



Review of Monitoring Parameters of the Kostanjek Landslide (Zagreb, Croatia)

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Abstract

Since 2011, in the framework of the Croatian-Japanese SATREPS FY2008 Project, scientists have been working on the establishment of the Kostanjek landslide monitoring system in the City of Zagreb (Croatia). External triggers at Kostanjek landslide are measured with rain gauge and accelerometers. Displacements at the surface are measured by GNSS sensors and extensometers, while subsurface displacement is measured by vertical extensometers and inclinometer. Hydrological measurements consist of groundwater level measurements, discharge measurements, chemical and isotope analysis. Monitoring sensors recorded landslide reactivation due to external triggers in the winter period of 2012/2013. During the period from September 2012 to March 2013 the total cumulative precipitation was 793.7 mm and horizontal displacements were in the range of 9–20 cm. The installed monitoring sensor network proved to provide reliable data for the establishment of relations between landslide causal factors and landslide displacement rates aimed at establishing threshold values for early warning system.

Keywords

Kostanjek landslide • Monitoring system • Monitoring parameters • External triggers • Displacement • Hydrologic properties

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Introduction

Kostanjek landslide is a reactivated deep-seated large translational landslide in an urbanized part of the City of Zagreb (Croatia), in Sarmatian and Panonian marls. The landslide initially developed in 1963 as a consequence of mining activities, i.e. undercutting of the slope toe in an open marl pit and uncontrolled massive blasting. In 2009 Kostanjek landslide became a pilot area for research activities in the framework of Japanese-Croatian bilateral SATREPS FY2008 project 'Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia'. One of the objectives of the scientific research was establishment of a landslide monitoring system and assessment of the hazard of further slope movement. Landslide monitoring activities (equipment installation and data collection) were initiated in 2011 (Mihalić Arbanas et al. 2013).

The scope of the paper is to review the monitoring parameters which have been continuously and discontinuously observed at the Kostanjek landslide. According to Baroň et al. (2012) monitoring parameters are defined as any phenomenon or factor related to a slope (area of interest), which could be quantified and monitored over time. Parameters which can influence slope failure conditions and which are monitored at Kostanjek landslide are: (1) external triggers (rainfall and earthquakes); (2) slope movement; and, (3) hydrological properties (groundwater levels, discharge, water chemistry). The idea was to develop a system for the collection of reliable data which would be used in future application as: (1) input data for interpretation of engineering geological or kinematic models of this landslide; and (2) thresholds for decision-making and warning of citizens in the most dangerous zones inside the landslide area.

Monitoring at the Kostanjek landslide should provide high resolution spatial and temporal data, because this landslide is generally characterized by small oscillations of heterogeneous velocities. Except for the high resolution data, the data should be as accurate as possible to enable differentiation between minimal seasonal changes and changes related to periods of acceleration when failure can occur. High resolution and high accuracy of data are also necessary to define critical thresholds of triggering factors, i.e. to setup an early warning system.

External Triggers

Meteorological Conditions

According to historical data from the meteorological station Zagreb-Grič, the mean annual precipitation in the City of Zagreb for the period 1962–2012 is 874.4 mm. The Zagreb-

Grič station is the main meteorological station in the City of Zagreb, located about 9 km east from the Kostanjek landslide. Krkač et al. (2014) showed similar rainfall regimes between the Zagreb-Grič and the Kostanjek landslide locations. The City of Zagreb experienced a period of intense rainfall from September to December 2012 and a period of intense rainfall and snow from January to March 2013 (Fig. 1). During the 13th and 14th of January 54 cm of snow fell, which is the third highest snowfall recorded at the Zagreb-Grič station since its establishment in 1861 (DHMZ 2013). This extremely wet period with cumulative precipitation of 793.7 mm, which corresponds to about 90 % of mean annual precipitation, caused a reactivation of a large number of landslides in NW Croatia (Bernat et al. 2014) and reactivation of the Kostanjek landslide.

At the area of the Kostanjek landslide rainfall has been monitoring with a 0.5 mm tipping-bucket rain gauge, installed in the central part of the landslide, since September 2011. Figure 1 shows a comparison of cumulative precipitation from the Zagreb-Grič weather station and the Kostanjek rain gauge. The difference between precipitation and rainfall quantities (20 %) is greater than the real difference due to the limitations of the rain gauge: (1) it cannot measure rain during the winter period when snow cover blocks penetration of rain into the gauge; (2) it measures only water that originate from snow cover which melts on the funnel of the device—this snow cover, whose melting can be detected by this device, is usually smaller than the representative value, as a consequence of local meteorological conditions (e.g. wind). This implies limited use of a rain gauge, as a sensor for monitoring of meteorological trigger(s) in snowy periods, and the necessity of using data from a local meteorological station.

Seismicity/Earthquakes

The geophysical measurement sensor network at the Kostanjek landslide includes seven accelerometers installed inside the landslide area to: (1) monitor local micro earthquake activity in the landslide area; (2) monitor regional earthquake activity, including strong motion; (3) monitor any ground tremors associated with landslide movement, including possible ground inclination. The monitoring system consists of a 3-component Micro-Electro-Mechanical System (MEMS) accelerometers and 3-channel autonomous broadband digital recorders with GPS to maintain accurate synchronization. Three accelerometers are installed in the center of landslide: one below the sliding surface, at a depth of 90 m; and two inside the landslide mass, at depths of 20 m and 2 m. Four accelerometers are installed near the surface, at depths of approximately 1.5 m. They are spatially arranged to cover all parts of the landslide area.

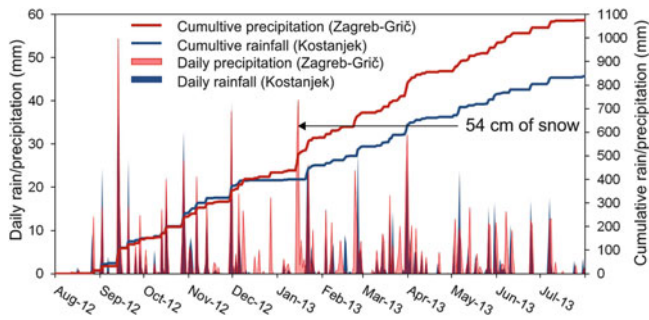


Fig. 1 Cumulative and daily precipitation from the Zagreb-Grič station and cumulative and daily rainfall from the Kostanjek rain gauge (August 2012–July 2013)

Since the start of seismic monitoring in April 2013, 16 earthquakes occurred. During this period none of the periods of displacement can be attributed to earthquake-induced ground motions. Examples of accelerograms for an earthquake $M=2.2$ that occurred approximately 19 km NE from Kostanjek landslide, at a depth of 2 km, are presented in Fig. 2.

Slope Movements

Subsurface movements at Kostanjek landslide are continuously monitored by four borehole wire extensometers and occasionally by one inclinometer. Direct monitoring of movements at the landslide surface, i.e. monitoring of the actual state of slope activity, is continuously performed by extensometers and GNSS sensors.

An inclinometer casing was installed in March 2012, in a 100 m deep borehole. The inclinometric profiles (Fig. 3), based on three measurements, indicate that the failure occurs in a thin basal shear zone in Sarmatian marls at a depth of 62.5 m. The total amount of displacement measured for the period from April 2012 to February 2013 was 60 mm. Deformation above 62.5 m can be considered as negligible with respect to the interpretation of landslide mechanisms. Deformation at the depth of 15–30 m is probably a consequence of inclinometer tube installation, because of the existence of the voids between the inclinometer casing and the in-situ ground (Stark and Choi 2008).

In September 2013 four vertical extensometers were installed in a 75 m deep borehole in the central part of the landslide, near borehole with inclinometer casing. In the period September 2013–November 2013 there were no measured displacements. This is partly because the measurements were undertaken after dry summer period without larger landslide movements. The second reason is that vertical extensometer measurements in the early stage of measurement are smaller and do not correspond to the actual displacements (Corominas et al. 2000).

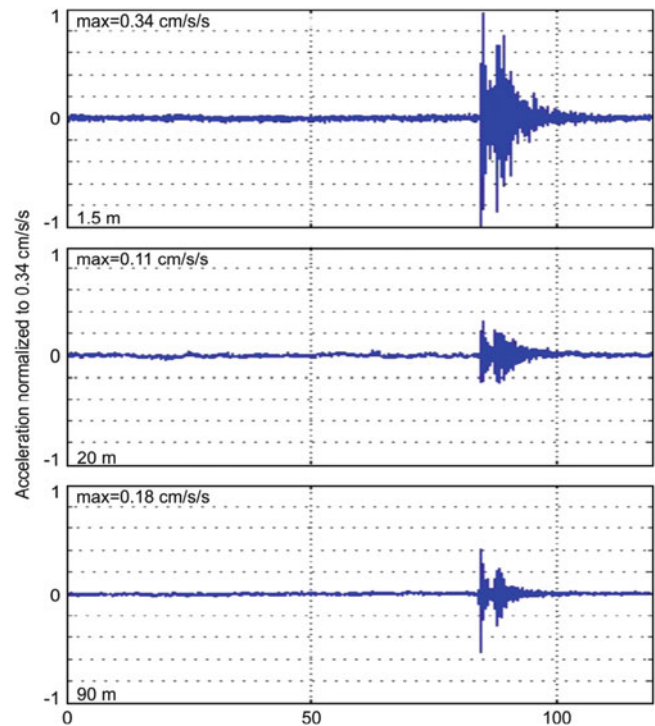


Fig. 2 Earthquake accelerograms recorded by MEMS accelerometers installed in the central part of landslide

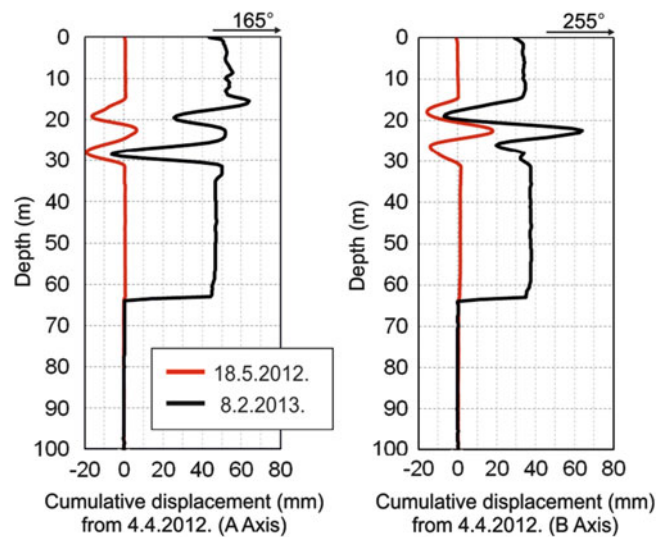


Fig. 3 Cumulative inclinometer displacements

Seven long- and two short-span wire extensometers, which provide continuous data on relative displacement between two points, were installed in the period from March 2011 to September 2013. During the winter period 2012/2013 three of seven extensometers installed at that time, showed significant displacement: a long-span extensometer crossing the main crack; a short-span extensometer

crossing a flank crack in the east side of landslide; and a short-span extensometer in the tunnel crossing the sliding surface (Fig. 4). All three extensometers displayed extension, but the amount of measured displacement varies from 40 mm on the fracture on the flank of the landslide body to 72.5 mm on the main crack and 97 mm in the central part of landslide where sliding surface intersects the tunnel.

GNSS monitoring system consists of 15 double-frequency NetR9 TI-2 GNSS receivers with Zephyr Geodetic 2 GNSS antennas installed at the landslide surface. All 15 GNSS sensors measure absolute displacement compared to 16th GNSS reference station, which is considered as a stable GNSS and is approximately 7 km from the landslide. The first GNSS sensor was installed in September 2012. During the monitoring period almost all sensors measured movement, from 4 to 20 cm. Figure 5 shows the evolution of surface displacement of four GNSS sensors with a major period of displacement from December 2012 to May 2013. The maximum rates of movement, with velocities of 2–4 mm/day, occurred during the first week of April. The amount of movements in the central part of landslide is approximately two to four times higher than movements near the landslide borders, which implies frictional resistance at the right flank (Allison and Brunsten 1990) and, together with 25 mm of subsiding, occurrence of graben in the northern part of landslide.

Hydrologic Properties

Groundwater Level/Pore-Water Pressure

Continuous water level monitoring started with installation of two water level sensors in two domestic wells with no or occasional usage in June 2012. The measuring was to determine the groundwater level of the shallowest aquifer. Wells are located near the main scarp, at the north (in Bizek II St.), and west from cuts at an abandoned marl open pit (in Vodopijjn Breg St.). Changes in groundwater level for both wells show a similar appearance (Fig. 6). However, a much deeper well in Vodopijjn Breg St. shows the much stronger influence of daily rainfall and a greater oscillation of groundwater depth (from 13 to 21 m), while the well in Bizek II shows a maximum change of only 4 m in groundwater level during the same period (Krkač et al. 2014).

An additional water level sensor was installed in the central part of landslide in a borehole with an accelerometer in January 2013. The data obtained from the water level sensor gives an average position of the water table between the top of the borehole and the depth of 35 m, whereas below this depth the borehole is sealed. Measurements are registered every hour. Figure 6 shows the averaged data over each 24 hour period. The three episodes of increased

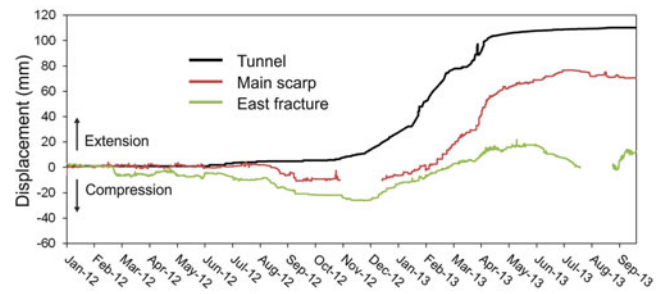


Fig. 4 Extensometer measurements in the underground (in the tunnel) and at the surface, across the main scarp and fracture in the eastern part of the landslide

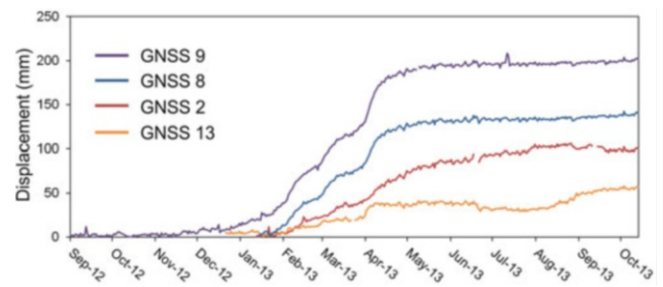


Fig. 5 Cumulative horizontal displacements versus time for GNSS 2 and 13 (near the landslide boundary) and GNSS 8 and 9 (in the central part of the landslide)

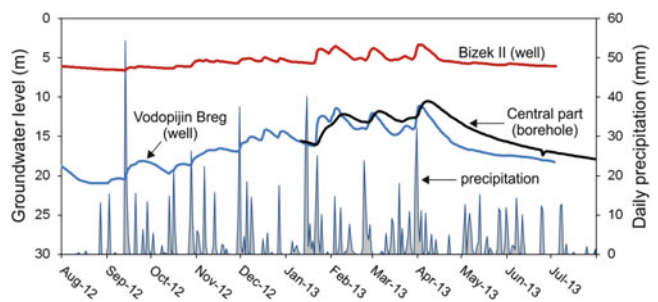


Fig. 6 Daily groundwater levels at Kostanjek landslide

groundwater levels in wells and in borehole, together with their peaks coincide with periods of accelerated movements in the winter of 2013.

Three pore pressure gauges were also installed in the central part of landslide in September 2013. The deepest one measures pore pressure within the area of the sliding surface in Sarmatian silts at a depth from 60 to 65 m. The middle one measures pore pressure within the landslide body, i.e. within the lower Panonian silts at a depth from 50 to 55 m, and the shallowest one measures pore pressure within upper Panonian silts and sandy silts at a depth from 30 to 38 m.

Water Balance: Inflow and Outflow, Surface Flow

The objective of hydrological research is study of groundwater dynamics and its relation to Kostanjek landslide movements. Inflow and discharge regime is continuously measured at two locations: (1) at the entrance of the tunnel which passes through the slip surface; (2) at the spring of the Dolje Stream, approximately one kilometer north from the landslide. At each location an outflow weir was constructed and water level sensor was installed. The relationships between water levels and discharge were established on the basis of several discharge measurements with a standard current meter. Daily discharges at the weirs are presented in Fig. 7.

Discharge at the spring of Dolje Stream varies in a range from 2.5 to 12.5 l/s. Discharge reacts relatively quickly and shows large oscillations related to rainfall. The maximum measured discharges, at the Dolje Spring, were in the following periods: 21–23 January 2012, 2–4 February 2013, and 30 March to 4 April 2013. These peaks of discharge, related to heavy rainfall and snow melting, together with peak from 9–10 March 2013, correspond to the periods of maximum landslide movement rates.

Discharge at the tunnel entrance varies from 4.2 to 7.5 l/s. The highest values of the discharge were in the following periods: 15 January to 1 February 2013, and 21 February to 15 March 2013. At the end of the March, the weir at the tunnel entrance was drowned because of landslide deformation in the downstream area.

Water Chemistry and Isotopic Compositions

The hydrochemical characteristics of groundwater reflect the mineralogical composition of solid phases of the parent rock through which the groundwater flows and also provide signatures as natural tracers to better understand groundwater migration (Watanabe et al. 2012). During the September 2011 and June 2012, one sample of spring water, seven samples of stream water, 11 samples from the tunnel and 74 groundwater samples from private wells were collected for hydrochemical and isotope analyses. The pH, EC and temperature of all samples were determined in the field, while Na, NH₄, K, Mg, Ca, Sr, HCO₃ and CO₃ as alkalinity, Cl, NO₃ and SO₄, also $\delta^{18}\text{O}$ and $\delta^2\text{H}$, were analyzed in the laboratory of the Niigata University.

The hydrochemistry of groundwater from shallow aquifers (wells) are classified into four types: (1) Ca-HCO₃ type; (2) SO₄-rich Ca-HCO₃ type ($0.28 < \text{SO}_4/\text{HCO}_3 < 0.40$); (3) Mg-rich HCO₃ type ($0.19 < \text{Mg}/\text{Ca} < 0.55$); (4) Cl-rich type ($\text{Cl} > 100 \text{ mg/L}$). Ca-HCO₃ type waters are closely related to the bedrock rock type (marls), and are

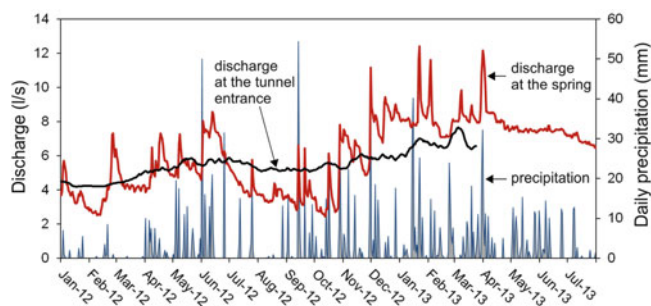


Fig. 7 Daily discharges at the tunnel entrance and spring of the Dolje Stream

predominately distributed over the research area. The SO₄-rich Ca-HCO₃ type waters, probably influenced by gypsum or aragonite in the landslide hinterland, are scattered in the northern and SW part of the research area. The Cl-rich type waters (most probably of anthropogenic origin) are scattered in the northern and western, relatively densely populated part of the research area. The Mg-rich HCO₃ type waters are sporadically distributed in the northernmost part, behind the head of landslide and in the eastern and south-eastern part of the landslide. In addition, spring water from dolomite in the tunnel is also of a Mg-rich HCO₃ type, but more enriched in Mg and depleted in Sr than the Mg-rich HCO₃ type waters in the landslide. It can be concluded that the dolomite is major source of Mg in waters from the research area.

Isotopic compositions of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of all waters are of meteoric origin, although spring waters in the tunnel are depleted in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ compared with other sources. The isotopic depleted compositions suggest that these waters are recharged in the higher (northern) dolomitic area and migrate through the dolomite aquifer to the depths of the landslide mass. Mg-rich HCO₃ groundwater types show a tendency to be slightly depleted in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ comparing with the other groundwater types. It seems that Mg-rich HCO₃ groundwater type is influenced by isotopic depleted waters from the dolomite aquifer.

According to chemical and isotopic compositions, it is clear that Mg-rich HCO₃ type waters are originally formed by mixing of common Ca-HCO₃ type water with Mg-Ca-HCO₃ type water derived from the dolomite aquifer. Therefore, it is most likely that the Mg-rich artesian waters from the deep dolomite aquifer are continuously injected into shallow aquifers in the landslide mass. Such injection of deep artesian waters has an impact upon groundwater behavior in the landslide mass and is also one of the key factors controlling the stability of the Kostanjek landslide. This interpretation coincides with Ortolan's (1996) hypothesis that an artesian aquifer in Badenian limestone and Triassic dolomite underlays Sarmatian and Panonian rocks and the Kostanjek landslide.

Discussion and Conclusions

External Triggers

Rainfall and earthquakes are monitored by sensors for continuous measurement installed at the Kostanjek landslide. External trigger monitoring is of crucial importance because of their influence on reactivation of the landslide and establishment of an early warning system.

A disadvantage of the installed rain gauge is that it does not provide accurate precipitation data during snowy periods. Moreover, the Kostanjek landslide reactivation in the winter and spring of 2013 was triggered by precipitation (rainfall and melting of thick snow cover). Because of this reason it is necessary to install an additional meteorological station in the area of the Kostanjek landslide which will monitor precipitation and other meteorological factors.

Seven accelerometers with continuous monitoring, installed at five locations at the landslide surface and at different depths, also provide good spatial and temporal data which can record local conditions inside the landslide body (depth of 90 m; total landslide area of 1 km²) and in the rock mass below the sliding surface. These accelerometers can record ground shaking (accelerations) in response to earthquakes (trigger) and response to landslide movements (activity). According to Massey (2010), there is possibility that installed accelerometers can not record low strain rate displacements such as creep.

Slope Movements

Slope movement measurements provide data about the actual state of slope activity, i.e. they define the dynamic status of a mass movement, enable recognition and quantification of the reactivation phase, enable definition of threshold values and eventually enable forecasting of the catastrophic phase (Baroň et al. 2012). Subsurface movement at the Kostanjek landslide, measured by inclinometer, provided reliable data about sliding surface depth, mechanical behavior and displacement rate until February 2013. After this period the inclinometer casing became impassable due to large displacement at the sliding surface. Although the inclinometer data are of good quality, the temporal resolution (just a few measurements in 1 year) and spatial resolution (one borehole in the central part of the landslide) are very poor. Poor spatial resolutions spoiled the possibility of confirming the existing landslide model or reinterpretation for an improved landslide model.

Partial improvement of the subsurface movement monitoring was introduced by installation of four vertical wire extensometers of different depths, installed in the borehole

near the existing inclinometer casing. They will provide continuous displacement monitoring data even in the case of larger displacements. However, additional inclinometers in different part of the landslide are necessary to provide reliable data about landslide geometry.

High resolution temporal and spatial data at Kostanjek are obtained from surface movement monitoring by GNSS sensor network and a large number of wire extensometers. Fifteen densely distributed GNSS sensors can provide high accuracy data depending on post-processing time, while the temporal resolution of the data can be every second (in real time kinematic mode). These near-real and real time movement data satisfy the requirements for failure prediction, using for example the Fukuzono (1985) method. Seven extensometers provide data every 1 h. Unreliability of extensometer data can be caused by significant influence of meteorological conditions to registered displacements, however, which is necessary to take into consideration during interpretation of movement, velocity and acceleration.

Hydrologic Properties

Properties that have the most significant influences on landslide behavior are hydrological properties. Equipment for monitoring of superficial movements measured landslide displacements of 4–20 cm in different parts of landslide, with periods of maximum velocities (2–4 mm/day) which correspond to the peaks of ground-water levels measured in the central part of the landslide.

Pore water pressure/water level data at the Kostanjek landslide provide good temporal data (every 1 h), but the sensors are installed at only few locations and in different parts of the landslide body. Three piezometers with pore pressure gauges are installed in the central part of the landslide body: one is in the zone of the sliding surface and two are in the landslide mass. Other water level gauges are installed in the upper part of the landslide body. Although water level sensors installed in the upper part of the landslide body do not actually measure water level in the sliding surface area, the data shows good correlation with landslide movements. However, additional piezometers are necessary, in different part of the landslide, to provide measurements of pore water pressure for better understanding of landslide behavior and correlation with causal factors.

Geochemical measurements undertaken to better understand groundwater flow patterns were performed on samples taken at 74 locations. They provide high spatial resolution data. Samples taken in two different periods did not show any significant differences, which indicates that the temporal resolution is also of satisfying quality.

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References

- Allison RJ, Brunsten D (1990) Some mudslide movement patterns. *Earth Surf Process Landf* 15(4):297–311
- Baroň I, Supper R, Ottowitz D (2012) Report on evaluation of mass movement indicators. SafeLand deliverable D4.6. Geological Survey of Austria. Vienna, 382 p
- Bernat S, Mihalić Arbanas S, Krkač M (2014) Landslides triggered in the continental part of Croatia by extreme rainfalls in the winter of 2013. In: Proceedings of XII IAEG congress, 15–19 September 2014, Torino
- Corominas J, Moya J, Lloret J, Gili JA, Angeli MG, Pasuto A, Silvano S (2000) Measurement of landslide displacements using a wire extensometer. *Eng Geol* 55:149–166
- Fukuzono T (1985) A new method for predicting the failure time of a slope. In: Proceedings of IVth ICFL, Japan Landslide Soc, Tokyo
- DHMZ (Meteorological and Hydrological Service) (2013) Meteorological and hydrological bulletin 3 (in Croatian)
- Krkač M, Rubinić J, Kalajžić J (2014) Analysis of water fluctuation dynamics in the wider area of the Kostanjek landslide. In: Proceedings of 1st regional symposium on landslides in the Adriatic-Balkan Region, 6–9 April 2013, Zagreb
- Massey CI (2010) The dynamics of reactivated landslides: Utiku and Taihape, North Island, New Zealand. Ph.D. thesis, Durham University, Durham, UK
- Mihalić Arbanas S, Arbanas Ž, Krkač M (2013) TXT-tool 2.385-1.2 a comprehensive landslide monitoring system: the Kostanjek landslide, Croatia. In: Sassa K et al (eds) ICL landslide teaching tool. ICL, Kyoto, pp 158–168. ISBN 978-4-9903382-2-0
- Ortolan Ž (1996) Development of 3D engineering geological model of deep landslide with multiple sliding surfaces (Example of the Kostanjek Landslide). Ph.D. thesis, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb, Croatia (in Croatian).
- Stark TD, Choi H (2008) Slope inclinometers for landslides. *Landslides* 5(3):339–350
- Watanabe N, Krkač M, Furuya G, Wang C, Mihalić Arbanas S (2012) Hydrochemical characteristics of groundwater from the Kostanjek Landslide in Croatia. In: Proceedings of the 2nd project workshop of the Croatia - Japan project on risk identification and land-use planning for disaster mitigation of landslides and floods in Croatia, Rijeka, 15–17 Dec 2011