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Petrinja M6.2 earthquake in 2020 damaged also solid linear infrastructure: are there similar active faults in Croatia?

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Abstract

On 29 December 2020 destructive M6.2 earthquake hit well known Petrinja epicentral area, and caused strong damage on many buildings in Petrinja, Sisak, and Glina, as well as on solid modern linear infrastructure (roads, bridges, artificial river embankments, pipelines etc.). The seismic hazard is not depending only on the estimated coseismic ground acceleration that should be used for EUROCODE 8 constructional seismic design, but is also strongly dependent on local soil effects and on the secondary effects of a strong earthquake (landslides, liquefaction, suffosion, etc.). Besides, movement of the crustal blocks along the fault lines that cross the solid objects, in case of surface coseismic rupture such was the Petrinja event, should be evaluated. Local site amplification effects are the results of several physical processes (multiple reflections and diffractions, focusing, resonance, wave trapping) in the overlying superifical deposits and soil, resulting in variable damage distribution that were observed in different local geological units affected by an earthquake. Also, the variable surface topography and various mechanical properties of the terrain such as water table, slopes, presence of heterogeneities, structural discontinuities and cavities, certainly can contribute to the observed damage and increase geological hazard in epicentral area. How many unknown active faults we can identified in Croatia? What could be surface manifestation of a strong earthquake that will occur on a shallow thrust (reverse) fault? Is there any major normal active fault that can surprise seismotectonic experts and civil engineers? The authors published first scientific paper after the Zagreb 22 March 2020 event and are currently working on active tectonics in Kvarner region and Hrvatsko Zagorje. Besides, a new Croatian Science Foundation (HRZZ) project has just been started with special attention on soil dynamic properties and its influence on the seismic hazard of the older cultural buildings in Trakošćan, Šibenik and Dubrovnik.

Key words: active tectonics, strike-slip faults, earthquake, coseismic surface ruptures, linear infrastructure, EUROCODE 8, seismic hazard

1 Introduction

The mainshock of the Petrinja (Croatia) 2020 heavily damaging to destructive seismic sequence of intensity VIII-IX EMS-98, was on 29 December 2020 with the magnitude of 6.2 and estimated intensity of VIII-IX °EMS [1]. The mainshock caused considerable damage and numerous ground failures, mostly due to the local site effects. Because of a specific fault mechanism and relatively shallow focal depth [1], surface ruptures occurred [2], and there was also a significant damage on the structures crossing activated faults from the fault system.

Based on the preliminary geological analyses, the M6.2 earthquake event was the result of the activation of complex fault systems, the intersection of two regional faults (longitudinal and transverse ones) to the strike of the Dinarides that were probably inherited since the formation of the fold-and-thrust belt [1, 3]. Both fault systems consist of multiple faults with horizontal (strike-slip) block movements. Beside the main activated faults (Figure 1), there were other conjugated faults that caused linear surface cracks and sand spills, because of the liquefaction within the uppermost part of superficial deposits in the plains of Kupa, Glina and Sava rivers.

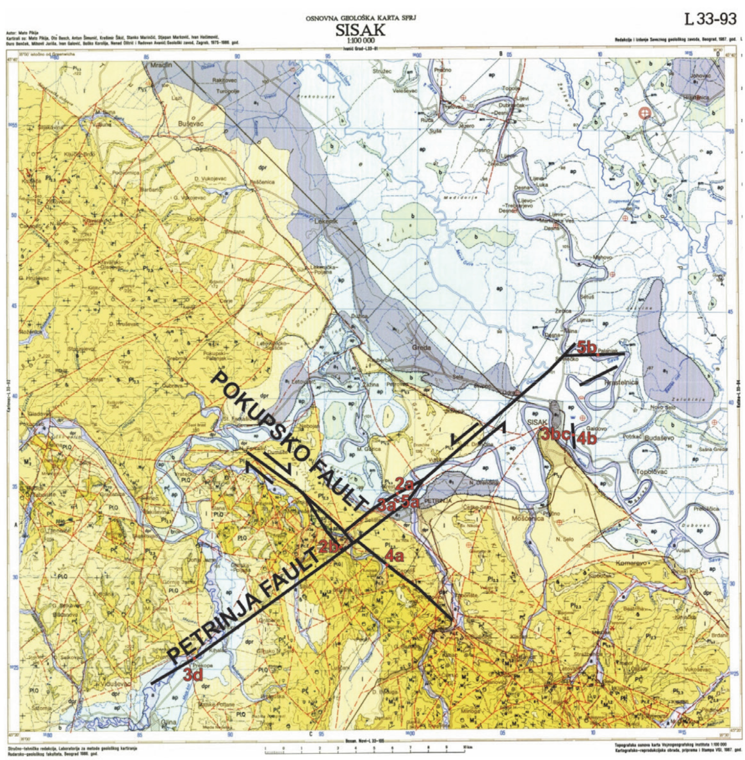

Figure 1. a) Geological map [4] showing the main activated faults (thick black lines) during the Petrinja 2020 sequence [1]. Red dots and numbers mark locations of the other Figure s.

The active tectonics of the territory of Republic of Croatia is caused by the continuous movement of the Adriatic lithospheric microplate (Adria) to the north [5]. Therefore, the strain occurs in the upper parts of the Earth's crust. When the strain reaches the critical level, individual faults from that system are becoming (re)activated. Considering this fact, the other potential epicentre areas in Croatia are also vulnerable in case of similar earthquake event. Besides, what we learned from the Petrinja event, is that potential aseismic (creeping) faults [6] exist in Croatia. The creeping faults must be investigated in the future, and considered during design and construction of the capital infrastructural objects.

According to the earthquake resistant design provisions in compliance with Eurocode 8 [7], the peak ground acceleration (PGA) and local site amplification effects should be considered [1]. However, the Petrinja earthquake effects raised the question of a damage on lifelines crossing active fault lines. Furthermore, the question is not reliable only in the cases of strong crustal block movements that cause coseismic surface ruptures along the active faults, but also in the cases of the aseismic active faults such is Petrinja creeping fault. Thus, a special attention should be given to geological and seismological characteristics of a terrain during the strategic planning of the infrastructure, as well as to the specific microlocations with respect to the active faults. Furthermore, construction plans for important infrastructural lifelines should be accompanied with analyses of possible active faults crossing the area, as well as analyses of (micro) seismological site effects that can strongly influence the coseismic ground acceleration at specific superficial geological deposits and certain soil types.

The authors recently published first scientific results on the Zagreb 22 March 2020 event [8], as well as on the active tectonics in Kvarner region [9], and we are currently still working on the topic [10]. Besides, a new Croatian Science Foundation (HRZZ) project has just been started with special attention on soil dynamic properties and its influence on the seismic hazard of the selected cultural buildings in Trakošćan, Šibenik and Dubrovnik [11]. Both project themes are closely related to the Petrinja 2020 earthquake that was characterized also by an unusual damage, and that is why we focused the last months to the destructive event.

2 Field observations on coseismic lifeline damage

During the Petrinja M6.2 earthquake sequence in 2020, there were several observed cases of lifeline damage crossing the active fault lines, that include roads, bridges, pipelines and artificial riverbanks.

2.1 Roads

Numerous reports in media allowed quick online research of the ground surface failures and infrastructure damage that appear along approx. 30 km long portion of sinistral NE-SW striking Petrinja Fault (Figure 1). A coseismic damage was observed in two locations on the Petrinja-Brest road (Figure s 2a and 2b). A quick field inspection revealed that cracks on the road, built on the bedrock of Hrastovička gora at Župić, appeared mostly along Pokupsko Fault, and revealed the clear dextral coseismic strike-slip displacements (Figure 2c).

Figure 2. a) Coseismic cracks and small transpressional structure (mole track) along one of the fault lines of the creeping sinistral Petrinja Fault crossing Petrinja-Brest road north of the Brest Bridge over Kupa river (CREDIT: Public media), b) Coseismic dextral ~10 cm displacement (white arrows) and tensional cracks (black arrows) along one of the fault lines of the Pokupsko Fault crossing Petrinja-Glina road west of Župić. (CREDIT: M. Vukovski, HGI)

2.2 Bridges

Beside the cracked road along the Petrinja Fault north and south of Brest Bridge on Kupa River, there was a significant damage on the bridge itself, since the bridge was in a tension zone between the two closely spaced sinistral faults that belong to Petrinja Fault zone (Figures 1 and 3a).

The new bridge at Galdovo (Sisak) on Sava River has been displaced along a left-lateral fault line striking N-S that is still not mapped (Figure 3b). The bridge is displaced for ~10 cm over the eastern basement (Figure 3c). The bridge on Glina River at Prekopa was cracked and displaced left-lateral for a few cm along the Petrinja-Glina Fault line (Figure 3d).

Figure 3. **a) Coseismic tensional cracks south of Brest Bridge located between two fault lines of the creeping sinistral Petrinja Fault (CREDIT: Public media), b) Coseismic sinistral displacement along generally N-S fault line of the activated complex fault system crossing the Galdovo Bridge over Sava river (Sisak), c) shifted construction of Galdovo Bridge (thick arrow) because of a sinistral movement (thin arrow) of the blocks along the fault line crossing eastern tip of Galdovo Bridge, d) Coseismic fractures along the main sinistral Sisak-Petrinja-Glina-Topusko Fault line crossing Prekopa Bridge over Glina river (CREDIT: D. Palenik, HGI).**

2.3 Pipelines

Water pipeline at Cepeliš was broken due to coseismic dextral movement of the fault blocks along dextral Pokupsko Fault (Figure 4a). The gas pipeline at Galdovo Bridge (Sisak) was damaged during the Petrinja earthquake, as well (Figure s 3b and 4b).

Figure 4. a) Reconstruction works on water pipeline at Cepeliš that is crossed by regional Pokupsko Fault (CREDIT: HGI EQ Team), b) Temporarily repaired Gas pipeline damaged because of sinistral coseismic displacement of Galdovo Bridge over Sava river (Sisak).

2.4 Artificial riverbanks

There were numerous cracks along the activated Petrinja Fault that crosses Kupa and Sava river's artificial riverbanks at Brest (Figure 5a) Drenčina, Pračno and Tišina. Besides, some conjugated faults from the system, possibly a horsetail splay termination at the tip of the activated segments of the main faults, damaged the Sava riverbanks at Palanjek (Figure 5b), Bok Palanječki, Hrastelnica and Galdovo.

Figure 5. a) Surface fault crossing the Kupa riverbank at Brest Bridge, b) Surface fault rupture crossing the Sava riverbank at Palanjek (CREDIT: Public media).

3 Design considerations for coseismic lifelines

After the Petrinja 2020 earthquake sequence, an urgent need for a better evaluation of the seismic hazard in the region evolved. It became obvious that the seismic hazard is not depending only upon the estimated coseismic ground acceleration that should be used for the earthquake resistant design provisions in compliance with Eurocode 8 [7], but is also strongly dependent on local soil effects and on the secondary effects of a strong earthquake (landslides, liquefaction, fast karstification, suffosion, etc.). Besides, the movement of the crustal blocks along the fault lines that cross the lifelines, in the case of surface coseismic rupture occurred during the Petrinja event, should be evaluated. The displacements along the fault lines would be even larger if the objects were on the bedrock. Superficial deposits of the Kupa, Sava and Glina rivers decreased a few metres block movements in the crust, and thus the linear objects are displaced only a few cm along some fault lines of the activated fault system.

The local site amplification effects were the consequence of several physical processes such as multiple reflections and diffractions, focusing, resonance, wave trapping in the overlying superficial deposits and soil. They resulted in the variable damage distribution observed in different local geological units affected by the earthquake.

The variable surface topography and various mechanical properties of the terrain, such as water table, slopes, presence of heterogeneities, structural discontinuities and cavities, evidently contributed to the observed damage and increased the geological hazard in the epicentre area.

Surface fault ruptures during strong earthquakes, including Petrinja 2020 event, lead to surface displacements in range of micro ruptures to a few decimetres, generally along traces of active faults. Co-seismic fault rupture is a relatively rare event and after such a strong earthquake, it is obvious that constructional seismic design EUROCODE 8 surpass direct damages along the surface fault ruptures. The goal of seismic design of structures is to withstand ground shaking effects (ground acceleration, site amplification) to limit damage and collapse. However, the question is what is the risk of damage for structures and linear objects constructed over the fault? EUROCODE 8 requires that buildings of importance category II (ordinary buildings), III (schools, assembly halls, cultural institutions) or IV (hospitals, fires stations, power plants) are not built in the immediate vicinity of such faults. But the main problem here is, firstly, the identification of active faults (known and unknown) and, secondary, assessment of sites prone to higher geological hazard in case of a strong earthquake. Then, we can point out that these kind of locations should be avoided for future construction or structures should be designed/retrofitted to withstand surface fault ruptures in case of a strong earthquake. However, from the economical point, seismic design and retrofitting of structures, foundations, and linear infrastructure objects to withstand more than a few centimetres of fault displacement is very questionable.

Assessment of secondary effects of strong earthquake in terms of site geological hazards that includes liquefaction, karst sinkholes, suffusion, slope instability, and particularly surface fault ruptures should be carried out for mitigation, evaluation, screening, urban planning and retrofitting by multidisciplinary team of seismologists, geologists, seismotectonic experts, geotechnical and construction engineers. This knowledge is important for future strong earthquakes seismic design, re-building and seismic strengthening of damaged buildings and linear infrastructural objects in the areas of active faults to mitigate its negative effects.

4 Conclusions

The coseismic lifeline damage observations after M6.2 Petrinja earthquake event, raised the following questions: How many unknown active faults do we already have identified in Croatia? What could be the surface manifestation of a strong earthquake that would occur on a shallow thrust (reverse) fault? Is there any major normal active fault that can surprise seismotectonic experts and civil (structural) engineers?

These questions highlight the necessity for a multidisciplinary approach, not only in the case of the capital infrastructural lifelines, but also in the case of other important structures (e.g. dam, power plants, etc.) that could be affected by strong coseismic ground motion and by displacement of the surface parts of the faulted blocks in cases of surface ruptures. It should be highlighted that the appearance of surface ruptures depends on the fault mechanism, the magnitude, and the focal depth.

The seismic hazard is not only depending on the estimated coseismic ground acceleration that should be used with the earthquake resistant design provisions (EUROCODE 8), but is also strongly dependent on the local soil effects and on the secondary effects of a strong earthquake (landslides, liquefaction, suffosion, etc.), as well as on the movement of the crustal blocks (and the overlying superficial deposits and soil) along the fault lines that crossing the lifelines, in cases of the surface coseismic ruptures such was the Petrinja event.

Local site amplification effects are the results of several physical processes (multiple reflections and diffractions, focusing, resonance, wave trapping) in the overlying superficial deposits and soil, resulting in variable damage distribution that were observed in different local geological units affected by this earthquake. Also, the variable surface topography and various mechanical properties of the terrain such as water table, slopes, presence of heterogeneities, structural discontinuities and cavities, along with possible deep crustal fluid flows to the surface triggered by the earthquake, certainly contributed to the observed damage and increased seismic hazard in the wider epicentre area.

These issues are imposing the question of re-evaluation of the existing and for a proper design of the new strategic structures, predominantly infrastructural lifelines as a part of their management and planning in Republic of Croatia.

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