, although the former typically denotes only the lowlands, the plain that remained after the Pliocene Epoch Pannonian Sea dried out. Pannonian Basin is a geomorphological sub-system of the Alps–Himalaya system, a sediment-filled-back-arc basin, which spread apart during the Miocene. Most of the plain consists of the Great Hungarian Plain to the south and southeast and Little Hungarian Plain to the northwest that is divided by Transdanubian mountains (**Figure 3.1**).

The Pannonian Basin forms a topographically discrete unit set in the European landscape, surrounded by the Carpathian Mountains, Dinarides, and the Alps. The basin extends roughly between Vienna in the northwest, Košice in the northeast, Zagreb in the southwest, Novi Sad in the south, and Satu Mare in the east. The rivers Danube and Tisza divide the basin roughly in half.

Petrinja is located near the southwestern edge of the Pannonian Basin, where the basin meets Dinarides (**Figure 3.1**). In addition, Petrinja is also located in the vicinity of the South Marginal Fault (SMF) of the Pannonian basin (**Figure 3.2**). The active tectonics of the Pokupsko–Petrinja–Sisak region is driven by the continuous movement of the Adria Microplate to the north. Consequently, strain occurs at the contact of Dinarides and the Pannonian basin in the upper part of the Earth's crust. Individual faults are activated and reactivated as strain reaches critical levels. A sudden movement of the blocks of the crust causes the release of energy, thus resulting in the occurrence of earthquakes.

Petrinja is located about 14 km southwest of Sisak while the epicenter of the December 29, 2020 earthquake was located 3 km southwest of Petrinja. A basic geological map of the Sisak unit is shown in **Figure 3.3**. Tectonically, this entire region belongs to the southwestern part of the Pannonian Basin. According to Pikija (1987) the oldest recognized rocks on the surface of this region are sedimentary and igneous rocks of Upper Cretaceous (Senonian) age. The most widespread sedimentary rocks are pelagic limestones of the “scaglia” type, the prevailing igneous rocks are tuffaceous rocks and spilites. Late Cretaceous events resulted in uplift while clastic deposition occurred during Paleocene and Eocene. Coarse-grained clastic rocks formed during the Helvetian after a long emersion.

The area most affected by the earthquake is covered by two Basic Geological Maps on a 1:100,000 scale: the Sisak sheet (**Figure 3.3**) and the Bosanski Novi sheet (**Figure 3.4**). In this brief review, only the rocks from the area surrounding the Petrinja area are described. According to Pikija (1987), the oldest rocks within the region are Upper Cretaceous sedimentary and igneous rocks. The most common sedimentary rocks are micritic and clayey limestones similar to ''Scaglia limestone'' and the most frequent igneous rocks are spilites and tuffitic rocks. Late Cretaceous tectonic movements resulted in uplift and formation of source areas for most clastic rocks deposited during Paleocene and Eocene. Deposition in Eocene was followed by a relatively long emergence phase during which Sava depression started to form. Middle Miocene sedimentation started by an accumulation of coarse-grained clastic rocks.

Marine transgression in the Badenian occurred throughout this entire region. While terrigenous clastic rocks were locally deposited in the basal part, the rest is characterized by the facial diversity of deposits. During the Sarmatian period, clastites are dominant rocks within the Sava depression, while carbonates and clastic rocks predominated in other areas. During Pannonian and Pontian (late Miocene) limestones, calcareous marls, marls, sands, and sandstones were deposited. Pliocene lacustrine deposits are represented by clays, sands, gravels and coal beds. Loess, marsh loess and alluvial sediments were deposited during the Pleistocene, while depositionin Holocene is dominated by slope, deluvial deposits, alluvial, and marsh deposits. The map shownin **Figure 3.3** indicates that the top soil layers near Petrinja are of Quartenary age, including 1) flood deposits (silts and sands; ap), 2) terrace deposits (silts, sands, and gravels; a1), 3) deluvium–proluvium deposits (silts, sands, gravels, blocks; dpr), and 4) loess (l).

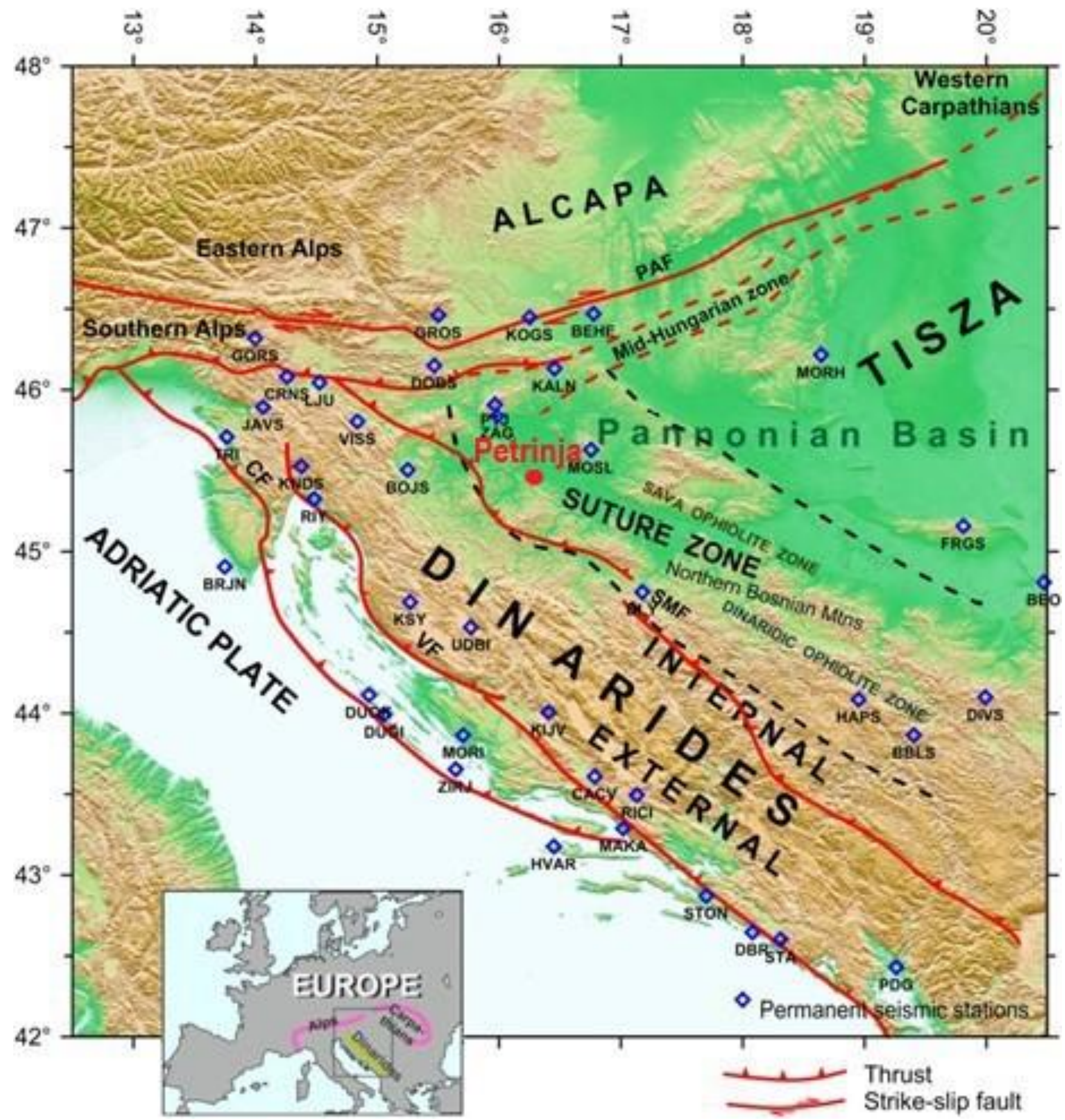

Figure 3.2 Topographic and tectonic map of the Pannonian–Dinaridic region with border part of the Alcapa (Alpine–Carpathian tectonic unit) with positions of the seismic stations. The main tectonic units and faults are superimposed on the topographic map (PAF – Periadriatic fault, CF – Ćićarija fault, VF – Velebit fault, SMF – South marginal fault of the Pannonian basin). The borders of the suture zone after Šumanovac (2010), (adapted from Šumanovac et al., 2017).

Two rivers, the Sava and Kupa rivers, have formed alluvial deposits at depths up to 50 m within the affected area. The interchanging layers of loose sands and loose gravels are underlain by 1 to 5 m thick clay with up to 26% organic content. Medium to stiff clay of low to high plasticity is located below the alluvial deposits. Heavy industrial buildings located in this area are typically founded on floating drilled shafts due to generally soft soils while one to two-story commercial and residential buildings are founded on shallow foundations. The groundwater level in the city of Sisak is about 4 to 5 m deep, but it can vary seasonally and even reach the ground level. It is strongly affected by the water level in the nearby Kupa and Sava rivers. Further details of a typical geotechnical profile and soil characteristics in this region are provided in Section 3.2 of this report.

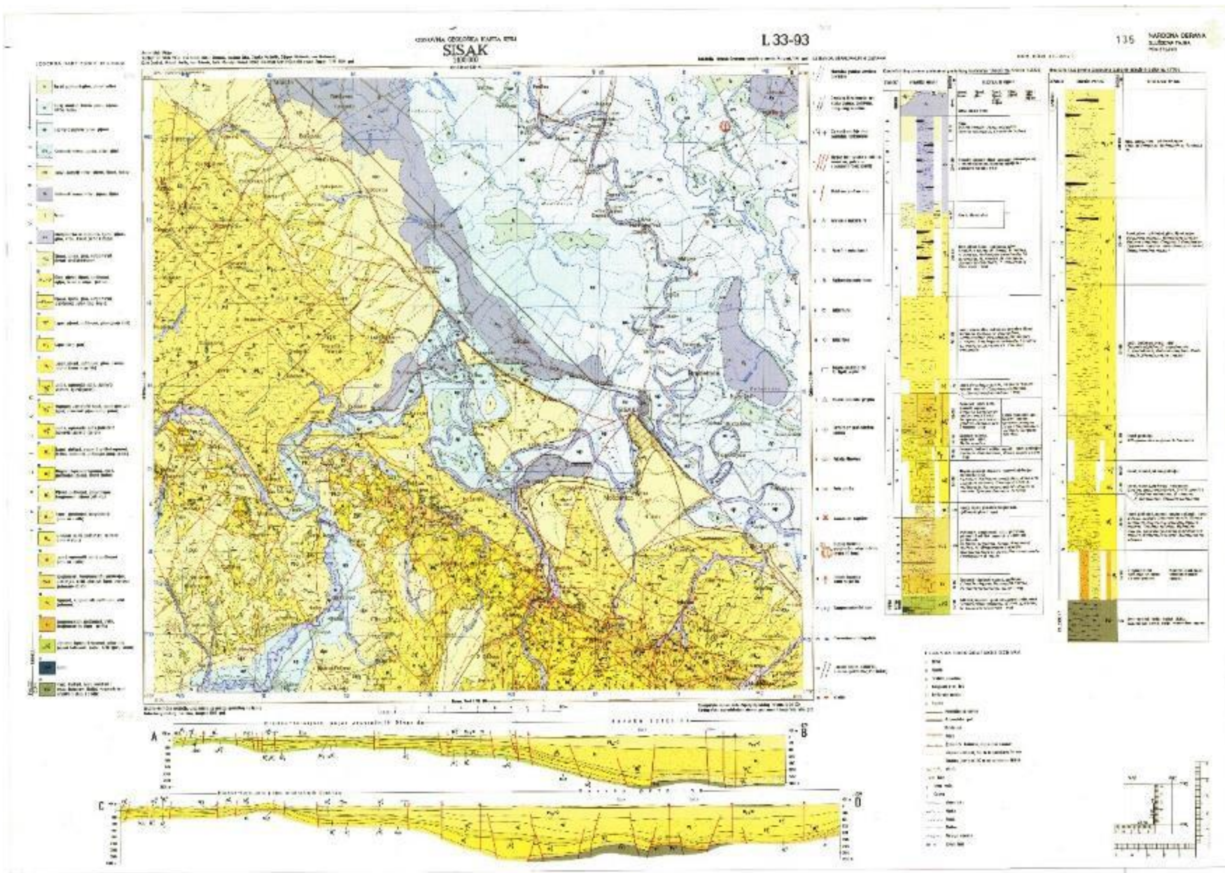

Figure 3.3 Basic geological map Sisak sheet 1:100,000 (Pikija 1987).

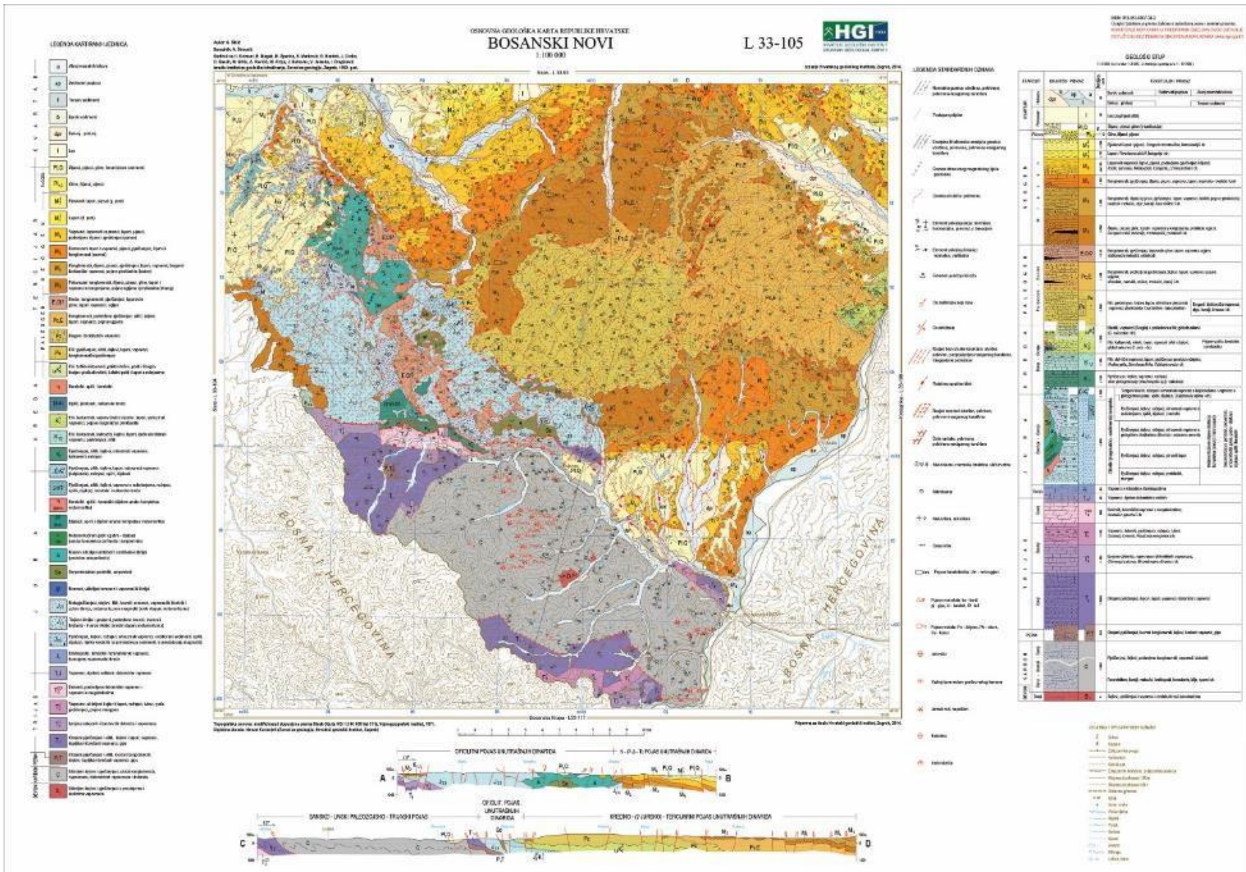

Figure 3.4 Basic geological map Bosanski Novi sheet 1:100,000 (Šikić, 2014).

3.2 Geotechnical Soil Characteristics

Several available geotechnical reports from locations in the sedimentary basin show layers of loose sand, that can have high liquefaction potential. For example, in Braće Hanžeka street nr. 23 in Petrinja, two 6 m deep borehole logs show SFs (silty sand, loose, wet, brown) at 5.7 and 6.0 m depth, with ground water registered at the top of the sand layer (Tomac, 2009). In Sisak, within the perimeter of thermal powerplant Čret heavy buildings and chimneys are founded on floating large diameter piles, 10-15 m deep (**Figure 3.5**). The pump station is founded on a 33.5 m deep diaphragm wall in the stiff clay layer under alluvial layers, showing small settlements. Primary consolidation for 12 m deep pile raft system took more than 15 years, w = 6.7 cm. Secondary consolidation was 1-2 cm. Calculated settlement values were slightly exceeded in the majority of cases. Reasons for the discrepancy between predicted and actual behavior is maybe because of seasonal water table changing up to 10 m, or machine vibrations in the power plant area that might cause some negative friction on piles. The location of the power plant is on alluvial deposits between rivers Sava and Kupa in the vicinity of town Sisak. The area is known for its weak soils that can reach depths of 50 m – composed of loose sand and gravel layers intermixed with soft and medium clays and organic material (Marić, 2005; Marić et al., 2007). A comprehensive geotechnical investigation performed in the past includes deep boreholes which also show various sand layers shown in **Figure 3.6**. Average SPT blow counts, collected from 31 deep boreholes (6 in 2005, and 25 earlier), are: N_{SPT} = 12 (5 - 10 m), N_{SPT} = 13 (10 - 15 m), N_{SPT} = 15 (15 - 20 m) and N_{SPT} = 10 (20 - 31.5 m).

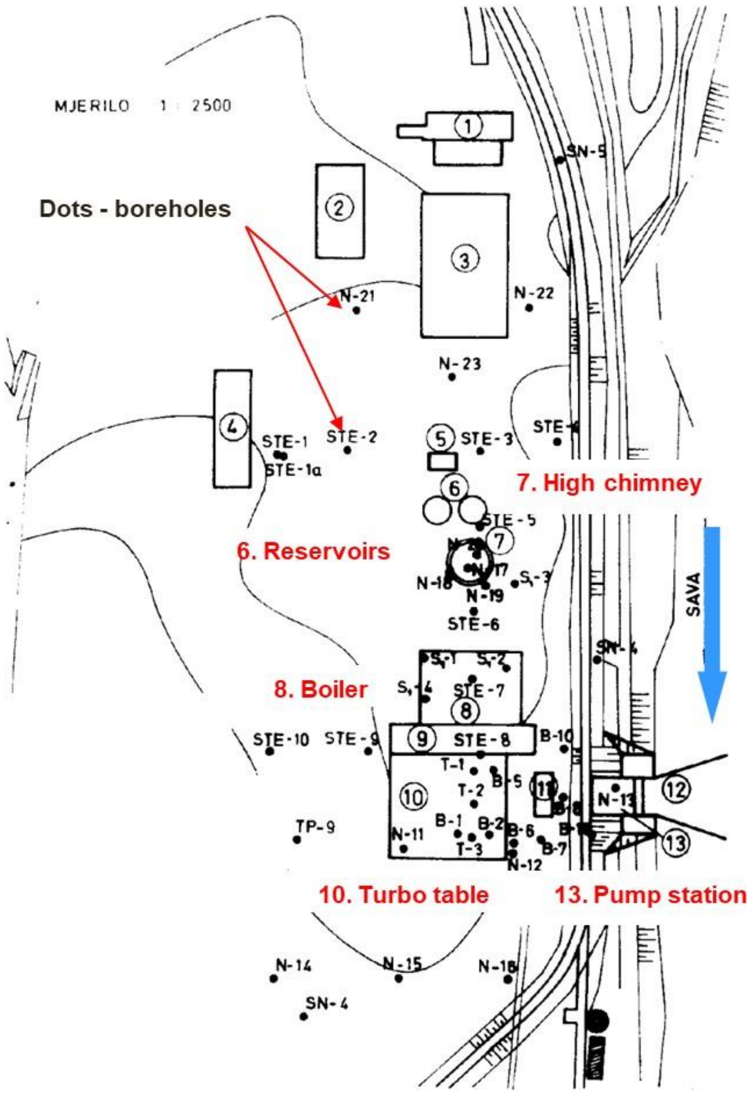

Figure 3.5 Plan view of the thermal powerplant Čret (45.4538, 16.4145).

Figure 3.6 Soil cores taken from the area near the thermal powerplant in Sisak, Čret (45.4538, 16.4145) (Marić, 2005).

On the location of the Čret thermal powerplant, the soil water level varies from 5.5 to 6.5 m below ground surface and strongly depends on the river Sava water level. Six borehole logs indicate strong soil layer heterogeneity that is typical for alluvial deposits. A surficial (I) fill layer is up to 3 m thick and is composed of brown fine sand and gravel; below is a 0.5 - 2.6 m thick brown (II) clay

(CL-CH) layer, with soft consistency, very silty (w_0 = 26.3 - 28.6%, w_L = 16.2 - 63.2%, w_P = 12.4 - 26.0%, I_P = 9.5 - 44.4%, g = 18.6 - 19.5 kN/m^3, g$_d$ = 14.6 - 15.4 kN/m^3, q_u = 18 - 195 kPa, c' = 20 - 50 kPa, f'= 24 - 28°). Below the clay layer is (III) 3.5 - 13 m thick sand, with various classifications: SFs, SFc, SP, SU, typically as fine sands, light-brown color. The SPT results are N_{SPT}=5-16, indicating loose to medium compacted sands. Granulometry shows particle sizes ranges: sand 59 - 99%, silt 6 - 38% and clay 1 - 6%. The next detected layer is also (IV) sand (SFs, SP), 2.1 - 14.5 m thick, fine, poorly graded, with clay and silt, sometimes with gravel, loose to medium dense, with N_{SPT}=5 - 16. Below is a layer of (V) gravel (GW, GP, GFs) 1.8 - 11.0 m thick. However, at the same depths, some boreholes demonstrated thinner or thicker layers of sand (SP), somewhere even 7.0 m thick. Gravel granulometry shows particle size ranges: gravels 19 - 88%, sands 12 - 81% and silt 0 - 2%. The bottom layer is (VI) clay (CL-CH), with varied plasticity in different boreholes, stiff to very stiff, of blue-grey color. Clay strata are detected at depths 22.5 - 28.0 m from the surface, while some 30 m boreholes did not display the bottom clay layer, but only sand. Clay properties are as follows: w_0 = 18.2 - 30.7%, w_L = 21.8 - 63.5%, w_P = 17.1 - 23.5%, I_P = 0.1 - 40.9%, γ = 15.6 - 20.4 kN/m^3, γ_d = 15.2 - 17.4 kN/m^3, q_u = 81 - 366 kPa, c' = 6 - 64 kPa, ϕ' = 13 - 31°. **Figure 3.7** shows CPTU tests performed within a perimeter of the thermal powerplant.

Oprema: **GEOTECH**

Klasa: **CPT3**

	q_c	f_c	u		
Kalibracijski kod:	**HZ**	**KQ**	**KF**	Datum:	12.02.2008
Nulto čitanje prije sondiranja	0	0	100	Posao:	**Sisak**
Nulto čitanje poslije sondiranja	-11.42	0	100	Datoteka:	12040102.CPT

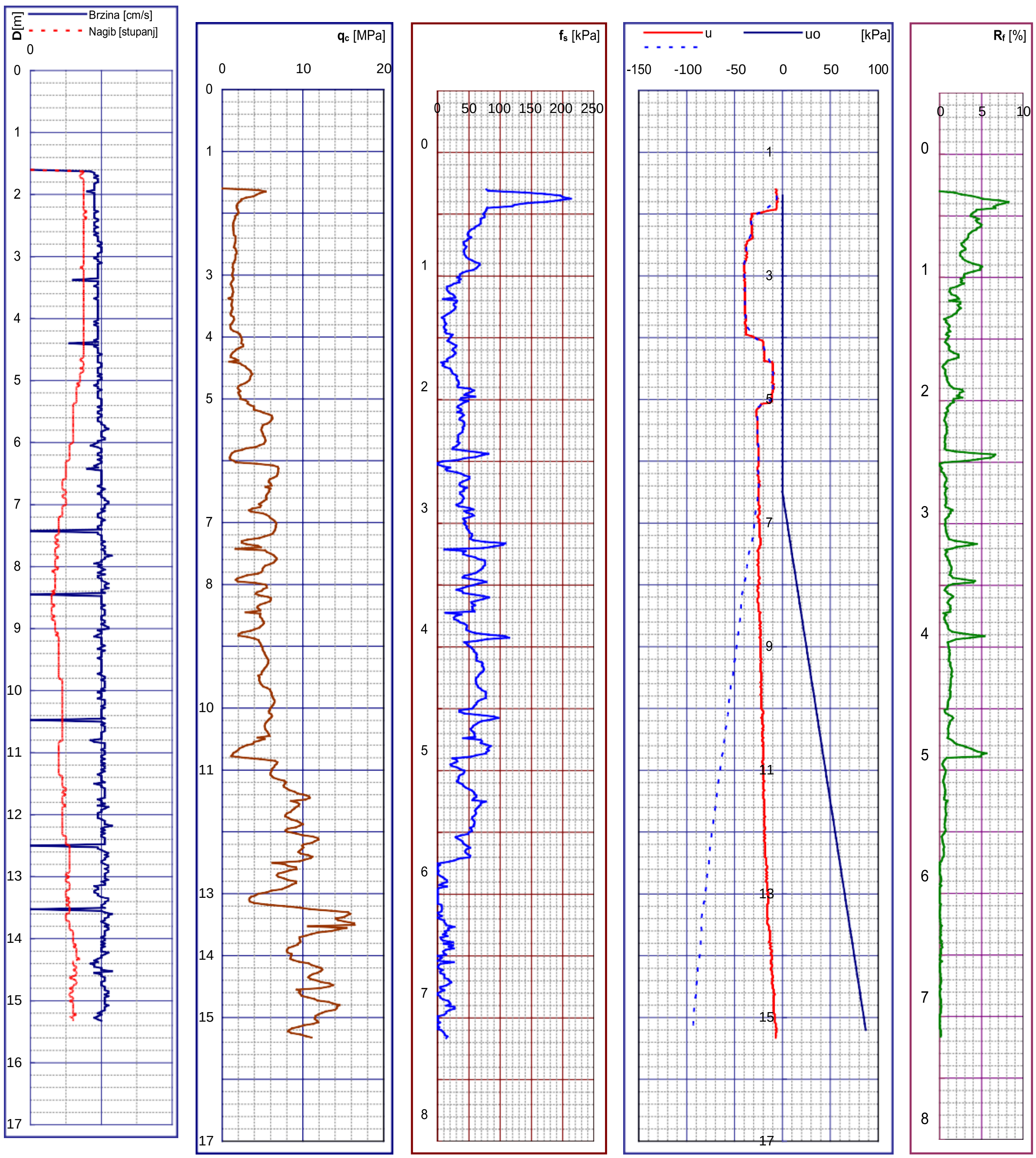

Figure 3.7 CPTU from thermal powerplant in Sisak, “Blok 3” Čret, (45.4538, 16.4145) (Marić, 2005).

References

Horváth, F., Musitz, B., Balázs, A., Végh, A., Uhrin, A., Nádor, A. Koroknai, B., Pap, N., Tóth, T.,Wórum, G. (2015). 'Evolution of the Pannonian basin and its geothermal resources.' *Geothermics*, 53, pp. 328–352.

Marić, B. (2005). *TE Sisak, Kombi-elektrana, BLOK 3, Sisak. Geotehnički Izvještaj, broj.pr. 09-05(Combi-Power Plant Geotechnical Report) 02/2005*. Zagreb: Conex Ltd.

Marić, B., Tomac, I., Puljak, S. and Lovrenćić, D. (2007). *Settlement measurements in the area ofthe town of Sisak over a period of 30 years*. Proceedings of the 6th Austrian Geotechnik Tagung, "Vienna - Terzaghi Lecture". Vienna, Austria, 18-19 January 2007. VOEBU, Wien.

Pikija, M. (1987) Osnovna geološka karta SFRJ 1:100.000, List Sisak L33–93. – Geološki zavod, Zagreb (1975–1986); Savezni geološki institut, Beograd. Geologic map available on requestat https://www.hgi-cgs.hr/osnovna-geoloska-karta-republike-hrvatske-1100-000/.

Šikić, K. (2014) Osnovna geološka karta SFRJ 1:100.000, List Bosanski Novi L33-105. – Fond stručne dokumentacije Instituta za geološka istraživanja, Zagreb. (manuskript) Geologicmap available on request at https://www.hgi-cgs.hr/osnovna-geoloska-karta-republike-hrvatske-1100-000/.

Šumanovac, F. (2010). 'Lithosphere structure at the contact of the Adriatic microplate and the Pannonian segment based on the gravity modelling'. *Tectonophysics*, 485(1–4), pp. 94–106.Available at: https://doi.org/10.1016/j.tecto.2009.12.005.

Šumanovac, F., Markušić, S., Engelsfeld, T., Jurković, K., Orešković, J. (2017). 'Shallow and deeplithosphere slabs beneath the Dinarides from teleseismic tomography as the result of the Adriatic lithosphere downwelling'. *Tectonophysics*, 712–713, pp. 523–541. Available at: https://doi.org/10.1016/j.tecto.2017.06.018.

Tomac, I. (2019). *Family House, Ul. Braće Hanžeka, Petrinja, k.č. 254, k.o. Petrinja. GeotechnicalReport nr. 02/2009*. Zagreb: Projekt Adrion Ltd.