STOP 1: Landslide Kostanjek

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The Kostanjek landslide is the largest landslide in the Republic of Croatia. It is a reactivated deep-seated translational landslide located in the urbanized area of the City of Zagreb at the base of the southwestern slopes of Medvednica Mt. (Fig. 4). The sliding surface is developed in Sarmatian laminated marl, characterized by alternation of very thin light and dark laminae known as varves (according to WEINHEIMER & BIONDI, 2003). Displaced mass above the Sarmatian sediments consist of Lower Pannonian clayey marls with thin limestone layers and Upper Pannonian massive clayey marls. The width of the displaced mass is 960 m, and the total length of the Kostanjek landslide is 1.26 km. The maximal depth of the sliding surface is 90 m, according to interpretation of ORTOLAN & PLEŠKO (1992). The total landslide area is approximately 1 km^2, and the volume of the sliding mass is evaluated to be 32 × 10^6 m^3 (STANIĆ & NONVEILLER, 1996). Since its activation in 1963, Kostanjek landslide has caused substantial damage to buildings and infrastructure in the residential (Fig. 5) and in industrial zones. The deep-seated landslide was caused by anthropogenic factors, mainly by excavations in a marl quarry placed in the toe part of the landslide (Fig. 6). Uncontrolled blasting during the 1960s and 1970s in the marl quarry and the limestone quarry, placed approximately 1 km to the north from the upper part of the landslide, were also important destabilizing factors. Surface deformations are mostly expressed as ductile deformations with rare opening of cracks, even at the landslide boundaries. Despite extremely slow to slow landslide movements for 52 years, the risk in the area of the Kostanjek landslide is very high for residential properties (approximately 300 single-family houses and infrastructure networks are placed on the moving landslide mass).

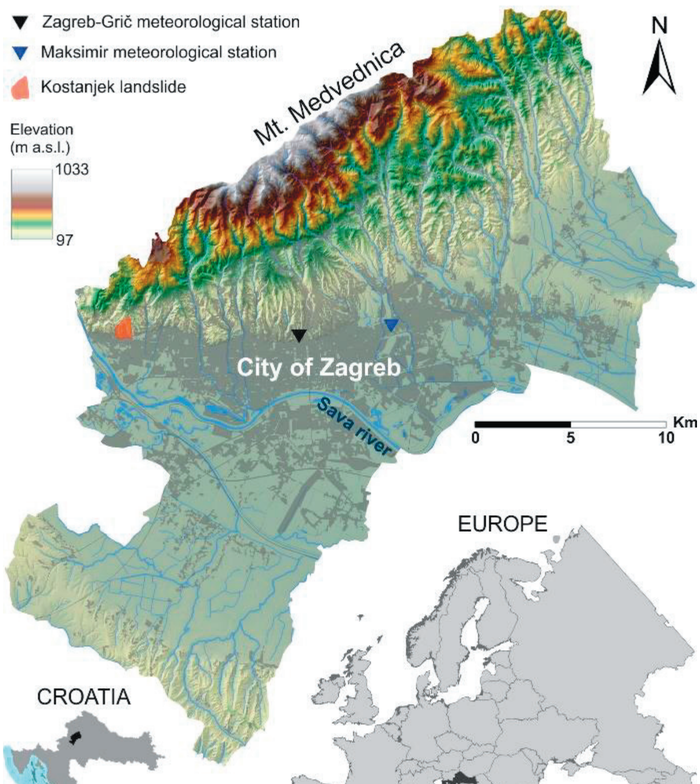

Figure 4. Location of the Kostanjek landslide and the meteorological station Zagreb-Grič (KRKAČ et al., 2017).

Figure 5. Damage caused by sliding (photo by D. Tibljaš).

Monitoring system

The Kostanjek landslide monitoring system was established in the framework of the scientific Japanese-Croatian bilateral SATREPS FY2008 project „Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia“, with the main objective of landslide mitigation though the development of an early-warning system (MIHALIĆ ARBANAS et al., 2013). In the period 2011–2014, multiple sensor networks (Fig. 6) were set up for continuous observations of (1) displacement (Global Navigation Satellite System or GNSS stations, extensometers, borehole extensometers), (2) hydrological properties (pore pressure gauges and water level sensors in boreholes and domestic wells, water level sensors at outflow weirs), and (3) external triggers (rain gauge and accelerometers). The majority of monitoring equipment is installed at a central monitoring station, located in the central part of the Kostanjek landslide (Fig. 6).

Analysis of monitoring data from all GNSS stations at showed similar patterns of movements across the entire landslide area, with the maximal velocities in the central part of the landslide and the lowest velocities along the landslide boundaries (KRKAČ, 2015). The total surface displacement in the period 2013-2016, measured by GNSS in central part of lanidslide was 440 mm. The displacement mainly occured durring the six periods of faster movements. The maximal observed velocity during the periods of faster movement was 3.3 mm/day, while during the periods of slower movement, the landslide velocities were up to 3 mm/month (0.1 mm/day). All periods of faster movement occurred as a consequence of groundwater level (GWL) rising (Fig. 7). The minimal observed GWL depth at the central part of the lanidslide was 10.5 m, and the maximal GWL depth was 19.03 m. Altogether, 17 periods of GWL rise occurred, during which GWL relatively changed up to 5.25 m. 12 of the 17 periods of high GWLs correspond to six periods of faster displacement. All GWL rising periods occurred after periods of intensive precipitations and snowmelt (Fig. 7).

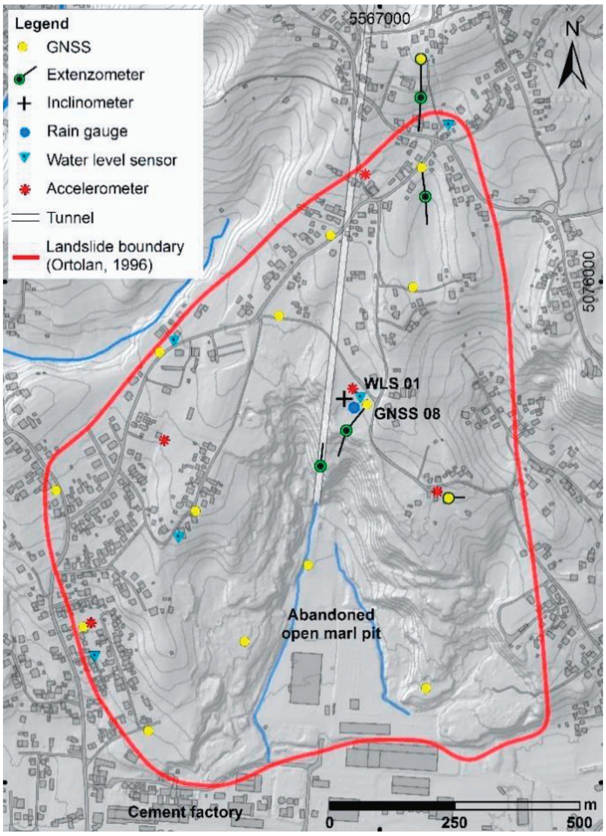

Figure 6. Multiple sensor networks at the Kostanjek landslide (KRKAČ et al., 2017).

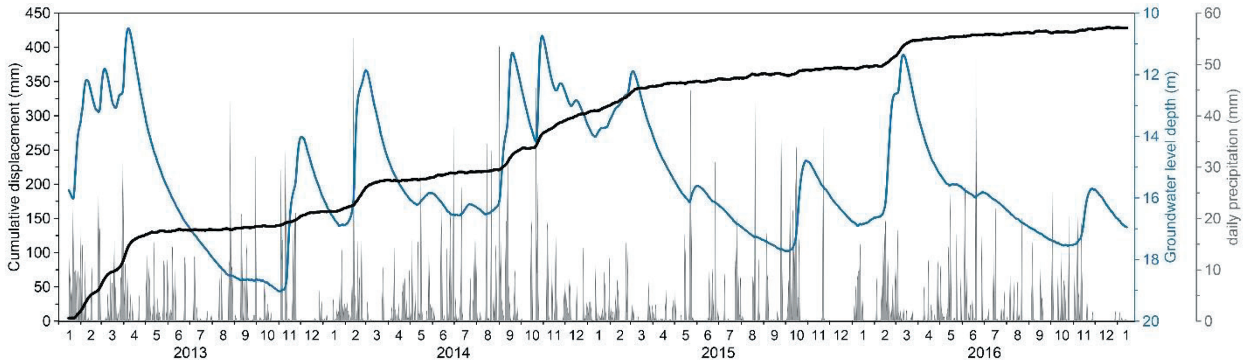

Figure 7. Displacements and groundwater level depths measured at the central monitoring station of the Kostanjek landslide and 1-day antecedent precipitations measured at Zagreb-Grič meteorological station.

Clay mineralogy

The slip surface in the mid-part of the Kostanjek landslide has been identified by KRKAČ (2015) using inclinometer measurement in the B-1 borehole to be in the Sarmatian unit, at the depth of 62–63 meters, consisting of thinly laminated marl rich with clay named varvites. Varvites or laminites, as defined by KOCHANSKY (1944), are interchangeable layers of light marl with calcite and dark marl with organic matter ("Tripoli" sediments).

Among the first mineralogical research done on the Kostanjek landslide site was by BALEN et al. (1975) using microscope analyses. Among their samples, they differentiated two structures: homogenous marl, corresponding with the Lower Panonian unit, and marl with white and grey alternating layers, corresponding with the Sarmatian thinly layered clays. In the latter unit, the white layers were identified as a carbonate component, while the grey layers were rich with clay minerals.

In SLOVENEC (1989), the Sarmatian unit was further researched. The alternating white and grey layers were attributed to the Tripoli Fm. in accordance with the abundance of diatomite and radiolarian fragments. Both the white and grey components were determined as containing a large amount of amorphous SiO_2 and organic matter. The white component contained mostly aragonite, with a smaller amount of calcite, gypsum and a minor amount of clay minerals, while the grey component consisted also of aragonite and calcite, along with dolomite and less amorphous matter than the white, but more organic matter and irregularly interstratified phyllosilicate minerals. The phyllosilicates identified were montmorillonite (15–20 %) and chlorite, while samples from the Upper Sarmatian showed a significant presence of micaceous minerals.

Mineralogical analysis by X-Ray diffraction was done by MARTINČEVIĆ et al. (2013) on samples from the B-1 borehole in the mid-part of the landslide area. Four stratigraphic units were differentiated: Quaternary soils, Upper Panonian massive marl, Lower Panonian marl and Samatian laminated clays. Clay minerals were the main component in all units except one, the Lower Panonian, where they are present in the same amount as calcite. The amount of calcite generally increases with depth. The clay minerals determined in these samples were smectite with 50–70 wt% throughout the analyzed interval, along with kaolinite, chlorite, illite and muscovite (Fig. 8). In MARTINČEVIĆ LAZAR et al. (2013), the mineralogical composition of these samples was confirmed, along with the presence of a calcite component. They refer to the fact that, along with sliding, the Kostanjek Landslide area had been experiencing settlement and sinking which can be linked to swelling processes.

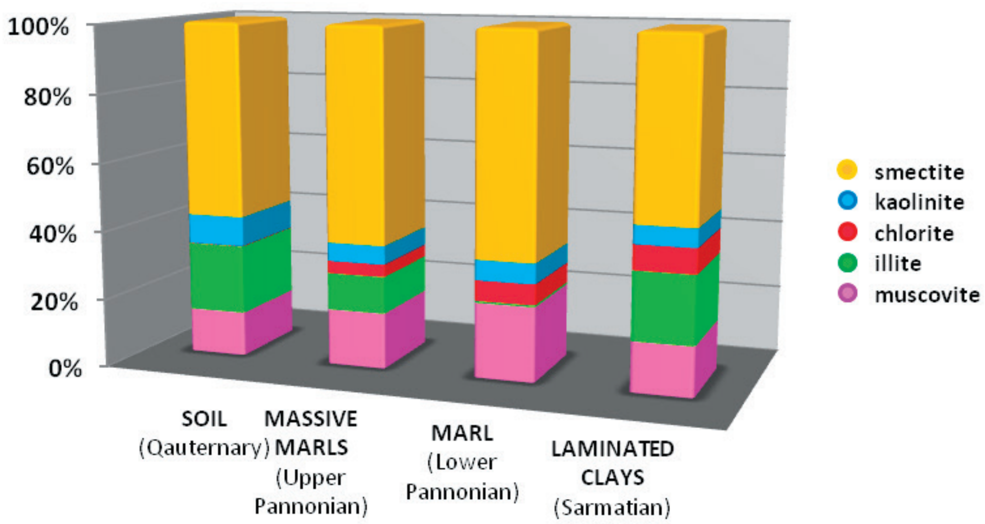

Figure 8. Prorportion of clay minerals in each sedimentary unit (MARTINČEVIĆ et al., 2013).

In ŠTIMAC (2016), an interval of Upper (59.03 m – 62.95 m) and Middle Sarmatian samples (63.40 m – 63.51 m) from the B-1 borehole were analyzed, keeping in mind the depth of the slip surface previously identified by KRKAČ (2015). The Upper Sarmatian samples consisted of smectite, illite, kaolinite (both well and poorly ordered) and chlorite, while the Middle Sarmatian samples showed presence of dominantly mixed-layered clays (Fig. 9). The first decline in clay mineral content happens in the Upper Sarmatian unit at 62.75 meters, then increasing before decreasing again in the Middle Sarmatian. Another significant difference was the content of carbonate minerals, where the amount of aragonite increased significantly in the Middle Sarmatian samples - up to 66 wt% as opposed to as low as 11 wt% in the Upper Sarmatian. The dominant cation in the Upper Sarmatian samples was estimated as Ca, possibly as a consequence of carbonate dissolution, with Na assuming this role in the Middle Sarmatian, increasing the tendency of chemical bond breaking.

All of the above, indicating a change in mineral content on and around the boundary of two Sarmatian lithostratigraphic units, and especially the presence of mixed-layered clays that include smectite layers, holds the possibility of a negative effect on the engineering properties of these sediments and the activation of the sliding process.

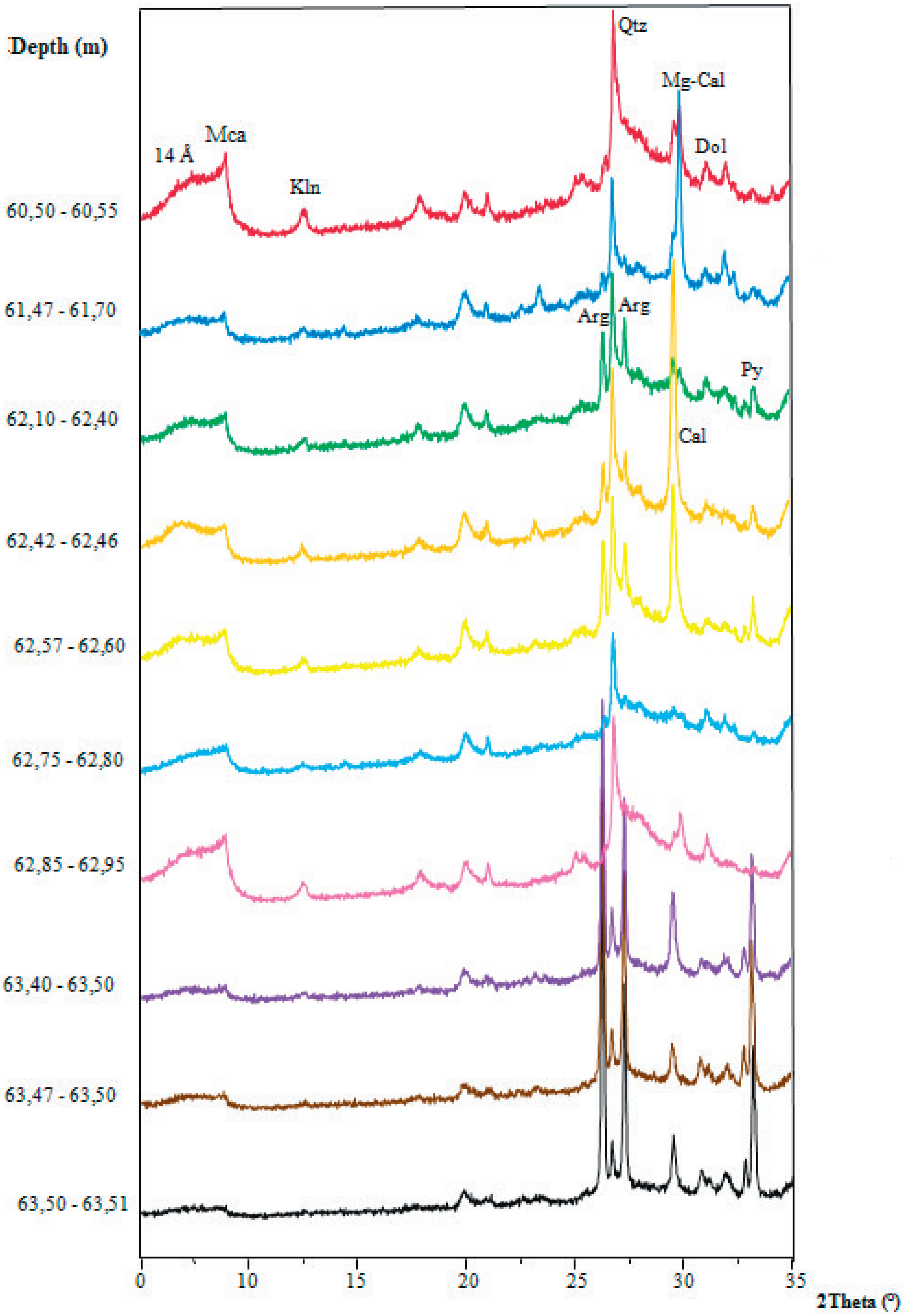

Figure 9. Difractograms of the <2μm fraction by depth (ŠTIMAC, 2016). Key: Mca – micaeous minerals; 14 Å – minerals with 14 Å diffraction maximum (smectite,vermiculite, chlorite); Kln – kaolinite; Qtz – quartz, Cal – calcite, Mg-Cal – magnesium calcite, Dol – dolomite, Py – pyrite, Arg – aragonite. Note: micaeous minerals include muscovite, illitic material and mixed-layer illite-smectite