Geologia Croatica | 64/3 | 239–249 | 12 Figs. | Zagreb 2011

A Complex landslide in the Rječina Valley: results of monitoring from 1998–2010

Čedomir Benac[1], Sanja Dugonjić[1], Martina Vivoda[1], Maja Oštrić[2] and Željko Arbanas[1]

[1] Faculty of Civil Engineering, University of Rijeka, V. Cara-Emina-5, 51 000 Rijeka, Croatia
[2] Disaster Prevention Research Institute Kyoto University, Gokasho, Uji, Kyoto 611-0011

doi: 104154/gc.2011.20

Geologia Croatica

ABSTRACT

Results of landslide monitoring undertaken between 1998–2010 on the north-eastern slope of the central part of Rječina Valley in front of Grohovo village (north-eastern coastal part of Adriatic Sea, Croatia) are presented. This is the largest regional active landslide. The slopes around the Rječina riverbed are formed in siliciclastic sedimentary rocks with flysch characteristics. The bedrock is mostly covered with unstable slope formations. A limestone rock mass is visible on the cliffs around the top of the river valley. The landslide is complex and retrogressive, with 13 sliding bodies. It occurred in December 1996 by displacement of an initial landslide body where movement had been registered in the 19th century. The limestone mega-blocks and separated rocky towers on the top of the slope have also moved, which is an atypical phenomenon of the flysch slopes in the area of Rijeka. After initial sliding ceased, and major movements subsided, monitoring of benchmark movements from 1998 until 2010 determined further maximum displacements on the upper part of the slope, and minimum movement in the lower part. The area of the Rječina Valley from the Valići Dam to the Pašac Bridge was selected as a pilot area in the framework of the Croatian-Japanese bilateral joint research project. Monitoring results provided the basis of establishing an early warning system for possible landslide occurrence and estimating the degree of landslide risk.

Keywords: landslide, flysch, karst, displacement, monitoring

1. INTRODUCTION

The Rječina River flows through three different geomorphological zones. The first occupies the area from the river source at the foot of the Gorski kotar Mountains to the Lukeži Village. The second zone extends from Lukeži Village to the canyon entrance near the Pašac Bridge, while the third stretches from the entrance of the canyon and the alluvial plain near the river mouth in the centre of Rijeka City.

The part of the valley between Valići Reservoir and the Pašac Bridge (situated at the entrance to the canyon (Fig. 1)), is the most unstable part of the broad Rijeka region, with a high degree of geohazard risk (BENAC et al., 2005B). A few mass movement phenomena have been noted since the end of the 19th century (ANON, 2011) (Fig. 2). Different types of mass movements can be distinguished including the slippage of slope deposits over the flysch bedrock, rockfalls from limestone cliffs and the slippage of rocky blocks larger than 200 m^3. These phenomena prevail on the northeastern slopes, but are relatively rare on the southwestern slopes of the Rječina – Sušačka Draga and Bakar Bay – Vinodol Valleys morphostructural unit (BENAC et al., 2009).

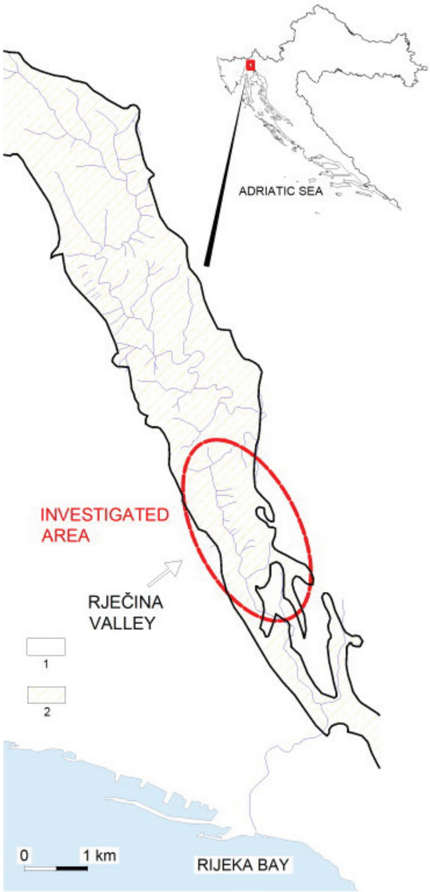

Figure 1: Simplified geological map of the Rječina catchment area (according to VELIĆ & VLAHOVIĆ, 2009): 1 – karstic terrain, 2 – Palaeogene siliciclastic sedimentary rocks.

The slopes in the Rječina Valley between the Valići Reservoir and the Pašac Bridge are at the limit of a stable equilibrium state. The investigated landslide area is not a recent phenomenon. Mass movements were recorded in 1885 after which the, initial landslide body probably moved several times (MAGAŠ & PALINIĆ, 1999).

The investigated landslide is situated on the north-eastern slope of the Rječina Valley (Fig. 3 and 6). The last mass movement was observed on December 5th 1996. Damming of the Rječina riverbed was a secondary effect of the movement. After the initial landslide displacement, there was a retrogressive development from toe to head, as well as the formation of smaller landslides. At the end of the process, isolated rocky blocks were moved, and fractures on the slope head opened (BENAC et al. 1999; 2005A). Further slippage has taken place in stages ever since and has not yet ended, so small mass movements, together with the opening of new fractures in the talus material and rockfalls from limestone ridges have been observed.

This is the biggest known active landslide in the Adriatic coast and is located in the unstable zone with numerous signs of dormant landslides. The dynamics and complexity of the whole phenomena was determined by analysis of movements that were monitored between 1998–2010.

The area of the Rječina Valley described from the Valići Dam to the Pašac Bridge, was selected as one of the pilot areas in the Croatian-Japanese bilateral joint research project „Risk identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia" (MIHALIĆ et al., 2010). A major part of the monitoring equipment will be installed in the active landslide zone on the north-eastern

Figure 2: A view of investigated zone of the Rječina Valley (photo: ARBANAS, Ž.)

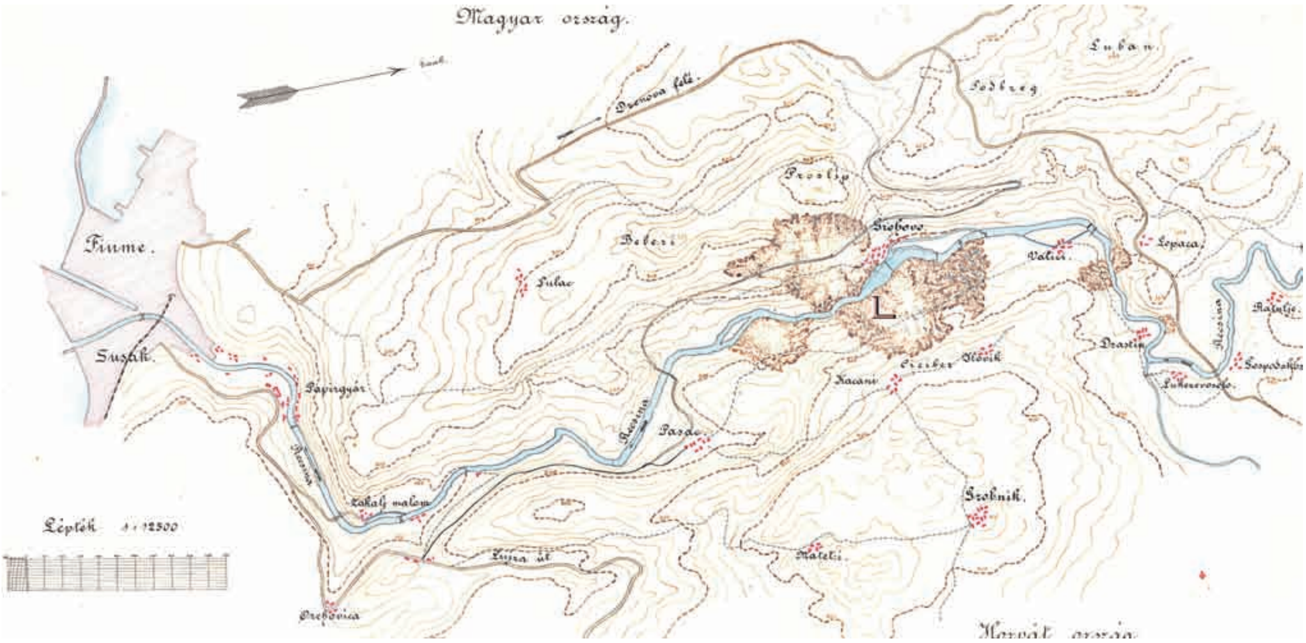

Figure 3: A map of Rječina Valley from 1894: L – position of investigated active landslide (ANON, 2011).

slope of the Rječina Valley, and some on the opposite, south-western slope. All equipment will have a continuous comprehensive monitoring capability, and the data will be exported to the central computer unit of the Faculty of Civil Engineering at the University of Rijeka. An early warning system for possible landslide occurrence and degree of landslide risk will be established based on the monitoring results. These continuous real-time monitoring results will be used to determine threshold values of triggering factors including rainfall intensity and seismic activity.

2. MORPHOLOGY, HYDROLOGY AND GEOLOGY OF THE STUDIED AREA

The tectonic structure that includes the studied part of the Rječina Valley is part of a dominant morphostructural unit which strikes in the direction of the Rječina – Sušačka Draga – Bakar Bay – Vinodol Valleys (VELIĆ & VLAHOVIĆ, 2009) (Fig. 1). This geologic structure could be considered as a flysch syncline limited by faults, analogous with the tectonic style of the Vinodol Valley (BLAŠKOVIĆ, 1999). Tectonic interpretation of the Rječina Valley has not yet been performed. Given the different morphological characteristics and the intensity of the geomorphological processes operating in the area, there are probably significant differences compared to the Vinodol Valley.

The Rječina watercourse is 18.7 km long with the river mouth located in the centre of Rijeka city (Fig. 1). Rječina is a typical karstic river, originating from a strong karstic spring located at the foot of the Gorski Kotar Mountains. The annual average flow of the Rječina spring is 7.76 m^3s^{-1}, with maximum flow rates ranging from 0–100 m^3s^{-1} (KALEUŠA et al., 2003). The Rječina River has few tributaries, the most important of which is the Sušica River. The Sušica River is a West? bank tributary with an annual average flow of 0.72 m^3s^{-1}. Although dry for most of the year, the maximum flow rate of the Sušica can reach 43.8 m^3s^{-1}. Part of the water balance from the Rječina spring is used for the water supply of Rijeka, while part of the water from the Valići Reservoir is used for electric power production in the Rijeka Hydropower Plant of Rijeka.

The aforementioned part of the Rječina Valley between the Valići Reservoir and the Pašac Bridge has an uneven morphology, about 3 km in length and from 0.8 to 1.5 km in width trending NW–SE. The bottom of the valley is 150 to 200 m above sea level. The peaks reach the height of 432 m in the south-western and 412 m in the north-eastern part of the valley (Fig 3).

The kinematics of the structural elements of this part of the Rječina Valley, as in the morphostructural unit mentioned above, are based on the relationship between the relatively rigid carbonate rocks and relatively ductile siliciclastic rocks during simultaneous deformation. The Cretaceous and the Palaeogene limestones are situated on the top of the slopes, while the Palaeogene siliciclastic rocks or flysch are located on the lower slopes, including the bottom of the valley (Figs. 4 & 5). The Flysch complex is a block squeezed between the limestone rock complex to the north-east and south-west. The effects of deformations are most distinctive on the contact between the two rock complexes. This explains why the relatively rigid limestone rock mass is pushed into a more ductile siliciclastic rock. In this way, a former straight line tectonic contact, could have taken on the present toothed appearance (BLAŠKOVIĆ, 1999; BENAC et al., 2006).

Unlike limestone rocks on the top of the slope, the flysch rock mass is almost completely covered by weathered material, slope formation and talus deposits (Fig. 5). Sandstone layers, which are visible only on the outcrops of the Rječina riverbed, have a dip of 10°–15° towards the north-east.

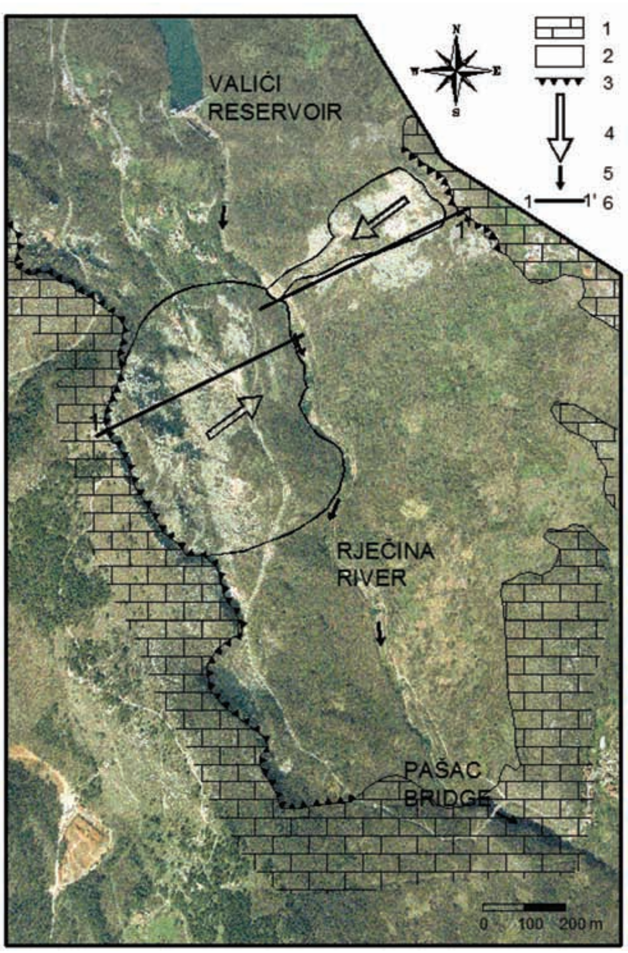

Figure 4: Simplified geological map of the Rječina Valley:
1 – Palaeogene limestone; 2 – Palaeogene siliciclastic rock mass (flysch) mostly covered by slope deposits; 3 – rocky scarps; 4 – active investigated landslide; 5 – Rječina river stream; 6 – geological cross-section (see Fig. 5)

Neotectonic and recent tectonic movements, induced by subduction of the Adriatic plate beneath the Dinarides, caused irregular subsidence of the squeezed basal syncline and uplift of the surrounding terrain (KORBAR, 2009). During this process, the limestone rock mass was repeatedly faulted and fractured. Such tectonic movements and weathering processes enabled separation of the limestone blocks and their gravitational sliding on the flysch bedrock, disintegration of the rock mass, as well as the accumulation of talus deposits at the foot of the rock cliffs (Fig. 5).

Siliciclastic or flysch bedrock is characterized by great lithological heterogeneity, because of the frequent vertical and lateral alternation of different lithological sequences. Microscopic petrological analysis of the bedrock has shown the presence of silty marl, laminated silt to silty shale, as well as fine grained sandstones (BENAC et al., 2005A). Unlike the limestones, the flysch rock mass is more prone to weathering, resulting in a clayey weathering zone on the flysch bedrock. Over time, coarse grained fragments originating from the rock falls were mixed with clay from the weathered flysch zone and slope deposits several metres thick were formed (Fig. 5).

3. LANDSLIDE DESCRIPTION

Field investigations were conducted in two phases. The first phase included topographical (terrestrial photogrammetry) and geophysical (shallow seismic-refraction profiling) surveying methods, as well as engineering-geological mapping of the slope. A second phase of investigation focused on the landslide body itself using five supplementary seismic-refraction profiles, and seven investigation boreholes. Inclinometers and deformeters were installed into two central boreholes and piezometers were built into the remaining five. Electrical sounding in the mega-block movement zone ascertained the contact between the limestone mega block from the top of the slope and the flysch bedrock (BENAC et al., 1999; 2002).

The results indicate the formation of a complex landslide with thirteen sliding bodies. Boundaries between these bodies are mostly clearly visible and represent different types of mass movements (Fig. 7).

The thickness of the displaced material has been estimated from the geological mapping and geophysical surveys results, together with the position of the slip surfaces. The geometry of the total complex landslide is described according to the WP/WLI Suggested Nomenclature for Landslides (IAEG, 1990):

– total length: L = 425 m;

– length of the displaced mass: L_d = 420 m;

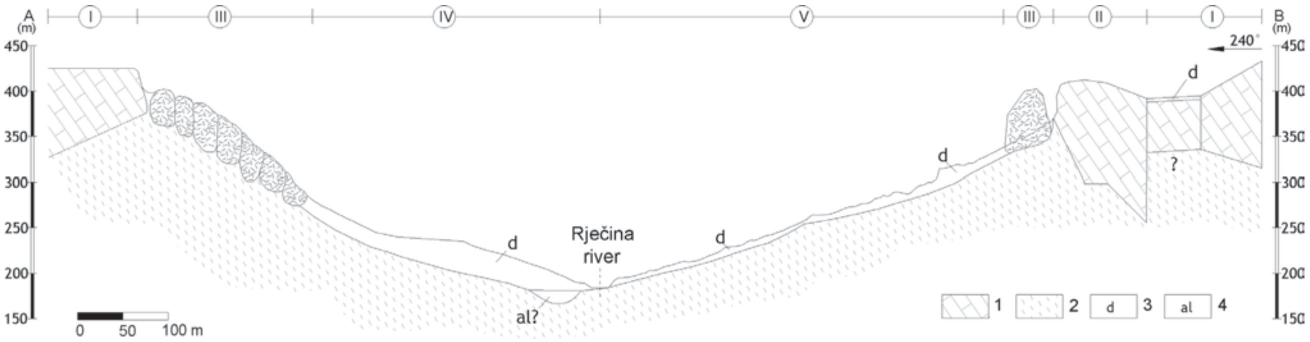

Figure 5: Geological cross-section of the Rječina Valley
1 – Palaeogene foraminiferal limestone; 2 – Palaeogene siliciclastics sedimentary rocks (flysch); 3 – slope deposits; 4 – alluvial sediments (assumed position); I – relatively stable rock mass; II – separated megablock; III – block slide; IV – dormant rock avalanche; V – active landslide

Figure 6: Grohovo landslide on the north eastern slope of the Rječina Valley (photo: BENAC, Č.).

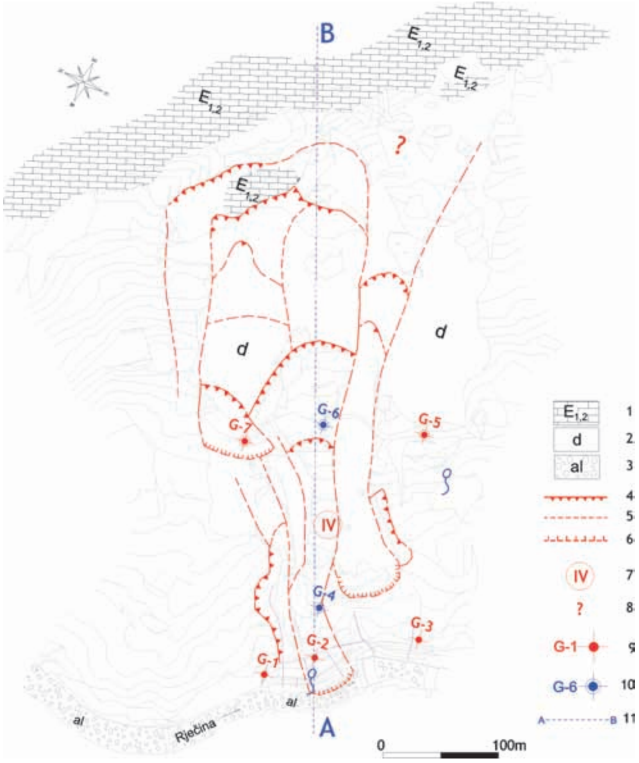

Figure 7: Engineering geological map of the landside
1 – carbonate bedrock (Palaeogene foraminiferal limestone); 2 – slope deposits (silty clay and fragments, fragments and blocks) over Palaeogene siliciclastic bedrock; 3 – recent alluvial sediments (pebbles and gravels); 4 – open fracture (scarp); 5 – shearing fracture; 6 – position of the toe of the landslide (December 1996); 7 – initial body of the landslide; 8 – assumed new body of the landslide; 9 – borehole (installed piezometer); 10 – borehole (installed inclinometer); 11 – trace of engineering geological cross-section (see Fig. 8)

– length of the rupture surface: L_r =405 m;
– width of the displaced mass: W_d = 200 m;
– width of the rupture surface: W_r = 200 m;
– depth of the displaced mass: D_d = 6–20 m;
– depth of the rupture surface: D_r = 6–9 (20) m;
– total height (the height from the crown to the tip of the toe) ΔH = 165 m.

The initial landslide body had been transported the furthest, observed from the range of displaced material in the Rječina riverbed, and by the tilted trees. Due to the magnitude of displacement (up to 20 m), the former relationship of deposits was completely disturbed. A failure surface was formed along the contact of the slope deposits and the flysch bedrock (Fig. 8).

Landslides in talus deposits or colluvium extend to the foot of the limestone cliff near the top of the slope, and the material consists mostly of rocky fragments and blocks. There are visible scars in the head of some landslip bodies up to 10 m in height. Lateral sliding bodies in soil-like materials were probably formed last. They are „typical" of landslides on flysch slopes. Limestone mega-block movements, separated from the limestone rock mass, are special phenomena, atypical of the geodynamic processes on flysch slopes in the Rijeka area. Blocks are probably moving on the flysch bedrock (Figs. 8 and 9). The contact with the rock mass beneath the cliff, as well as their boundaries is masked by talus deposits. There are many open fractures visible in the disintegrated mass of the limestone on the cliff.

According to the accepted classifications, the investigated landslide is a complex composite and retrogressive landslide (SKEMPTON & HUTCHINSON, 1969). Move-

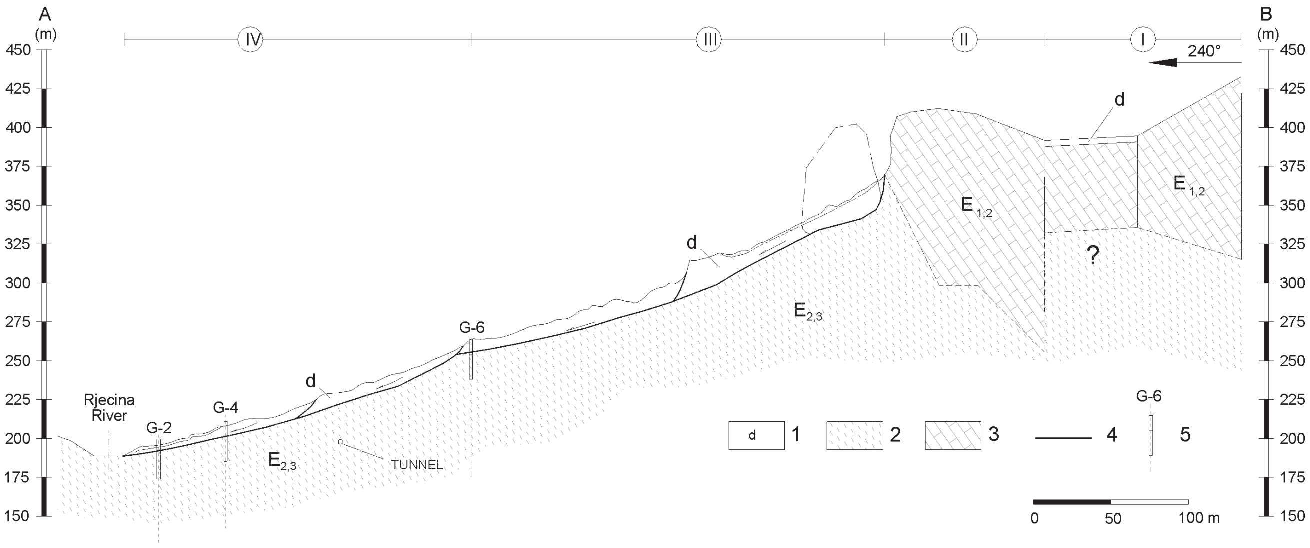

Figure 8: Engineering geological cross-section of the landslide.
1 – slope deposits; 2 – flysch (bedrock); 3 – limestone (bedrock); 4 – boundary of landslide; 5 – borehole; I – relatively stable rock mass; II – separated megablock; III – active landslide; IV – initial landslide
Note: the position of bedding in limestones is only symbolic

Figure 9: Isolated rocky tower (photo: BENAC, Č.)

ments of mixed rock and soil material in the initial landslide body show characteristics of debris avalanches, according to their movement velocities (VARNES, 1978; CRUDEN, & VARNES, 1996). Block sliding of a rock mass is a special phenomenon. Due to the fact that the position of the slip surface was predisposed by geological composition, the landslide can also be considered as a consequent translational, as well as the blocky slide type IIIb (ANTOINE & GIRAUD, 1995). It could also be considered a reactivated landslide on unstable slope, type Ib based on the sliding activity (CROZIER, 1984).

The affected slope has distinctive filtration anisotropy. Groundwater flow in cohesionless talus material is very rapid, in contrast to cohesive talus material, where infiltration and water flow are very slow. Subsurface groundwater can be accumulated locally in clayey to silty slope material and in the weathered bedrock zone. This water originates either from direct infiltration of precipitation, or from the karst aquifer on the top and behind the slope. Surface flow usually occurs in the cover overlying the contact with the impermeable flysch bedrock. Groundwater discharges along the Rječina Channel (BENAC et al., 2005 A).

The ground water level fluctuates with rainfall. Slope deposits could be totally saturated after a long rainy period and consequently, surface flow can appear. Springs in the foot of the landslide are active even after longer dry periods. An ephemeral spring (active only in periods of intense precipitation) is located in the foot of the coarse-grained slope deposits (Fig.7).

4. RESULTS OF MONITORING AND THE NEW MONITORING SYSTEM

A monitoring system was set up for observation of further movements of the landslide body. After the 1st phase of investigation, sixteen benchmarks were placed on parts of the slope, around and on the landslide, and on the cliffs above. After the 2nd phase of investigation works, benchmarks were placed at all seven boreholes. Combined casings for an inclinometer and a deformeter were installed in two boreholes (G-4 and G-6), in the central part of the landslide, Piezometers were installed into another five boreholes to facilitate observation of changes in groundwater levels (Fig. 7).

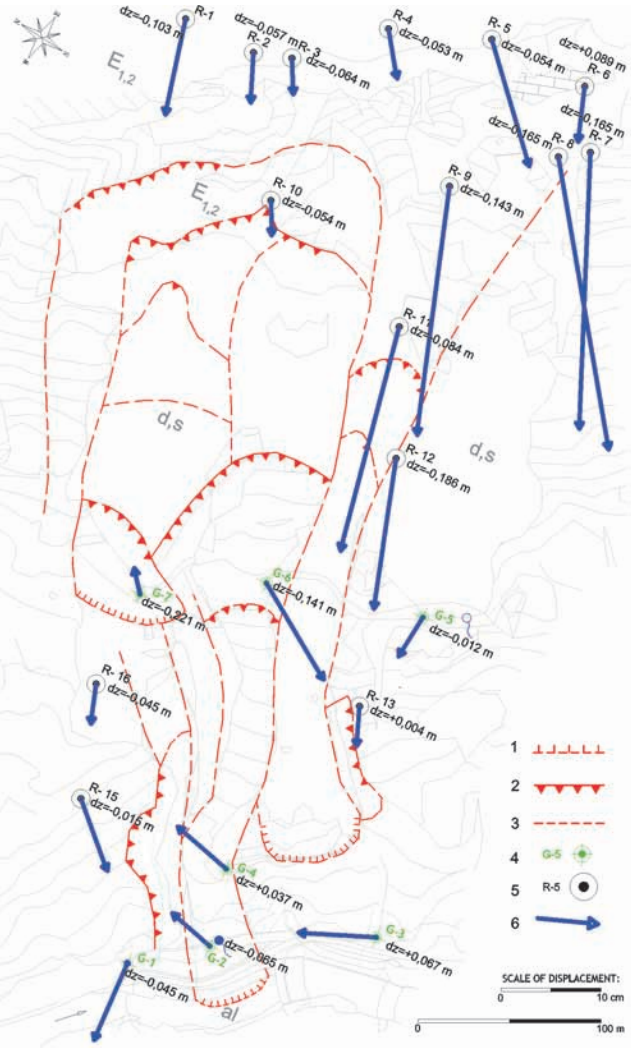

Figure 10: Map of total horizontal and vertical displacement of benchmark.
1 – position of toe of the landslide (December 1996); 2 – margin of landslide (open fractures); 3 – margin of landslide (shearing fractures); 4 – borehole with benchmark: 5 – benchmark; 6 – total horizontal displacement of benchmark (not at the scale of the map)

Observation of the benchmarks (R-1 to R-16) began in December 1998. Benchmark R-14 was destroyed after installation. Observation of the benchmarks at boreholes (G-1 to G-7) began in September 1999. Topographic surveys were carried out from the base point on the opposite side of the Rječina Valley, from a distance of 1000 m. It was possible to measure horizontal displacement (x, y) with an accuracy of ± 1.0 cm, and vertical displacement (z) to ± 1.5 cm (BENAC et al., 2002; BENAC et al., 2005 A). Measurements were conducted approximately every 2 to 3 months (4 to 6 times per year), shown as both trends, and total displacements (Fig. 10).

According to different rates of movement, the investigated slope could be subdivided into three zones, but without clearly visible boundaries. Benchmarks (R-1 to R-5) located on the limestone mega-block, have a relative different horizontal downslope displacement (4 to 12 cm) and uniform subsidence (5 to 6 cm). Benchmark R-1 is located on part of the mega-block separated by a tension crack, and it shows greater subsidence (10 cm) (Fig. 9). Benchmark R-10, located on the west isolated rocky block (tower), had the most rapid trend of horizontal downslope displacement, (8 cm), until it was destroyed. Conversely, benchmark R-6, on the eastern rocky tower, had a relatively small horizontal displacement of 5 cm and a vertical one of 8 cm. Benchmarks on the talus at the foot of the cliffs, and those on their eastern edge (R-7, R-8, R-9, R-11 and R-12) show the most distinctive trends of downslope displacement (25–32 cm), as well as subsidence (up from 8 to 19 cm). Formation of a new slide body on this part of the slope is indicated by the presence of open fractures (Figs. 10 and 11).

Benchmarks on the lower part of the slope (R-13, R-15 and R-16) as well as those at the boreholes (G-1–G-7), have relatively small horizontal displacements in different directions. However, higher benchmarks (G-5, G-6 & G-7), recorded relatively large vertical displacements (12–22 cm).

The difference in subsidence of benchmarks (progress of vertical displacement on the z axis) is closely related to their location on the slope (Fig. 12).

An integrated geodetic and geotechnical monitoring system will be installed in the Grohovo landslide as part of the research activities in the Croatian-Japanese bilateral project. Geodetic monitoring will include observing geodetic benchmark (prism) displacements with a robotic total station, and displacements of GPS points (rovers). In total, 25 geodetic prisms and 15 GPS rovers are predicted.

Figure 11: New open fracture on the higher eastern part of the slope (photo: BENAC, Č.).

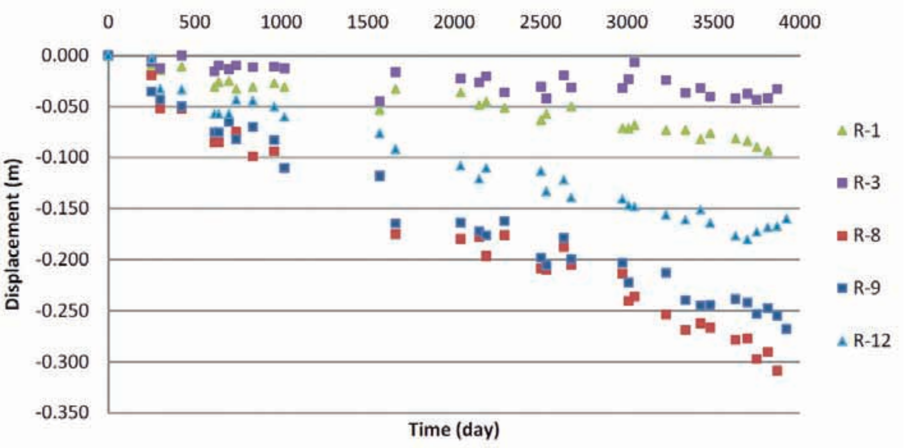

Figure 12: Vertical displacement of benchmarks from December 1996 to June 2010 (positions of benchmarks as shown in Fig. 10).

Equipment for geotechnical monitoring will include vertical inclinometers and long span extensometers, pore pressure gauges, seismographs and rain gauges. This equipment will be installed in the area of the active landslide on the north-eastern slope of Rječina Valley. Piezometers, inclinometers and vertical extensometers will be installed at three locations, two inside the central landslide body and one on the slope to the east. Extensometers will be installed from the Rječina riverbed all through the limestone blocks to the top of the slope. All monitoring equipment will be connected into a single unique comprehensive system with continuous real-time monitoring. This will enable real-time transmission to the control centre and provide a publicly available presentation of the measured data. Such an early warning system based on real time transmission will enable landslide alerts to be issued if the measured values exceed defined limits of values at which possible hazards occur. The system can only be established through the local authority and related services which requires necessary cooperation between the researchers and local government.

5. DISCUSSION

The Rječina Valley – Sušačka Draga Valley – Bakar Bay – Vinodol Valley morphostructural unit has a consistent geological fabric (BLAŠKOVIĆ, 1999),comprising a flysch syncline compressed between the limestone rocky blocks. Mass movements are more frequent and more distinctive on the northeastern slopes in the unit. Talus breccia and cohesive colluvium deposits, resulting from older morphogenetic phases, are also common in these zones (BENAC et al., 2009). In contrast, intensive mass movements are visible on both slopes in the central area of the Rječina Valley (Fig. 3 and 4). Movement of carbonate blocks near the contact with the flysch zones is not a common phenomenon, but similar to phenomena observed in the Alps (MOSER, 2002). For this reason, the investigated part of the Rječina Valley is probable younger than a large part of the aforementioned morphostructural unit.

Changes in topographic relief are due to neotectonic movements, as well as changes of the local base level, and the position of the Rječina riverbed. This also explains differences in the degree of erosive capacity of the river. Morphogenetic development mentioned above was probably not continuous, with periods of accumulation of deposits resulting in the formation of slopes varying from stable to potentially unstable (BENAC et al., 2002).

For this reason, one of the possible causes of slope instabilities in the studied area of the Rječina Valley is probably the different geological setting of this part of the valley compared to most of the rest of the Rječina Valley – Sušačka Draga Valley – Bakar Bay – Vinodol Valley unit. However, the tectonic features of this part of the Rječina Valley have not yet been explained in detail. Secondly, recent intensive tectonic movements that caused the opening of the Rječina canyon may also have resulted in slope instabilities. As a result of base level fall, the Rječina river has been rejuvenated in its erosive capacity.

Talus breccias, indicative of older intensive morphogenetic phases during the Pleistocene, are absent from the slopes of the study area, but occur more frequently in other parts of the morphostructural unit (BLAŠKOVIĆ, 1999). Therefore, it can be assumed that in the Rječina Valley, morphogenetic development is younger than in surrounding areas, resulting in intensive recent mass movements.

Lateral erosion of the riverbed, and simultaneous erosion of the foot of the slopes, are factors causing mass movements. Historic data for the area of Rijeka, record the occurrence of flood events, (some of which caused catastrophic damage), that are closely related to the timing of mass movements in the study area (ANON, 2011). Such catastrophic floods of the Rječina River occurred 1849, 1852, 1853, 1883 and 1898 and 1899 (MAGAŠ & PALINIĆ, 1999). According to data from the Croatian State Archive in Rijeka, the landslides appeared on the south-western slope in 1885 and 1898, and in 1893 on the north-eastern slope, at the location of the studied landslide. The area affected by mass movements is clearly visible on the map from 1894 (Fig. 2). Investigation of the whole area of the valley between Valići Reservoir and the downstream canyon entrance, reveals the presence of more dormant landslides, some of which were active during the 20th century (BENAC et al., 2005A; 2006). The influence of river erosion was reduced after completion of the Rječina riverbed regulation in 1908. Instability on the north-east slope is due to a reactivated landslide, as shown by recorded historic activity. Frequent rockfalls from the top of the limestone cliff accelerated the accumulation of potentially unstable deposits.

Topographic maps from 1981 and 1998 have shown changes in slope morphology (BENAC et al., 1999). Observation of geodetic benchmarks from 1998–2010 highlighted displacements, not only in the part of the slope affected by slippage, but also the formation of a new landside body on the upper part of the slope, indicating further development of the landslide along the slope (Fig. 6 and 8).

The Rječina Valley is the epicentre of Rijeka's seismic area, where earthquakes > M 6.0 have occurred during the last two millennia (HERAK et al., 1996; TOMLJENOVIĆ et al., 2010). Strong earthquakes could decrease the stability of the slopes, and may have caused mass movements, i.e. in slope deposits that are already unstable. This can be followed by separation and rockfalls from the scarp on the top of the slope. According to archive data, mass movements were registered on the slopes around the Rječina River after the destructive earthquake of 1870 (epicentre near Klana village), north-west of the Rječina Valley.

Since 1998, two relatively strong earthquakes occurred that could have been a major triggering factor: 2003, M 4.0, epicentre near Viškovo; 2004, M 4.5 in the area of Fužine (ANON, 2010). However, the direct impact of earthquakes on slope movement cannot be established due to the relatively long period between the measurements. Many researchers have found strong correlation between periods of intensive rainfall and landslide reactivation (HONG et al., 2005; BORGATTI et al., 2006).

There were very heavy periods of rainfall and extreme rainfall events (> 100 mm/day), during the 12 yr monitoring period. Precipitation data was recorded at the meteorological station in Rijeka, 3 km from the study location (RUBINIĆ et al., 2010). Clay, with a relatively low permeability, underlies the coarse rocky talus in the cover. This is expressed by the low hydraulic conductivity, relatively low infiltration of surface water, and a high run out coefficient. Similarly infiltration in the unsaturated part, together with water level rise, occurs relatively slowly, which influences the rate of increase in pore pressures and a decrease in strength from total to effective values. Therefore, long rainy periods are crucial for landslide initiation, and all landslide appearances occurred after long periods of heavy rainfall.

Results analysis showed the variable velocity of the movement of benchmarks over time (Fig. 12). The groundwater level in the piezometers, and displacements of benchmarks, were measured 4 to 6 times a year. Although the measurements of groundwater level were adjusted for the rainy periods, it was still not possible to establish a correlation between rainfall amount and displacements. Installation of monitoring equipment, (inclinometers, extensometers, pore pressure gauges, seismograph and rain gauges), and continuous monitoring will facilitate the measurement and establishment of any correlation between displacement triggers including earthquakes and rainfall events and any consequent movements initiated.

An innovative technique for the remote assessment of ground displacements, based on radar interferometry, and implemented using ground-based instrumentation (GB-InSAR), has been tested in recent years on a number of selected case studies (ANTONELLO et al., 2004) especially with regard to its use for early warning (CASAGLI et al., 2010). Both GPS and InSAR techniques provided complementary measurements, with the GPS providing horizontal movement and InSAR providing vertical motion (YIN et al., 2010). The system of integrated geodetic and geotechnical monitoring that will be installed in the wider landslide area should provide better quality of data. Certainly, the continuous gathering of data should allow better correlation between the triggers and scale of new movements of the landslide body.

6. CONCLUSIONS

The Grohovo landslide was formed in the Rječina Valley, with unstable slopes, and is the result of both complex geological composition and the dynamics of its morphological evolution. It is a complex thirteen individual landslide bodies, developed from the toe to the top of the slope. The initial landslide body moved first and buried the Rječina riverbed. Sliding affected colluvial deposits from the sedimentary cover, and the slip surfaces were mostly predisposed by the morphology of the flysch bedrock. Permanent rock fall from highly disintegrated scarps has played a role of adding to the colluvial deposits over time.

This unstable phenomenon of the north eastern slope of the Rječina Valley is a reactivated landslide. Various instabilities were registered in the 19th century in this part of the valley. Frequent rockfalls from the top of the limestone cliff accelerated the accumulation of potentially unstable deposits.

Results of previous investigations and monitoring will determine remedial measures for unstable colluvial deposits above the flysch bedrock. According to slope stability analysis, sliding in the lower part of the slope could cause retrogressive development of the process upslope. Therefore, it is necessary to make remedial measures for the lowest parts of the slope, which will increase the stability of the upper part. Stabilization of rock toppling is practically impossible. Some analyses indicate that remedial measures will be very expensive. It is necessary to prevent the infilling (and therefore damming of the Rječina river, because of the location of the city of Rijeka 5 km downstream. This is the main risk of further sliding. Accumulated water behind any such dam would be at risk of overflow, in the case of heavy rainfall resulting in rapid water level rise and/or subsequent overflow. After such a collapse, the water wave could cause fatalities and serious damage to infrastructure in the urban area of the City of Rijeka at the mouth of the Rječina River. In the upper part of the slope remedial measures could be applied at a later date, should further monitoring results indicate their necessity.

According to different rates of movement, the investigated slope could be subdivided into three zones. Benchmarks located on limestone mega-blocks, have a relatively different horizontal downslope displacement (4 to 12 cm) and uniform subsidence (5 to 6 cm). Benchmark R-1, located on the part of the mega-block split by a tension crack, has larger subsidence of 10 cm.

Benchmarks on the isolated rocky blocks (tower), have relatively small horizontal and vertical displacement. Benchmarks on the talus at the foot of the cliffs and those on their eastern edge show the most distinctive trend of downslope displacements: 25 to 32 cm, as well as distinctive subsidence up from 8 to 19 cm. A new landslide body could be formed on this part of the slope.

Benchmarks on the lower part of the slope as well as those at the boreholes, have relatively small horizontal displacements in different directions. However, benchmarks placed at the higher borehole locations show relative large vertical displacements (12 to 22 cm). The difference in subsidence of the benchmarks (progress of vertical displacement on z axis) is evident. A system of integrated geodetic and geotechnical monitoring that will be established on the wider landslide area will provide better quality of data and enable the establishment of an early warning system.

ACKNOWLEDGMENT

This paper is result of research activity under the projects 114-0822695-2568 of the Ministry and Science, Education and Sports, Republic of Croatia, and Croatia-Japan project „Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides and Floods in Croatia”.

REFERENCES

ANON (2010): Earthquakes report, Department for geophysics Faculty of Natural Sciences and Mathematics, Zagreb, www.gfz.hr (in Croatian).

ANON (2011): City of Rijeka. Technical department (1840–1918). State archive in Rijeka (unpublished documents, in Hungarian).

ANTOINE, P. & GIRAUD, A. (1995), Typologie des Mouvements de Versants dans un Contexte.– Bulletin IAEG, 51, 57–62.

ANTONELLO, G., CASAGLI, N., FARINA, P., LEVA, D., NICO, G., SIEBER, A.J. & TARCHI, D. (2004): Ground-based SAR interferometry for monitoring mass movements.– Landslides, 1, 21–28. doi: 10.1007/s10346-003-0009-6.

BENAC, Č., ARBANAS, Ž., JARDAS, B., KASAPOVIĆ, S. & JURAK, V. (1999): Complex Landslide in the Rječina River Valley, Faculty of mining-geology and petrology.– Almanac, 11, 81–90. (in Croatian).

BENAC, Č., ARBANAS, Ž., JARDAS, B., JURAK, V. & KOVAČEVIĆ, S.M. (2002): Complex landslide in the Rječina River valley (Croatia): results and monitoring.– In: RIBAR, J., STEMBERK, J. & WAGNER, P. (eds.): Proceedings of the 1st European Conference on Landslides, Prague, June 2002. A.A.BALKEMA, Lisse-Abingdon-Exton-Tokyo, Landslides, 487–492.

BENAC, Č., ARBANAS, Ž., JURAK, V., OŠTRIĆ, M. & OŽANIĆ, N. (2005A): Complex landslide in the Rječina River valley (Croatia): origin and sliding mechanism.– Bulletin of Engineering Geology and the Environment 64/4, 361–371. doi: 10.1007/s10064-005-0002-5

BENAC, Č., JURAK, V. & OŠTRIĆ, M. (2005B): Qualitative assessment of geohazard in Rječina Valley, Croatia.– Geophysical Research Abstract, Vol. 7, 08943, 1–6.

BENAC, Č., JURAK, V. & OŠTRIĆ, M. (2006): Qualitative assessment of geohazard in the Rječina Valley, Croatia. Proceedings of the 10th IAEG International Congress: IAEG Engineering geology for tomorrow’s cities, 658 (1–7), The Geological Society of London.

BENAC, Č., DUGONJIĆ, S., ARBANAS, Ž., OŠTRIĆ, M. & JURAK, V. (2009): The Origin of Instability Phenomena Along The Karst-Flysch Contacts.– In: VRKLJAN, I., (ed.): ISRM International Symposium Rock Engineering in Difficult Ground Conditions: Soft Rock and Karst, October, 2009, Cavtat. CRC Press, Boca Raton-London-New York- Leiden, 757–761.

BENAC, Č., DUGONJIĆ, S., OŠTRIĆ, M., ARBANAS, Ž. & ĐOMLIJA, P. (2010): Complex landslide in the Rječina River valley: monitoring results.– In: HORVAT, M. (ed.): 4th Croatian Geological Congress, Šibenik 14.–15.2010. Abstract Book, Croatian Geological Survey, Zagreb, 157–158.

BLAŠKOVIĆ, I. (1999): Tectonics of part of the Vinodol Valley within the model of the continental crust subduction.– Geol. Croat. 52/2, 153–189.

BORGATTI, L., CORSINI, A., BARBIERI, M., SARTINI, G., TRUFFELLI, G., CAPUTO, G. & PUGLISI, C. (2006): Large reactivated landslides in weak rock masses: a case study from the Northern Apennines (Italy).– Landslides, 3, 115–124. doi: 10.1007/s10346-005-0033-9.

CASAGLI, N., CATANI, F., DEL VENTISETTE, C. & LUZI, G. (2010): Monitoring, prediction, and early warning using ground-based radar interferometry.– Landslides, 7, 291–301. doi: 10.1007/s10346-010-0215-y.

CRUDEN, D.M. & VARNES, D.J. (1996): Landslide type and processes.– In: TURNER, A.K. & SCHUSTER, R.L. (eds): Landslides: Investigation and Mitigation. National Academy Press, Washington, D.C. Special report, 247, 36–75.

CROZIER, M.J. (1984): Field assessment of slope instability.– In: BRUNSEN, D. & PRIOR, DB. (eds.): Slope Instability. John Wiley & Sons, New York, 103–142.

HERAK, M., HERAK, D. & MARKUŠIĆ, S. (1996): Revision of the earthquake catalogue and seismicity of Croatia, 1902–1992.– Terra Nova, 8, 86–94.

HONG, Y., HIURA, H., SHINO, K., SASSA, K. & FUKUOKA, H. (2005): Quantitative assessment on the influence of heavy rainfall on the crystalline schist landslide by monitoring system-case study on Zentoku landslide, Japan.– Landslides, 2, 31–41. doi: 10.1007/s10346-005-0044-6.

IAEG (1990): Suggested Nomenclature for Landslides.– Bulletin IAEG, 41, 13–16.

KARLEUŠA, B., OŠTRIĆ, M. & RUBINIĆ, J. (2003): Water management elements in regional planning in karst, Rječina catchment area – case study.– In: Proceedings: Water in karst area of watersheds Cetina, Neretva and Trebišnjica, University of Mostar, Mostar, 85–94 (in Croatian).

KORBAR, T. (2009): Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates.– Earth-Science Reviews, 96, 296–312. doi: 10.1016/j.earscirew.2009.07.004.

MAGAŠ, O. & PALINIĆ, N. (1999): Rječina and Zvir: regulation and revitalization, State archive in Rijeka, 76 p., (in Croatian).

MIHALIĆ, S., ARBANAS, Ž., KRKAČ, M., DUGONJIĆ, S. & FERIĆ, P. (2010): Landslide hazard maps and early warning systems aimed at landslide risk mitigation, Proceedings of Croatian platform for risk and catastrophe reduction, Zagreb, 18–22, (in Croatian).

MOSER, M. (2002): Geotechnical Aspects of Landslides in the Alps.– In: RIBAR, J. STEMBERK, J. & WAGNER, P. (eds.): Landslides, Proceedings of the 1st European Conference on Landslides, 24–26 June 2002, Prague. A.A. Balkema Publishers, 23–43.

RUBINIĆ, J., RUKAVINA, J., MILKOVIĆ, J., PILKO, J., ZEKO, J. & LUKARIĆ, S. (2010): Heavy precipitation occurrence in Rijeka – problems, measurements and analysis over time.– Proceedings of 2nd Regional Rainfall Conference of the Balkans: Regional rainfall and climate change, Belgrade, (in press).

SKEMPOTON, A.W. & HUTCHINSON, J.N. (1969): Stability of natural slopes and embankment foundations, State of the Art Report: 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico City, 291–340.

TOMLJENOVIĆ, B., HERAK, M., HERAK, D., KRALJ, K. & MATOŠ, B. (2010): New data on seismotectonic activity in Croatia.– In: HORVAT, M. (ed.): 4th Croatian Geological Congress, Šibenik 14.–15.10. 2010. Abstract Book, Croatian Geological Survey, Zagreb, 404–405.

VARNES, D.J. (1978): Slope Movements, Types and Processes.– In:. SCHUSTER, R.L. & KRIZEK, R.J. (eds.): Landslides, Analysis and Controls, Report, 176, 11–33, National Academy of Science, Washington D.C.

VELIĆ, I. & VLAHOVIĆ, I. (2009): Geological map of the Republic of Croatia 1:300.000, Croatian Geological Survey, Zagreb.

YIN, Y., ZHENG, W., LIU, Y., ZHANG, J. & LI, X. (2010): Integration of GPS with InSAR to monitoring of the Jiaju landslide in Sichuan, China.– Landslides, 7, 359–365. doi: 10.1007/s10346-010-0225-9.

Manuscript received June 01, 2011
Revised manuscript accepted September 01, 2011
Available online October 26, 2011