Žirovac landslide: a case study of the local scale landslide investigation for engineering purposes with its assessment on a regional scale

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Abstract A detailed analysis of the "Žirovac" landslide on Croatia's state road section in the village of Žirovac is given in this case study. The landslide was triggered by the Petrinja earthquake in December 2020 and was subject to fast-paced processes of investigation and mitigation. The engineering geological and geotechnical survey including boreholes and geophysical investigations were performed on a large local scale.

The earthquake-induced rotational landslide was observed on the road embankment section, which was reported to be an old landslide, continuously covered by new layers of gravel material. Despite the localized, earthquake-induced landslide, the wider slope area showed significant signs of terrain sliding and/or creeping which could be observed on the existing damaged buildings and shallow constructions.

Performed investigation results indicated the presence of two landsliding mechanisms: (1) The local, rotational landslide of the road embankment induced by the Petrinja earthquake combined with the unfavorable load of the continuously added embankment layers and the underlying material degradation due to groundwater flow; (2) The global, translational creeping landslide of the wider slope area caused by occasional but significant groundwater flow and consequential degradation of the deeper-seated bedrock. The local landslide, as a primary subject of the investigation works performed, was limited to the road embankment section and embankment material. Although 225 m wide, the length of the local landslide was only 20 m, with a sliding surface depth of 2.5 m. The global landslide was reported as an old creeping landslide, causing occasional but continuous damage to the surrounding buildings and infrastructure. According to the investigation works performed, the global landslide was defined as a translational landslide, approximately 300 m wide and 300 m long with its sliding surface formed at a depth of 5-8 m, just above the underlying impermeable cretaceous clays.

Although the investigated local landslide was induced by the Petrinja earthquake, the effect of the global landslide on the local sliding was taken into consideration in the engineering geological report for landslide mitigation purposes. The continuously reported local landslides, before the Petrinja earthquake, were probably induced by the continuous creep of the global landslide.

This case study also observes the imperfections of the fast-paced, local-scale investigations for quick mitigation purposes regarding the landslide characteristics determination on a regional scale.

Keywords: landslide, earthquake, local scale, engineering

Introduction

The event of the "Petrinja earthquake" occurred on December 29th, 2020, in Sisak-Moslavina County in Croatia (Tomac 2021; Miranda et al. 2021). A 6.4 magnitude earthquake was felt throughout Croatia and large parts of neighboring countries, reportedly affecting and damaging areas within an approximately 50 km radius.

The researched "Žirovac landslide" is situated over 20 km south of the reported earthquake epicenter and was one of the many road section instabilities triggered by the Petrinja earthquake. Although the Petrinja earthquake reportedly triggered the road section landslide, no slope movement around the road embankment followed the event. Regardless, the surrounding slope area showed significant signs of sliding and/or creeping.

Location

The observed instability on a Croatian state road section (state road: DC6, section 004), is situated in the village of Žirovac in the southern part of Sisačko-Moslavačka County. This part of the road section generally extends in the direction west-east and perpendicularly crosses the natural slope, inclined 10-25° towards the south. Within the observed area, the road gradually rises from 330-338 masl. towards the east.

Figure 1. Location of the "Žirovac" landslide on the satellite map; satellite map source (Google)

The left (south) side of the researched road section is made on an embankment, up to 2.5m in height. A relatively shallow embankment is also present in the central part of the right side of the road section. Existing embankments and shallow cuts had no protection in terms of supporting constructions or other instability mitigation measures as well as no organized drainage system.

Landslide event

The earthquake-induced landslide event encompassed the body of the road in its full width along with the 2.5 m high road embankment. Shortly after the landslide event, to ensure traffic functionality, the unstable part of the landslide was covered with gravel material, forming a relatively denivelated but flat surface road. Such actions consequently covered most of the landslide body and part of the scarp and slip surface, limiting the ability to properly assess the landslide in terms of size.

Disregarding several potholes formed due to the embankment material's internal erosion, the newly formed gravel road section showed no signs of sliding in terms of tension cracks or other significant signs of landsliding. The landslide was evident on a general denivelation of the gravel road section, as well as on the partly covered main scarp which extended along part of the right (north) edge of the road as a shallow, 0.5-1.0 m cut under the natural slope.

According to the local information, the researched road section represents an occasional but persistent landslide, continuously covered with new layers of gravel material.

Figure 2. View towards the west on the unstable road section with the partly covered slide scarp along the northern edge of the road.

Although no instabilities were reported in the nearby vicinity of the earthquake-induced landslide, the surrounding slope area showed significant signs of sliding and/or creeping. Regardless of the absence of newly formed tension cracks or scarps, many irregular forms such as elongated depressions, bulges, and traces of smaller, overgrown secondary scarps perpendicular to the slope decline, characterized the surrounding slope area indicating a continuous sliding/creeping of the wider area.

Most of the abandoned structures and present family houses on the wider slope area showed clear signs of differential subsidence, with many wide diagonal cracks on masonry walls, while almost every shallow construction on the slope (garden fences, paved infrastructure, wooden sheds, etc.) was partially dislocated or leaned.

According to the local information, the wider slope area represents a continuous, slow-moving/creeping landslide with high levels of groundwater during and shortly after the rainy periods.

The global sliding of the wider slope area wasn't initially defined within the scope of the planned research, but it was accounted for in the engineering-geological report to properly assess the engineering-geological characteristics of the unstable slope area and the geotechnical mitigation works needed.

Figure 3. Abandoned and highly damaged masonry building above the unstable road section.

Figure 4. A damaged and leaned wooden shed below the unstable road embankment and an undamaged residential building with completely removed infrastructure.

Methodology

Research works

To better approach and elaborate the given problem, engineering-geological and geotechnical research works (Terraforming Ltd. 2021) performed on the location consisted of:

- Engineering-geological mapping of the area
- Exploratory drilling
- Geophysical Research (seismic refraction)
- Laboratory tests

A more detailed review of the geotechnical research works performed on the location is given in “Tab. 1”, while their position concerning the researched landslide is shown in “Fig. 5”.

Table 1. Review of geotechnical research works performed on the landslide location.

Geotechnical research works		Qty / Amt (m)
Exploratory drilling (research boreholes)		11 / 79
Standard penetration test (SPT)		35 / 11.7
Geophysical Research (seismic refraction)		1 / 200
Laboratory tests	Atterberg limits	15 / NA
	Particle size distribution	3 / NA
	Unconfined compressive strength of soil	3 / NA
	Shear strength of soil	3 / NA
	Uniaxial compressive strength of rock	1 / NA

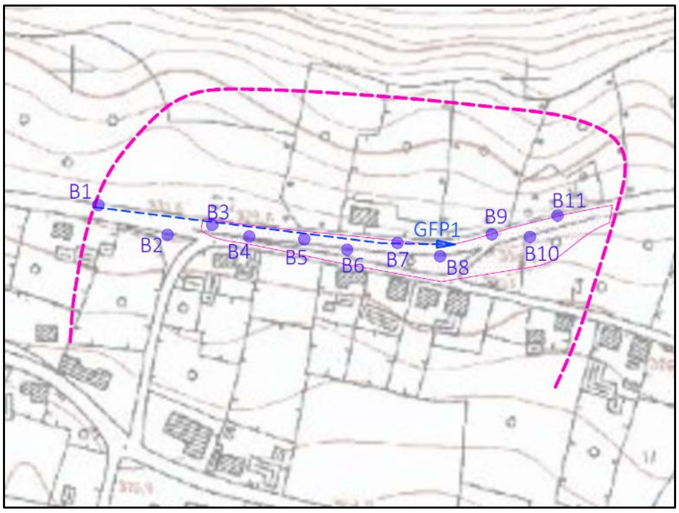

Figure 5. Review of the geotechnical research works performed on the location. Boreholes (purple dots) and geophysics (blue dashed line) within the researched landslides (magenta dashed line); topographic map source (DGU)

Engineering-geological mapping also encompassed the detection and measurement of the evident damages along the researched road section and the wider slope area, the determination of the landslide(s) type and size and the determination of the present instability causes with possible future development and consequences. Within engineering-geological research, the borehole logs determination and correlation with the laboratory test results and the geophysical research were performed. In addition, all the data obtained was cross-referenced with the existing research data of the location and the representative geological profile.

For the geotechnical interpretation of the geological profile, the determined cover and bedrock units were classified according to the governing standards ISO 14688 (EN ISO 14688-1:2002; EN ISO 14688-2:2004) and EN ISO 14689 (EN ISO 14689-1:2003) respectively.

Geological and geotechnical characteristics

Basic structural and geomorphological setting

Based on the existing data, the wider area tectonically represents the broken frontal thrust "Žirovac – D. Stupnica" of the "Inner Dinarides ophiolitic belt" on the "Sana-Una belt" (Šikić 2014; Šikić and Šimunić 2014). Structurally, it encompasses the frontal thrust of the "Ophiolithic complex of Banija" (K_1, ββ, $J_{2,3}$) within the "Inner Dinarides ophiolitic belt" on the structural unit of "Radašnica" ($T_3^{2,3}$) within the "Sana-Una belt" as shown in "Fig. 6".

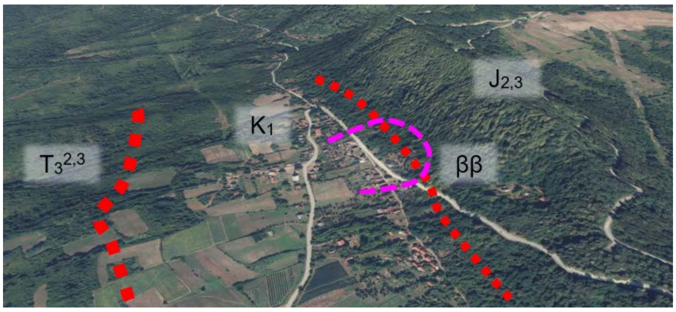

Figure 6. View on the geomorphological characteristics of the wider area with marked location of the global landslide (magenta dashed line) and frontal and secondary thrust (thick and thin red dashed line respectively); satellite map source (Google)

Considering the structural setting of the wider area, the main thrust area is characterized by a very small difference in slope inclination between the neighboring structural units represented with Cretaceous marls and limestones (K_1) and Triassic dolomites ($T_3^{2,3}$), where the dolomites governed area indicate a slight increase in slope steepness towards the south. The significant morphological difference is visible within the structural unit "Ophiolithic complex of Banija", at the secondary thrust of the metamorphic and Jurassic formations (ββ, $J_{2,3}$) on the Cretaceous sedimentary rocks (K_1) where the more resistant, metamorphous, and sedimentary rocks form the hill "Vratnik", while the weathered marls with limestones form the relatively slightly inclined area of the "Žirovac" village.

Engineering-geological characteristics

Based on the data obtained by geotechnical research works and engineering-geological mapping, the geological and geotechnical characteristics of the governing instabilities were determined.

The determined bedrock is represented by weathered marls with the occurrence of limestones in the central part of the landslide. This geological sequence corresponds well with the existing data which states that the wider area is built on lower-cretaceous marls interbedded with limestone layers (Šikić 2014). Limestones and marls represent the transgressional carbonates of terrestrial origin.

Bedrock layers are continuously covered by the deluvial/eluvial clay (younger) and clayey gravel (older), and the road embankment fill material. The thickness of the cover locally varies from 2.5-6.0 m in the central and eastern parts, with an increase to 7.0-9.5 m in the western part of the road section. This sequence can be observed on borehole cores in "Fig. 7".

Figure 7. View of the relatively adjacent borehole cores with the cover material overlaying weathered marls at 8.0 m depth (borehole B-3) and limestones at 7.0 m depth (borehole B-4).

A detailed review of the representative engineering-geological units and their characteristics are given in "Tab. 2" through "Tab. 4".

Table 2. Review of the representative engineering-geological units on the landslide location.

Engineering-geological units		Geotechnical classification	Unit
Cover (Quaternary)	Antropogenic (embankment) fill	clGr, GrP	C1
	Deluvium / eluvium	grsiClL, grsiClM	C2
		clGr, Co, Bo	C3
Bedrock (Lower Cretaceous)	Marl	siClL, siClM, siClH	BR1
	Limestone	Limestone	BR2

Table 3. Determined soil units' engineering-geological characteristics.

Unit	Plasticity[1]/ grading[2]	Consistency[1]/ density[2]	Thickness (m)
C1	poorly[2]	loose[2]	<2.5
C2	low – medium[1]	stiff – very stiff[1]	1.10 - 6.20
C3	undetermined	medium[2]	1.70 – 4.00
BR1	low – high[1]	hard[1]	undetermined
Plasticity/grading (EN ISO 14688-1:2002; EN ISO 14688-2:2004) Consistency/density determined by SPT values (Look 2007)			

Table 4. Determined bedrock (limestone) unit engineering-geological characteristics.

Unit	UCS (Mpa)	RQD (%)	GSI
BR2	123	0-25 (80)	25-30
UCS – Uniaxial Compressive Strength RQD – Rock Quality Designation (Hoek 2007) GSI – Geological Strength Index (Hoek 2007)			

Hydrogeological conditions

Hydrologically, the wider area belongs to the Sava River basin while hydrogeologically, it belongs to the northern part of the so-called "Inner area" with possible local aquifers of intergranular or secondary porosity (Ivković et al. 1983). Surface and groundwater flow is oriented in the direction of the slope decline (south), from the "Vratnik" hill toward the existing creek of "Žirovac".

In general, the Jurassic, and metamorphic complex of the upslope "Vratnik" hill represents the permeable media of secondary porosity with dominant groundwater flow. The Cretaceous sedimentary rocks within the researched landslide represent the media of generally low permeability and dominating intergranular porosity, with the possibility of forming local and irregular groundwater paths within the broken limestone layers. Consequently, in the close vicinity of the secondary thrust or at the contact of the metamorphic and Jurassic complex with the Cretaceous layers, temporary springs, and surface drainage paths are registered. Triassic dolomites further to the south also represent the media of low permeability and secondary porosity, maintaining the surface flow of the water ("Žirovac" creek).

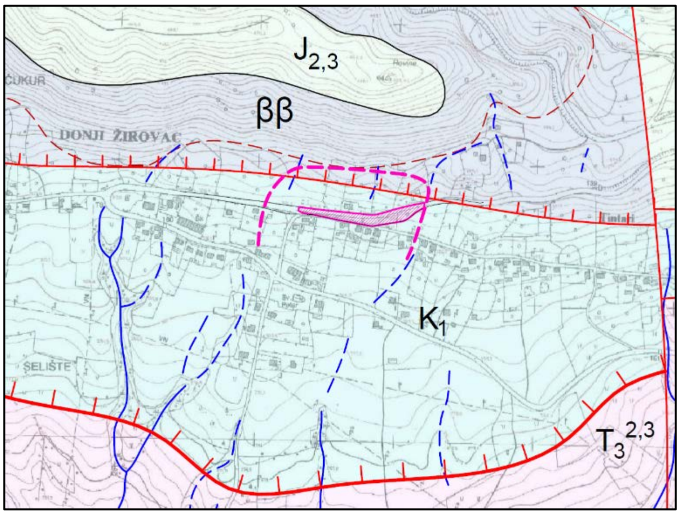

Figure 8. A review of the wider area's structural setting and representative stratigraphical units with specific hydrogeological characteristics; topographic map source (DGU)

Representative bedrock and cover on the landslide location are characterized by a high variety in permeability, where the gravel-dominated cover and limestone bedrock represent the permeable media, while the clay-based cover and bedrock represent the impermeable media as shown in "Tab. 5".

Table 5. Porosity and permeability of the representative engineering-geological units on the landslide location.

Unit	Porosity type	Permeability coefficient k (m/s) (Look 2007)
C1	Primary	$>10^{-4}$
C2		$10^{-5} – 10^{-7}$
C3		$10^{-3} – 10^{-5}$
BR1		$<10^{-7}$
BR2	Secondary	$>10^{-4}$

Locally, precipitated water is slowly infiltrated in the relatively impermeable natural cover (deluvial-eluvial clay) and tends to accumulate and flow through the permeable embankment material, consequently weakening and eroding the underlying clay material. Groundwater tends to flow through the more permeable layers of cover and bedrock in the direction of the slope decline, also consequently weakening and eroding the bordering clay material.

Groundwater level below the road was determined on the landslide edges at the depths of 3.0-6.5 m with a slight decline towards the west, while at the central part, the groundwater level wasn't reached due to the inadequate boreholes' depth.

Landslide characteristics

The performed engineering-geological and geotechnical research works indicated the presence of two instability mechanisms practically denoted as the local landslide and the global landslide.

Local landslide

The local landslide represents the earthquake-induced landslide of the road embankment in its full width. The road embankment consists of up to 2.5 m thick clayey gravel filling material, overlaying the deluvial-eluvial clay and gravel cover and the deeper bedrock of weathered marls interbedded with limestone layers, situated approximately 2.5-7.0 m below the surface level.

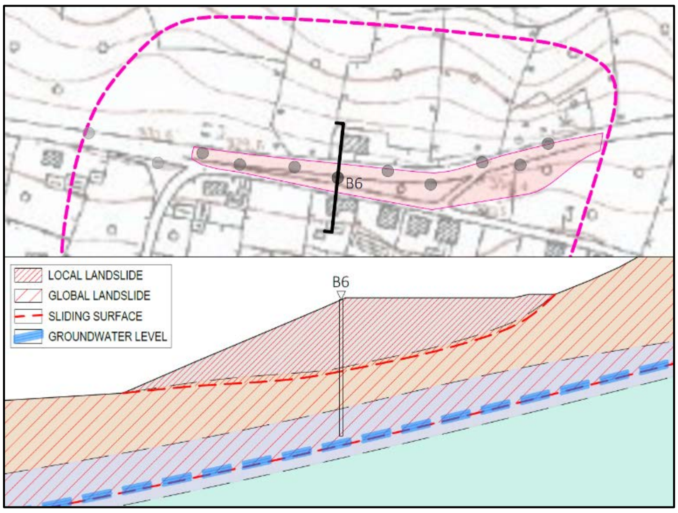

Figure 9. Cross-section of the central part of the "Žirovac landslide" area with the road embankment overlaying the deluvial-eluvial cover (brown), and bedrock of limestones (purple) interbedded within marls (green); topographic map source (DGU)

The earthquake-induced sliding represents the embankment material rotational sliding along the upper cover – deluvial-eluvial clays. Although the sliding material mostly consists of gravel and boulders, the local landslide can be defined as a clay/silt rotational slide, due to the probable failure in the clay cover.

Regardless of the earthquake event, the sliding was also potentiated by the embankment material weight and the sliding surface geotechnical characteristics degradation from groundwater flow. According to the local information, local landslide represents an occasional but persistent landslide, continuously covered with new layers of gravel material.

The Local landslide characteristics are presented in "Tab. 6".

Table 6. Review of the Local landslide characteristics

Landslide characteristics – Local landslide		
Classification (Hungr et al. 2014)		Clay/silt rotational slide
Dimensions		Width ≈ 225,0 m Length ≈ 20,0 m Sliding surface depth / Sliding material thickness = 2,5 m
Activity (Cruden and Varnes 1996)	State	Active
	Distribution	Undetermined
	Style	Complex
Material (Hungr et al. 2014)		C1 – dry gravel C2 – stiff clay

Global landslide

According to the research data, the global landslide is evaluated as the translational movement of the wider slope area with a sliding depth of 5.0-8.0 m below the road section.

Sliding material consists of both embankment material, and deluvial-eluvial cover, including the permeable limestone layer as an upper bedrock layer. This way the sliding surface of the limestone layer and the overlaying cover material is formed on a contact with weathered impermeable marls.

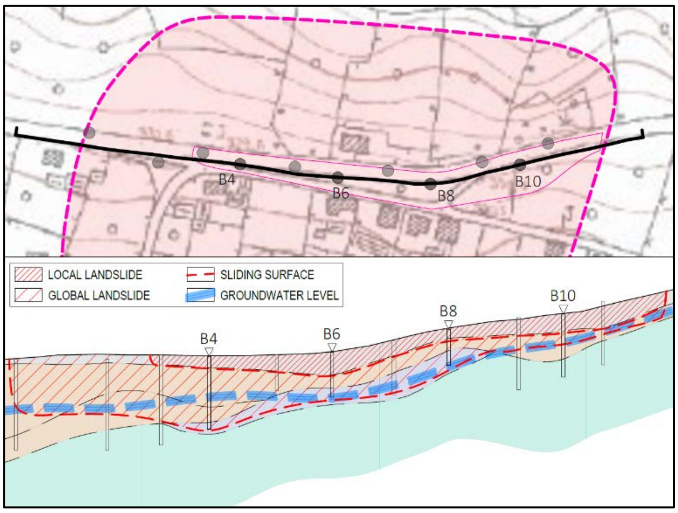

Figure 10. Frontal view of the "Žirovac landslide" along the embankment's southern edge with the surficial road embankment overlaying the deluvial-eluvial cover (brown), and bedrock of limestones (purple) interbedded within marls (green); topographic map source (DGU)

Although such a sliding mechanism could not be confirmed with the limited data acquired for the local landslide mitigation purposes, indications for the global landslide were significant, like the presence of the elongated depressions, bulges, and traces of smaller, overgrown secondary scarps perpendicular to the slope decline as well as the characteristical damages on the present constructions as shown in "Fig. 2" through "Fig. 4". This was also confirmed by the local information, according to which the wider slope area represents a continuous, slow-moving landslide with high levels of groundwater during and shortly after the rainy periods.

The Global landslide characteristics are presented in "Tab. 7".

Table 7. Review of the Global landslide characteristics

Landslide characteristics – Global landslide			
Classification (Hungr et al. 2014)			Rock and/or Clay/silt translational slide
Dimensions			Width ≈ 300,0 m Length = ND Sliding surface depth / Sliding material thickness >5 m
Activity (Cruden and Varnes 1996)	State		Active
	Distribution		Undetermined
	Style		Complex
Material (Hungr et al. 2014)			C1 – dry gravel C2 – stiff clay C3 – clayey gravel BR2 – strong rock (limestone)

Concluding remarks

The case study presented here observes the landslide event research for mitigation purposes. Due to the need for immediate mitigation of a state road section, relatively fast-paced geotechnical research works were planned and conducted. Such an approach neglected many of the initial geological aspects of the landslide which could be assessed by detailed analysis of the existing geological data of the wider area and existing topographic data of the area. By conducting previous analysis, geotechnical research works could be performed with a better understanding and focus on the existing problem.

Regarding the presented case study, engineering-geological research was done apart from the geotechnical research works and some of the problems that occurred within the research process are listed below:

- Performed boreholes in the central part of the unstable road section ended in the limestone layer. This is common in practice since the hard bedrock often indicates its continuous occurrence with increasing depth and considering the contracted limitation in total borehole depths, the drilling usually stops within 1 m. However, by assessing the existing geological data of the wider area, it was found that the limestone layers are interbedded within dominant marls, and the boreholes should be performed in a way to validate this since it represents an important factor for the global landslide.
- The researched instability was initially approached and contracted as a local, road section landslide, disregarding the evidence of the global landslide of the wider slope area. This also meant that the geotechnical research works were limited to the local landslide area so that the global landslide characteristics could be evaluated only by a superficial analysis of the existing geological and topographical data.
- The proper research of the global landslide would require additional time and resources that were not covered within the contract scope. Additionally, to prepare all the necessary documentation for the global landslide research, all owners of the affected parcels, including different local and/or state Administrations need to be involved. This often proves to be a long and problematic process, especially in large and inhabited areas.

In conclusion, the imperfections of the fast-paced, local-scale investigations for quick mitigation purposes are evident within this case study, where the global geological, morphological, and hydrogeological conditions were generally neglected within the scope of the geotechnical research works, but relevant regarding the present problem.

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