TXT-tool 2.385-1.2 A Comprehensive Landslide Monitoring System: The Kostanjek Landslide, Croatia

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Abstract

In this paper the general design of the integrated monitoring system of the Kostanjek landslide will be briefly presented. A comprehensive integrated real-time monitoring system has been installing as a part of the research activities in the Croatian–Japanese bilateral project on landslides from 2011. The monitoring system will consist of 40 sensors for geodetic, hydrological and geotechnical monitoring. Equipment for landslide monitoring at the surface and underground will include 15 precise GNSS rovers, long- and short-span extensometers, pore pressure gauges in boreholes, water level gauges in wells, rain gauge, weather station and accelerometers aimed at monitoring of landslide triggering factors. All monitoring equipment will be connected in one system with continuous monitoring and data transmitting to the central data unit. Installation of the system will be finished in 2013.

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GNSS, extensometer, accelerometer, rain gauge, landslide monitoring, Kostanjek landslide, SATREPS project

1. Introduction

Kostanjek landslide is an example of a reactivated deep-seated large translational landslide formed in soft rock-hard soil, i.e. marls. Landslide velocities have been changing over the last 50 years, from landslide activation until today, in a range from extremely slow to very slow. The initial landslide was developed as a consequence of loss of global stability of gentle to steep slopes above an open pit mine of marl and a cement factory 'Sloboda' (**Fig. 1**). Slope movements were caused by mining activities, i.e., undercutting of the slope toe and uncontrolled massive blasting. Following the initial slow movements that caused settlement and fractures of industrial cement factory objects in 1963, and damaging numerous private houses within an area of approximately 1 km^2 in a very short period, attention shifted to the unstable slopes above the cement factory known as Kostanjek landslide.

Although numerous surface exploration and visual studies were undertaken between the 1966 and 2010 (Ferić et al., 2010) the rudimentary nature of the monitoring undertaken did not provide conclusive evidence regarding the rate and extent of the movement of the Kostanjek landslide. Recently, more detailed assessments were carried out in the frame of the Japanese-Croatian scientific bilateral project 'Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia' (Mihalić and Arbanas, 2012) to assess the status of the historical monitoring points on the area of the landslide, to assess the hazard of further slope movement, and review the options for updated instrumentation to monitor movements of the landslide. Based on joint research from the period 2009-2011, the Kostanjek landslide monitoring project activities were initiated; this included installation of the instrumentation in a two-year period 2011-2013.

The Kostanjek landslide monitoring project activities were administered and developed by Project's Working Group 1, with working group members from the Faculty of Mining, Geology and Petroleum Engineering (University of Zagreb), Faculty of Civil Engineering (University of Rijeka), Research Institute for Natural Hazards and Disaster Recovery (Niigata University), International Consortium on Landslides and Disaster Prevention Research Institute (Kyoto University). It involved an international team of university research groups working together with consultants and contractors to implement a near–real-time monitoring network and conduct studies to better understand the geological settings of the area and mechanisms of failure. Prior to the completion of the Kostanjek landslide monitoring system in January, 2011, the Government of the City of Zagreb determined that the continued long-term monitoring of the Kostanjek landslide was important for public safety of the residents.

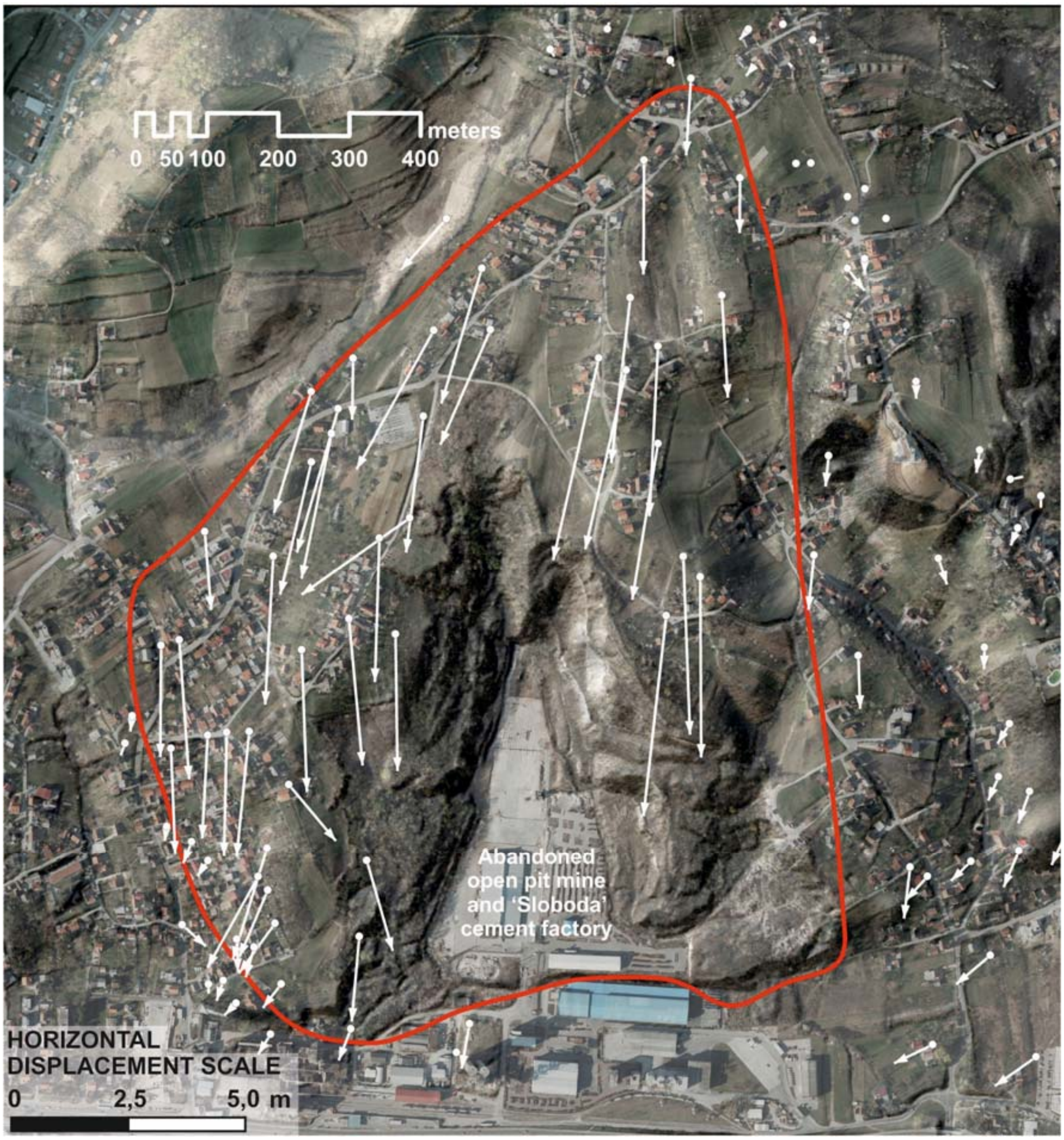

Fig. 1 Horizontal displacements (white arrows) at the Kostanjek landslide area in the period 1963-1988 based on interpretation of stereo pairs of aerial photographs from 1963, 1979, 1981, 1985 and 1988 (Ortolan and Pleško, 1992). Red line depicts the outline of the Kostanjek landslide according to interpretation by Ortolan (1996). In the background are maps from March 2012: hillshade map (with an azimuth of 315° and a sun angle of 45°) generated from 2x2 m bare earth DEM overlain by an orthophoto image. Devastated slopes of the abandoned open pit mine are clearly expressed by rough relief forms in the middle of the Kostanjek landslide. The former cement factory 'Sloboda' was placed in the plain area in the bottom middle part of the landslide.

The first priority of the monitoring system is to provide an early warning to residents of the potential for dangerous sliding originating from slope movements in the area of the Kostanjek landslide. The secondary priority is to provide an opportunity for the research community to test and develop instrumentation and monitoring technologies and to better understand the mechanics of slowly moving masses of soft rock-hard soil. Hence, the working name for the system is planned to change to Kostanjek Landslide Field Laboratory (KLFLab). It is the intention of the Faculty of Mining, Geology and Petroleum Engineering (University of Zagreb) to make all data from the KLFLab available to the research community and to work with researchers and companies to test and develop new monitoring technologies applicable to similar phenomena. This ongoing research will aid in understanding the movements of the entire Kostanjek landslide mass, including the lower artificial slopes in the abandoned open pit as well as urbanized slopes which are populated (**Fig. 1**), in order to provide a better model for prediction of future movements.

The purpose of this teaching material is to provide the researchers and students with a synthesized review of the results of bilateral scientific project joint research activities of the landslide in an urban area as a stimulus for further research.

2. Historical Data from Landslide Investigation and Existing Landslide Model

Since its activation in 1963, there have been various studies and interpretations of the geology, mechanism, causal factors and remedial measures of the Kostanjek landslide. Initial studies from the period 1966-1970 focused on the monitoring of displacements of industrial buildings in the toe part of the landslide and interpretation of subsidence and uplifting of the ground. Swelling of the unloaded marl layers caused by the excavation was identified as a possible cause of the damage (Pehnec, 1967). Several years later Nonveiller (1976) highlighted the potential for sliding on the basis of analysis of incurred movements. Excavation in the quarry was stopped in 1988 after mining activities and excavation were identified as the main triggering factors of the landslide. A total volume of 5.3×10^6 m^3 of rock was excavated.

More recently, more detailed investigation, studies and interpretations of the geology and landslide model were undertaken in the period 1984-1994, and results were published in Ortolan et al. (1987), Ortolan and Pleško (1992), Stanić and Nonveiller (1995, 1996) and Ortolan (1996). It has been widely recognized that the 1963 displacements originated in the foot part of the large landslide with the following dimensions: total landslide area of approximately 1 km2; volume of moving landslide mass of 32x106 m3; depth of displaced mass 90 m. Interpretation of the landslide model was done on the basis of results of the most comprehensive investigations of the Kostanjek landslide from the period 1988-1989, including surface exploration and engineering geological mapping; subsurface investigation; geodetic and geotechnical monitoring; and laboratory analysis. The main disadvantage of this landslide model is the high level of uncertainty of interpretation caused by (1) a lack of clearly expressed landslide features, especially main scarp, flanks and accumulation at the toe; and (2) a lack of subsurface investigations and monitoring (e.g., only 6 boreholes were drilled inside or near the landslide area). For the interpretation of landslide movement, the most important data from this period of investigation are traces of sliding surfaces and vectors of displacements. During engineering geological mapping in 1987, dug wells cut by sliding were systematically recorded, providing evidence of sliding surfaces along the western, north-western and northern boundary of the landslide. According to the photo interpretation of aerial stereo pairs from 1963, 1979, 1981, 1985 and 1988, horizontal displacements of the ground surface in the period 1963-1988 were detected in a range 3-6 meters (average 12-24 cm per year), as is depicted in Figure 1.

A geotechnical report prepared by Croatian Civil Engineering Institute (IGH) in 2008 provides a comprehensive review of all historical investigations at the area of the Kostanjek landslide, with the presentation of the historical landslide model, its geometry, mechanism and contributing factors. With respect to an interpreted historical movement of the Kostanjek landslide, as the specific mechanism of recent movement is not known, there is need to better define the subsurface conditions and contours of landslide bodies contributing to the movement.

Recent field studies have been carried out in the frame of the Croatian-Japanese scientific joint research project (in the period 2009-2012) by Krkač et al. (Engineering Geological Model of Kostanjek Landslide Area, work in progress) to characterize the landslide contour patterns at the surface (Furuya et al., 2011) and geological units in the landslide body (Vrsaljko et al., 2011). Field mapping has also been supplemented by reviews of morphology derived from the available (2x2 m) digital elevation model (DEM) and by monitoring of recent movements from the period 2010-2012 at the 35 stable geodetic points shown in **Figure 2** (Županović et al., 2012). Subsequent mapping of the Kostanjek landslide area has highlighted the similar geological conditions. Although undercutting of slopes by excavation in an open pit mine was considered to be the main driver for historical sliding in the central part of the area, other factors are believed to have contributed to the actual movements, including:

- weakening of the marl due to blast-induced seismic activity in 1963 in the wider area,
- creeping of the superficial deposits due to daily and seasonal changes of soil moisture,
- water accumulation in cracks at the locations of damaged sewage utilities,
- decrease of slope stability due to mining activities (excavation and fills) in the area of the abandoned open pit mine,
- expansion of marl due to unloading.

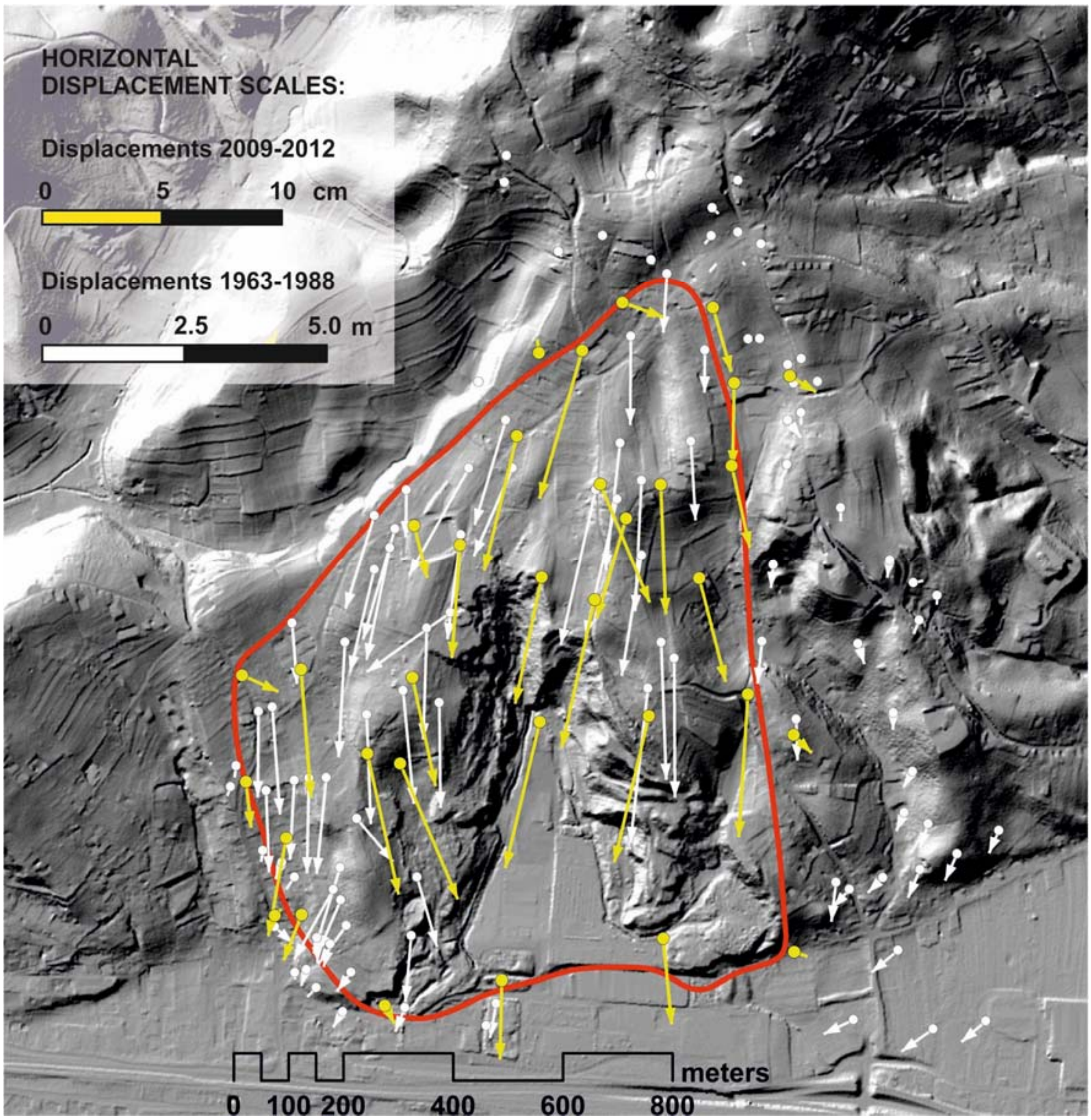

Fig. 2 Recent horizontal displacements (yellow arrows) at the Kostanjek landslide area in the period 2010-2012 (Županović et al., 2012) compared with historical horizontal displacement (white arrows) for the period 1963-1988 (Ortolan and Pleško, 1992). Red line depicts Kostanjek landslide outline according to Ortolan (1996). The background is a hillshade map (with an azimuth of 315° and a sun angle of 45°) generated from a 2x2 m LiDAR bare earth DEM (scanned in March 2012).

Future work is expected to utilize new data from: chemical, isotope and mineralogical analysis of rock samples (Martinčević et al., 2013) and groundwater samples (Watanabe et al., 2011; Yamamoto et al., 2013), hydrological investigations (Krkač et al., 2011; Krkač and Rubinić, 2013), laboratory testing of mechanical properties (Oštrić et al., 2012) and additional surface geophysical data to further improve understanding of the subsurface structure of the landslide area, including groundwater, soil and rock properties. The most important data will be collected by continuous monitoring of landslide movement and landslide causal factors, precipitation and earthquakes. Integration of real-time GNSS monitoring data with other sensor data in the frame of GIS software is shortly presented in the paper by Baučić et al. (2013).

3. Monitoring System Development and Sensor Network

Based on the joint research in the frame of Croatian-Japanese project, the monitoring system on the Kostanjek landslide was designed to include a number of different types of instruments communicating in near–real time to a data acquisition-processing center located at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb (UNIZG-RGNF). The system, whose conceptual design was outlined by Nagai et al. (2011), is meant to improve or influence public safety, public education, scientific research, and university education.

The system is designed to measure changes in conditions that affect the potential for a reactivation of sliding from slope cuts of abandoned open pit mines, and to provide early warning of extreme conditions to authorities responsible for emergency preparedness. The public education role involves raising the level of awareness of the general public regarding natural hazards and their potential impacts. The scientific research role of the system is to provide long-term monitoring data that can be used to gain a better understanding of the mechanisms associated with landslide in hard soil-soft rock (Pannonian and Sarmatian marl), and to advance the development of technology in landslide monitoring. Finally, a monitoring system that is housed at the UNIZG-RGNF has the potential to increase the educational potential of the University of Zagreb, and thereby benefit the national educational capacities.

The design process involved defining the preliminary data requirements and reviewing options for instrument types and locations, measurement frequency, and equipment required for data acquisition and management. The monitoring framework should provide complementary types of instruments with varying sensitivities to movement and climatic influences, and also have enough redundancy built into the system to be able to distinguish actual movements. In considering the types of sensors most suitable for providing early warning for impending slope movements, the sensors were grouped as follows:

1) Sensors for displacement measurement (GNSS receivers, short- and long-span extensometers, inclinometer),
2) Sensors for hydrological measurements (rain gauge, meteorological station, outflow weirs, water level sensors, piezometers),
3) Sensors for geophysical measurements (accelerometers).

The sensor network installed at the Kostanjek landslide area encompasses approximately 40 sensors for the monitoring of landslide movement and landslide causal factors. **Figure 3** provides the layout of the sensor network which is currently installed or under installation at the Kostanjek landslide.

3.1 Sensors for Displacement Measurement

The sensors for displacement measurements are those that provide a reliable data stream on a year-round basis and measure easily interpretable parameters of the superficial and subsurface movements. The displacement measurement sensor network includes 15 Global Navigation Satellite System (GNSS) receivers, 9 extensometers and 1 inclinometer.

A Trimble GNSS monitoring system consists of fifteen double-frequency NetR9 TI-2 GNSS reference stations with Zephyr Geodetic 2 GNSS antennas installed on each of GNSS reference points. GNSS receivers are fixed to 4 meter high poles with 1 meter deep reinforced foundations. They collect GNSS raw data and deliver this data in real-time, over communication lines (using routers), to Trimble 4D Control software installed on an application/data server in a data center at UNIZG-RGNF. GNSS receivers provide data on absolute positions of surficial points with precisions for measuring movement in the range of cm to mm. All monitoring stations are supplied with electricity from public network.

The locations of GNSS receivers (**Fig. 3**) can be grouped as follows: above the landslide crown, i.e., outside the landslide area to check the assumption that this area is stable (1 GNSS receiver); near the top of the abandoned slope cuts (4 GNSS receivers); inside a slope cut/fill in the eastern part of the landslide (1 GNSS receiver); inside a slope cut in the western part of the landslide (1 GNSS receiver); inside a flat area in the central part of the abandoned open pit mine with the evidence of uplifting (1 GNSS receiver); along the western and north-western landslide border (5 GNSS receivers); and in northern part of landslide (2 GNSS).

To be able to calculate very precise coordinates of 15 GNSS reference stations at the landslide area, the system needs at least one GNSS reference stations outside of the landslide zone. For that purpose, the system is using data from a permanent GNSS reference station in Gornji Stupnik, which is 7 km away from Kostanjek, and for T4DC monitoring software it will be the 16th GNSS reference station. T4DC monitoring software installed on an application/data server collects GNSS raw data and synchronizes, calculates and adjusts the collected data, then operates an alarm if needed and analyzes measurement results.

The long- and short-span wire extensometers, type NetLG-501E Osasi, provide data on absolute deformation with submillimetre-level precision. Five long-span extensometers are placed from the top of the most stable point above the landslide, perpendicular to the main scarp, and in the direction of sliding. One short-span extensometer is placed perpendicular to the left landslide flank, where a scarp with steep displacement is clearly visible. Two long-span extensometers are installed to cross the crown of an artificial steep slope where the highest magnitude of displacement is expected. One short-span extensometer is installed underground, in a tunnel which crosses the sliding surface. Extensometers with data loggers are fixed on 4 meter high poles with reinforced foundations and some are on the same poles as the GNSS routers. Data collection from extensometers is manual, but data transfer using routers is currently underway.

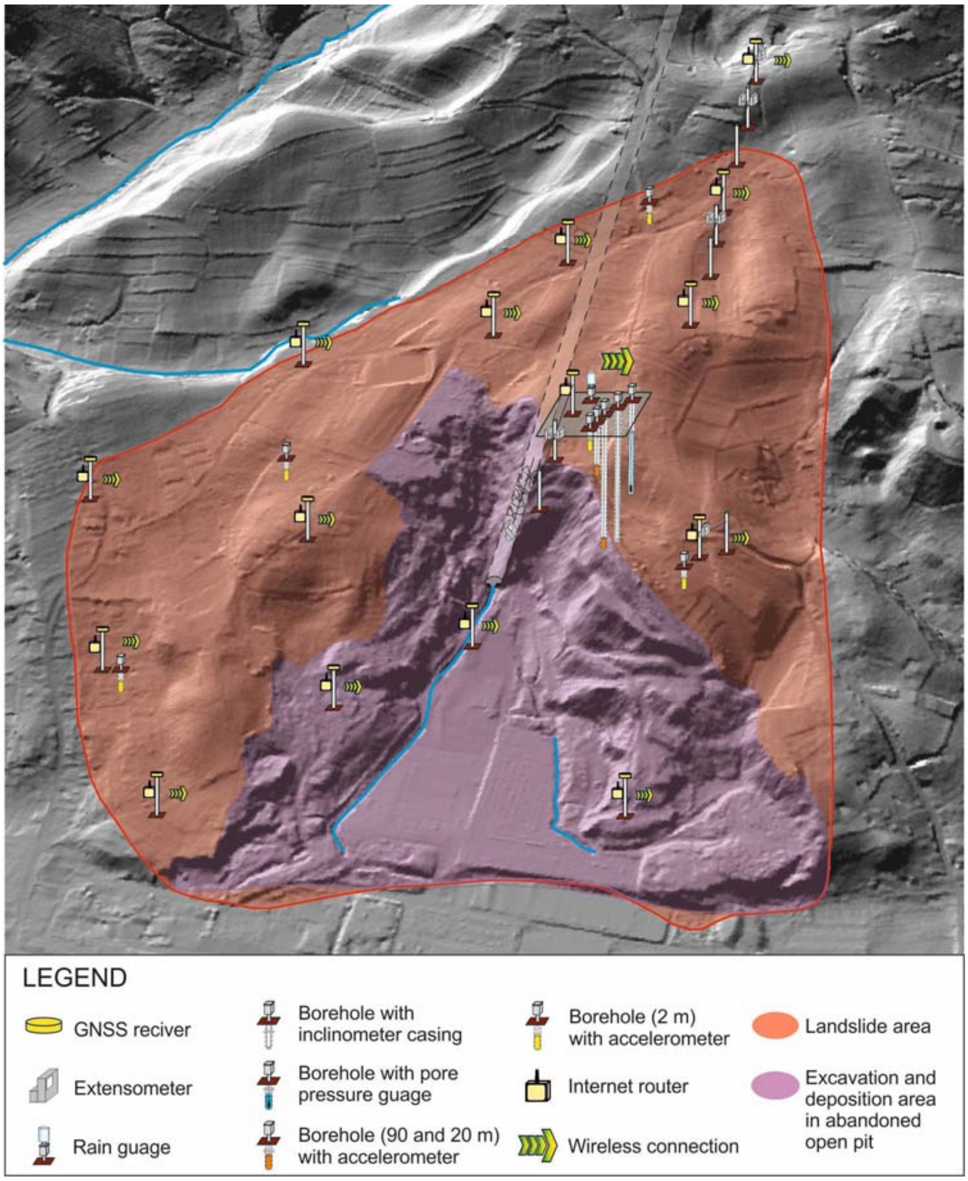

Fig. 3 Sensor network at the Kostanjek landslide area established in the frame of SATREPS scientific joint research Croatian-Japanese project (Krkač et al., 2013)

One inclinometer casing is installed in a 100 m deep vertical borehole in the middle of the landslide for measurements of the inclination of the pipe by a high-precision probe in even distances, for example, every 50 cm. The depth of the present-day major active shear surface is at 62.5 m (on the basis of two measurements, in May 2012 and in February 2013). There is also some evidence of shallower sliding in the same borehole, at an approximate depth of 30 m. The deeper sliding surface is considered very important for the appraisal of future scenarios of the evolution of mass movement. Registered cumulative movement in last 8 months is approximately 4 cm.

3.2 Sensors for Hydrological Measurement

Sensors for hydrological measurements are necessary to provide background data that are useful in the interpretation of displacement measurement results. The planned hydrological measurement sensors include a rain gauge and meteorological station (rain, wind, temperature, barometric pressure). The rain gauge has been installed in the middle part of the landslide from 2011. Work is currently underway to purchase a meteorological station. The data recorded from these sensors is being used to correlate observed displacements with meteorological changes. Two outflow weirs (at the mouth of the abandoned tunnel and on a spring outside the landslide area) and three water level sensors (two in dug wells and one in a borehole) are installed to assess delays in superficial and groundwater discharge and pore pressure after precipitation. The purchase of three piezometers (pore pressure gauges and pluviometer) is currently underway to measure pore pressure and groundwater levels at two depths inside the landslide mass and one below the landslide.

All hydrological sensors have a power supply from batteries because of their low power consumption. Until now, data collections have been manual, but data transfer using routers is currently underway.

3.3 Sensors for Geophysical Measurement

The geophysical measurement sensor network encompasses seven accelerometers installed inside the landslide area for the purpose of (i) monitoring local micro-earthquake activity in the landslide area; (ii) monitoring regional earthquake activity, including strong motion; and (iii) monitoring of any ground tremors associated with the landslide, including possible ground inclination. This is a low cost and hi-fidelity broad-band monitoring system consisting of a three-component MEMS accelerometer and three-channel autonomous broadband digital recorders with GPS to keep accurate synchronization between each other. A Seismic Source DAQ3-3 3CH high-fidelity digital logger with accurate GPS clocking enables continuous recording, with data harvesting by the attached USB memory every three weeks. Power is supplied using rechargeable batteries.

Three accelerometers (JGI-SVAC-3C MEMS, Colibrys 1600) are installed in three boreholes at the central monitoring station in the middle of landslide: one is in a deep borehole below the landslide (90 m depth); one is in a borehole at depth inside the landslide body (20 m); and one is installed in a shallow borehole near the surface. Four accelerometers (Colibrys SF3000L 3-C MEMS) are installed near the surface, in shallow boreholes at depths of approximately 1.5 m. They are spatially arranged to cover all parts of the landslide area that are supposed to be separate landslide bodies: the upper part of the landslide, the left (eastern) landslide flank and the adjacent valley with shallow creeping phenomena.

4. Conclusion

Present-day movements of the Kostanjek landslide in the period from December 2012 to February 2013, ranging from 0.1 to more than 0.5 mm/month at the surface and at depth, cause, on a yearly basis, damage to private houses and infrastructure. Moreover, a very attractive city area over the last 50 years in the area of the Kostanjek landslide has been situated near the toe of the landslide, which has prevented development of this part of the city.

As the specific and total risk arising from this situation is potentially significant, both in relation to the extent and magnitude of the landslide and the socioeconomic vulnerability and value of the elements at risk, monitoring has been carried out in close collaboration with end-users from city government, within the scientific Croatian-Japanese research project. In principle, a landslide hazard can be fully assessed only by defining where, how and when slope instability will take place, thus defining the spatial, kinematical and temporal components of the hazard respectively. The monitoring data presented in this paper are principally aimed at assessing the magnitude of the Kostanjek landslide that, expressed in terms of volume, velocity or energy, makes up the kinematical component of the hazard. Nonetheless, the same monitoring data can also support a full assessment of the spatial and temporal component of the hazard. The spatial component of the hazard, for instance, depends upon how prone the slope is to fail in relation to various causal factors and is related to the expected extent of the phenomenon, including possible retrogression, enlargement or advancement of the landslide. This, in the specific case of the Kostanjek landslide, will have to be estimated through the use of slope stability models built up and validated using geomorphological evidence and monitoring data. On the other hand, the temporal component of the hazard is related to the frequency in time with which a certain damaging landslide scenario with given spatial and kinematics characteristics is expected to occur. It can in principle be assessed using data from the inclinometers, piezometers, the meteorological station and accelerometers installed on the Kostanjek landslide. However, this is only possible if a close relationship between movements and triggering factors, such as critical rainfall or groundwater levels or earthquake shaking, can be highlighted.

All measurements will be integrated in GIS monitoring software for landslide risk management and an early warning system. Establishment of an early warning system and defining of alarm thresholds will be based on existing knowledge of the Kostanjek landslide behavior so far, based on collected consequent comprehensive monitoring data.

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References

Baučić M, Mihalić Arbanas S, Krkač M (2013) Geographic information system of landslide Kostanjek: Integration of real-time GNSS monitoring data with other sensor data. Proc 1st Reg Symp on Landslides in the Adriatic-Balkan Region. Zagreb, Croatia:12-13.

Ferić P, Mihalić S, Krkač M, Arbanas Ž, Podolszki L (2010) Kostanjek landslide: current state and planned project activities. Proc 1st Workshop of the Project Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia. Dubrovnik, Croatia:6–6.

Furuya G, Miyagi T, Hamasaki E, Krkač M (2011) Geomorphologic mapping and 3D modeling of the Kostanjek Landslide, Zagreb. Proc 2nd Workshop of the Project Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia. Dubrovnik, Croatia:21-23.

Krkač M, Mihalić Arbanas S, Nagai O, Arbanas Ž (2013) The Kostanjek landslide - Monitoring system development and sensor network. Proc 1st Reg Symp on Landslides in the Adriatic-Balkan Region. Zagreb, Croatia:11-11.

Krkač M, Rubinić J (2013) Analysis of water fluctuation dynamics in the wider area of the Kostanjek landslide. Proc 1st Reg Symp on Landslides in the Adriatic-Balkan Region. Zagreb, Croatia:10-10.

Krkač M, Rubinić J, Mihalić S (2011) Kostanjek Landslide - analyses of groundwater discharge as a basis for the new hydrological monitoring. Proc 2nd Workshop of the Project Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia. Dubrovnik, Croatia:17-20.

Martinčević J, Mihalić Arbanas S, Krkač M, Bernat S, Miklin Ž, Podolszki L (2013) Mineralogical composition of the Kostanjek landslide sediments and its possible influence on the sliding and swelling processes. Proc 1st Reg Symp on Landslides in the Adriatic-Balkan Region. Zagreb, Croatia:7-8.

Mihalić S, Arbanas Ž (2012) The Croatian–Japanese Joint Research Project on Landslides: Activities and Public Benefits. In Sassa K et al (eds): Landslides: Global Risk Preparedness, DOI 10.1007/978-3-642-22087-6_24, Springer-Verlag:335-351.

Nagai O, Krkač M, Mihalić S (2011) Introduction of one of methods to predict failure time of a slope widely used in Japan and application to the Kostanjek Landslide. Proc 2nd Workshop of the Project Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia. Dubrovnik, Croatia:46-50.

Ortolan Ž (1996) Development of 3D engineering geological model of deep landslide with multiple sliding surffaces (Example of the Kostanjek Landslide). PhD thesis. Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb (In Croatian).

Ortolan Ž, Mihalinec Z, Stanić B, Pleško J (1995) Application of photogrammetric measurements at shaping geotechnical repeated models of multi-layer landslides. Proc 6th Int Symp on Landslides, Christchurch, New Zealand: 1685-1691.

Ortolan Ž, Pleško J (1992) Repeated photogrammetric measurements at shaping geotechnical models of multi-layer landslides. Rudarsko – geološko – naftni zbornik 4: 51-58.

Ortolan Ž, Stanić B, Nonveiller E, Pleško J (1987) Consequences of mining in the marl quarry Kostanjek – Podsused. Proc 9th Yug. Symp. on Hydrology and Eng Geol 2:117-128 (In Croatian).

Oštrić M, Ljutić K, Krkač M, Setiawan H, He B, Sassa K (2012) Undrained Ring Shear Tests Performed on Samples from Kostanjek and Grohovo Landslide. Proc ICL Symposium, Kyoto, Japan:47-52.

Pehnec V (1967) Damage of the factory buildings in Podsused due to swelling of marl. Građevinar, 6:197-201 (In Croatian).

Stanić B, Nonveiller E (1995) Large scale landslide in Kostanjek area. Građevinar 47(4):201-209 (In Croatian).

Stanić B, Nonveiller E (1996) The Kostanjek landslide in Zagreb. Eng Geology 42:269-283.

Watanabe N, Krkač M, Furuya G, Wang C, Mihalić S (2011) Hydrochemical characteristics of groundwater from the Kostanjek Landslide in Croatia. Proc 2nd Workshop of the Project Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia. Dubrovnik, Croatia:14-16.

Yamamoto S, Watanabe N, Krkač M, Furuya G, Wang C, Mihalić Arbanas S (2013) Geochemical constraints on the origins of groundwater from the Kostanjek landslide in the western part of Zagreb, Croatia. Proc 1st Reg Symp on Landslides in the Adriatic-Balkan Region. Zagreb, Croatia: 9-10.

Županović Lj, Opatić K, Bernat S (2012) Determination displacements of landslides Kostanjek with relative static method. Ekscentar 15:46-53 (In Croatian).