Qualitative assessment of geohazard in the Rječina valley, Croatia

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Abstract: The Rjecina watercourse is 18.7 km long and its river mouth is in the center of Rijeka city. The central part of the Rjecina river is 1.8 km long, and 0.8 to 1.1 km wide and represents a narrow flysch valley between a karst plateau. Maximal annual discharge is 248 m^3s^{-1} during a 100 yr return period. Cretaceous and Paleogene limestone rocks are situated on the top of the slope, while Paleogene flysch forms the lower slopes, including the bottom of the valley.

The south-western slope of the valley is covered by predominantly coarse soils of limestone composition. The crown of instability is clearly marked by cliffs formed in limestone rocks, which are very disintegrated with recently opened fractures clearly visible. On the north-eastern valley side, slope deposits are mostly a mixture of clayey silt, formed by weathering of flysch bedrock, and fragments to blocks of limestone originating from the cliffs at the top of the slope. On both slopes, different types of instabilities, according to type of movement, type of material involved and state of activity, can be found.

Only in the above-mentioned part of Rjecina valley, are instabilities on both slopes formed. A potential geohazard event could involve movement of slope deposits towards the channel of the Rjecina River. Since both slopes are at or near to the limiting state of equilibrium for stability, preparatory factors already exist. Heavy precipitation and/or earthquakes may be potential triggers of rockfalls and rockslides. Daily precipitation higher then 100 mm is frequent in this area. This could cause two secondary effects: damming of the Rjecina River leading to the formation of landslide-dammed lakes; as well as formation of a flooding wave due to destruction of the natural landslide dams, and consequent flooding of the lower central area of Rijeka city.

Résumé: Le cours d'eau de Rjecina est de 18.7 kilomètres de long et son embouchure est au centre de la ville de Rijeka. La partie centrale du fleuve de Rjecina est de 1.8 kilomètres de long, et 0.8 à 1.1 kilomètres de large et elle représente une vallée étroite de flysch entre un plateau de karst. Le débit annuel maximal est 248 m^3s^{-1} pendant la période de renvoi de 100 ans. Les roches crétacées et paléogènes de calcaire sont situés sur la cime de la pente, alors que le flysch paléogène est situé plus bas sur la pente, y compris le fond de la vallée.

La pente du sud-ouest de la vallée est couverte par les sols principalement bruts de composition de calcaire. La couronne de l'instabilité est clairement marquée par des falaises formées dans les roches de calcaire qui sont très désagrégées et les ruptures récemment ouvertes sont évidentes. Sur la pente du nord-est, les dépôts de pente sont la plupart du temps un mélange de l’argile limoneuse qui a été constituée par la désagrégation de la roche en place et des fragments de flysch aux blocs de calcaire provenant des falaises sur le dessus de la pente. Sur les deux pentes, différents types d'instabilités, selon le type de déplacement, le type de matériel impliqué et l'état d'activité, peuvent être trouvés.

Seulement dans la partie mentionnée ci-dessus de la vallée de Rjecina, des instabilités sur les deux pentes sont formées. L'événement de base de l’alea géologique pourrait être mouvement des dépôts de pente vers le canal du fleuve de Rjecina. Puisque les deux pentes sont au bord d'un état fixe d'équilibre, les facteurs préparatoires existent déjà. La précipitation lourde ou les tremblements de terre peuvent être des déclenchements efficaces des blocks écroulements et des glissements de rocheux. La précipitation quotidienne plus haute de 100 millimètres est fréquente dans ce secteur. Ceci peut causer deux effets secondaires : barrage de Rjecina et formation des lacs ; aussi bien que la formation de la vague d'inondation attribuée à la destruction du barrage naturel, et par conséquent l'inondation de la zone centrale inférieure de la ville de Rijeka.

Keywords: geological hazards, landslides, mass movement, slope stability, floods

INTRODUCTION

The Rječina watercourse, in the northwestern Adriatic part of Croatia, is 18.7 km long with the river mouth located in the center of the city of Rijeka (Figure 1). The Rječina is a typical karstic river originating from a strong karstic spring located at the foot of Gorski Kotar Mountains. The annual average flow of the Rječina spring is 7.76 m^3s^{-1} with maximal flow rates ranging from 0 to over 100 m^3s^{-1} (Kaleuša, Ostric & Rubinic 2003). The Rječina has a few tributaries, the most important being the Sušica River. The Sušica River is a left bank tributary with an annual average flow of 0.72 m^3s^{-1}. Although dry for most of the year, the maximal flow of the Sušica can reach 43.8 m^3s^{-1}. Part of the water balance from the Rječina spring is used for water supply to Rijeka city, while part of the water from the Valići reservoir (Figure 1) is used for electric power production in the hydroelectric power plant of Rijeka.

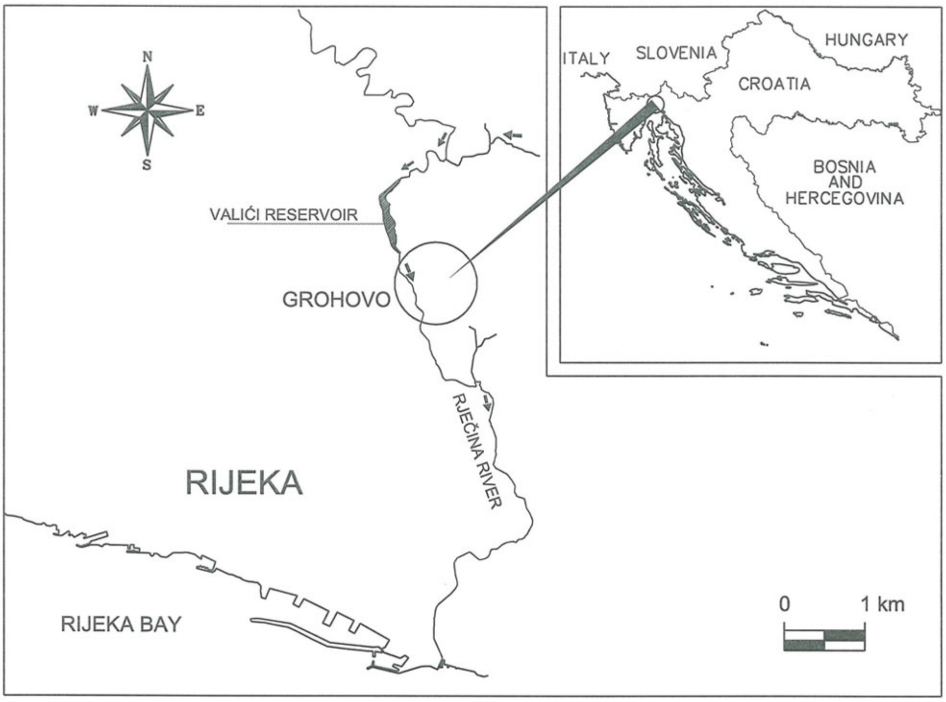

Figure 1. Location map

The Rječina River extends through two distinctive geomorphological units. The upstream and central part of the river valley is relatively narrow and formed in rocks of Paleogene flysch. This part of the valley also consists of Upper Cretaceous and the Paleogene limestones. The downstream part of the watercourse flows through deep canyon cut into the Cretaceous and Paleogene carbonate rocks (Benac, Jurak & Ostric 2005).

The central part of the watercourse, between the Valići Dam and the Pašac Bridge, is 1.8 km long, and 0.8 to 1.1 km wide. This is the most unstable part of the Rijeka area, with the highest degree of geological hazard. Here, mass movements are occurring mainly at the contact of fractured and karstified carbonate rocks with the flysch rock complex. In the central part of the valley, on the south-western side, historic data records two large rockfalls. The first huge rockfall covered the village Grohovo in 1908, and the second one covered a regional road in 1979 (Figure 2). In the north-eastern part of the valley the largest active landslide along the Croatian Adriatic Sea region was formed in 1996. In 1912 a tunnel was excavated for a water supply pipeline, with constructors noticing at that time the presence of instabilities on the toe of a recent landslide. Different types of movements can be distinguished, such as the sliding of slope deposits over the flysch bedrock, the sliding of large rocky blocks and rockfalls from cliffs.

RIVER VALLEY GEOLOGY

The dominant tectonic structure in the investigated part of the Rječina River Valley is a part of a major geomorphological unit that strikes in the direction of the Rječina River Valley-the Sušačka Draga Valley-the Bakar Bay-and the Vinodol Valley. The structure was considered to be a flysch syncline confined by faults. Due to analogy with the tectonic style of the Vinodol Valley, which represents the continuation of the Rječina Valley structures, it was possible to apply an interpretation of the tectonic relationships in terms of the process of continental subduction. The main zone of shallow subduction of the Adriatic carbonate platform under Dinaric to the north-east, is assumed to be placed in a wide area of the Rječina River Valley and the Vinodol Valley (Blaškovič 1999).

The kinematics of structural elements of the entire tectonic unit (Rječina Valley- Bakar Bay - Vinodol Valley, is based on the relationship of the relatively rigid carbonate rocks and relatively ductile flysch rock complex during simultaneous deformations. This scenario also applies to the structure of the Rječina River Valley. The Cretaceous and Paleogene limestones are situated on the top of the slopes, while the Paleogene flysch forms the lower slopes and the valley bottom. The flysch complex bedrock is characterized by lithological heterogeneity, because of frequent vertical and lateral alternation of different lithological sequences. Microscopic petrological analysis of the bedrock showed the presence of silty marl, laminated silt to silty shale, as well as fine grained sandstone. Unlike the limestone rocks at the top of the slope, the flysch rock mass is almost completely covered by weathering zone material and rockfall talus.

The flysch rock complex represents a squeezed 'block' between the limestone rock blocks on the north-eastern and south-western side. The effects of deformation are most distinctive at the carbonate and flysch rock contact, with the relatively rigid limestone rock mass deforming the more ductile flysch, which is less resistant due to its complex geological fabric. In this respect, a former straight tectonic contact could have assumed its present irregular appearance.

Neotectonic and recent movements induced by the Adriatic plate subduction under Dinaric probably caused irregular subsidence of the squeezed synclinal valley bottom and the uplifting of the surrounding terrain (Blašković

1999). Due to this, the limestone rock mass was repeatedly faulted and fractured. These tectonic movements enabled separation of limestone rock blocks and fragments and their gravitational sliding over the flysch bedrock, disintegration of rock mass, and the accumulation of talus on the foot of rocky scarps (Figures 2 and 3). Unlike the limestones, the flysch rock mass is more prone to weathering, and this is particularly evident with respect to the silts and shales which are predominant in the flysch. Thus, a clayey weathering zone formed in the flysch bedrock. In time, coarse-grained fragments originating from rockfalls were inter-mixed with clay from the flysch weathered zone to produce slope deposits a few meters thick (Benac et al. 1999).

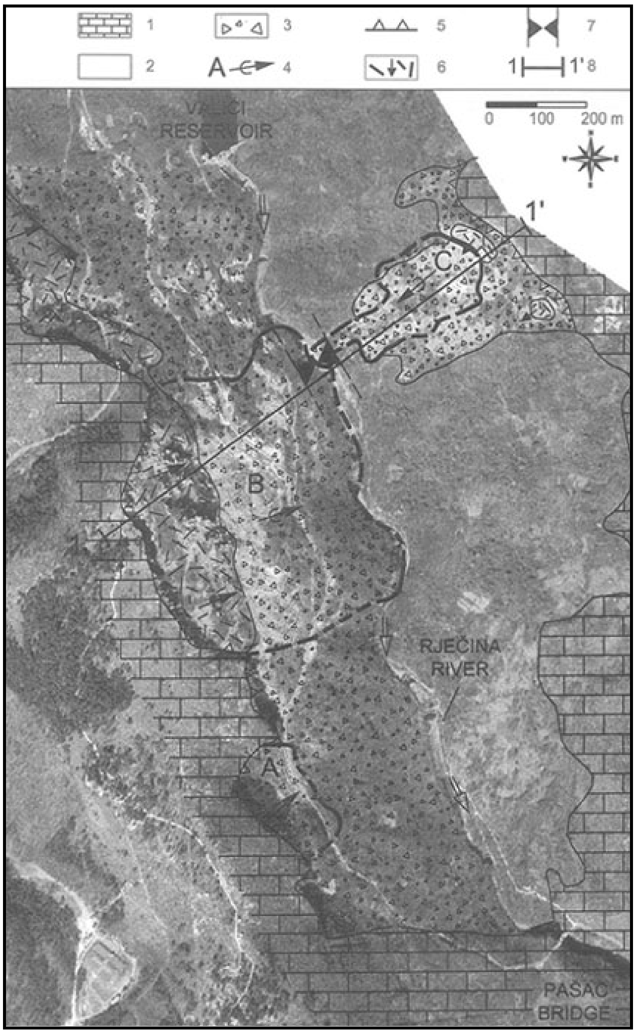

Figure 2. Simplified engineering geological map of Rječina River valley: 1- carbonate bedrock (Cretaceous and Paleogene limestones); 2- flysch deposits (Paleogene silty marl, shale and sandstone) covered by mostly fine-grained slope deposits; 3- flysch deposits covered by rockfall talus; 4- mass movements in 20th century: A- 1979; B- 1908; C- 1979; 5- scarps; 6- isolated rock block on flysch deposits; 7- area of high hazard damming; 8- engineering geological cross section

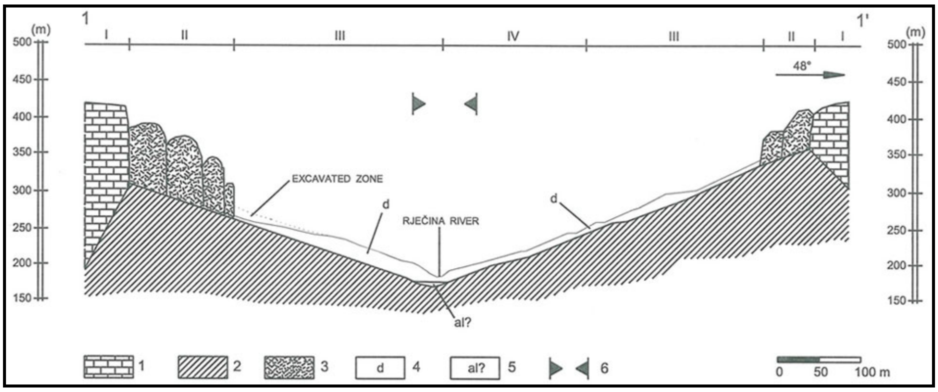

Figure 3. Engineering geological cross section of Rječina River Valley: 1- carbonate bedrock (Cretaceous and Paleogene limestones); 2- flysch deposits (Paleogene silty marl, shale and sandstone); 3- isolated rock block; 4- slope deposits; 5- possible alluvial deposits; 6- area of high hazard damming; I - rock mass disintegration; II - movements of isolated rock block; III - movements of debris deposit; IV - initial sliding.

Stress relief of the Rječina River Valley slopes has been changing due to neotectonic movements, climatic changes during the Quaternary and changes of local erosion base level, namely, the position of the Rječina riverbed. Hence, the intensity of the erosion has frequently changed. The morphogenetic development described above was probably not continuous, but involved periods of higher or lower intensity of slope deposit accumulations (Benac et al. 2000).

DESCRIPTION OF INSTABILITIES

Almost the entire south-western slope of the valley, composed of flysch bedrock, is covered by predominantly coarse slope deposits of limestone composition. The crown of instability is clearly marked by rocky scarps that have been formed in the limestone rocks. The crown represents the rim of the karst plateau. The limestone cliff from the top of the south-western slope is highly disintegrated and recently-opened fractures are visible. Rockfalls are permanently occurring and debris slides are formed of predominantly coarse soils. There are no visible boundaries between the instabilities (Figure 2). However, two phenomena on the south-western slope can be distinguished and are described below.

On the north-eastern slope, the slope deposits mostly range from a mixture of clayey silt formed by weathering of flysch bedrock and fragments originating from the rocky scarps on the top of the slope. Only in the area of the active complex landslide can coarse-grained slope deposits or rockfall talus, like those from south-western slope, be found. On the north-eastern slope a debris avalanche and a complex landslide (Figure 6) can be distinguished.

On both slopes different types of instabilities can be identified, based upon type of movement, material involved and state of activity (Cruden & Varnes 1996).

Debris avalanche on SW slope (Figure 4; marked as A on Figure 2):

The crown of this recent landslide is clearly bounded by limestone cliffs, while the toe reaches the regional road. The displaced mass is composed of coarse fragments to blocks in excess of 10 m^3 in volume. The slip plane is probably predisposed by the flysch bedrock morphology. Excavation of rock materials caused the rock avalanche that buried the regional road in 1979. It was estimated that the mass movement had a volume over 170 000 m^3. Estimated dimensions and geometry of this instability are described according to the ‘World Landslide Inventory Working Party: Suggested Nomenclature for Landslides’ (IAEG 1990):

- total length: L = 110 m;
- width of the displaced mass: W_d = 150 m;
- depth of the displaced mass: D_d = 10 m.

Figure 4. Debris avalanche and rock slide on SW slope of river valley, marked as A on Figure 2

Debris avalanche and rock slide on SW slope (Figure 5; marked as B on Figure 2):

The material of this landslide is composed of coarse fragments to blocks up to 50 m^3 in volume. The slip plane is probably predisposed by the morphology of flysch bedrock. In 1908, a debris avalanche buried the village of Grohovo and partially dammed the Rječina riverbed. It was estimated that this mass movement had a volume of 1 650 000 m3. Estimated dimensions and geometry of this instability are:

- total length: L = 450 m;
- width of the displaced mass: W_d = 300 m;
- depth of the displaced mass: D_d = 10 m.

The crown of the instability reaches to the foot of a rocky block of dimensions 450 m wide and 150 m long. The limestone rock mass comprising the block is disintegrated. Indications of recent movements are not evident and it can be considered as an inactive, dormant landslide. However, movements during a period of reactivation were very rapid. A large limestone block separated from the karst plateau can be considered as a separate phenomenon representing an inactive, dormant rock slide.

Figure 5. Debris avalanche and rock slide on SW slope of river valley, marked as B on Figure 2

Landslide on the NE slope (Figure 6; marked as C on Figure 2):

The crown of this landslide is clearly marked by carbonate rock scarps that form the rim of the karst plateau (Figure 6). The slip plane was predisposed by the position of flysch bedrock. The limestone rock mass is very deformed and karstified with recently-opened fractures, and has been prone to rockfalls and sliding. At the foot of the limestone cliffs, coarse-grained slope deposits are found and debris slides have formed. In the lower part of the slope fine-grained material prevails and consequently earth slides are formed. Estimated dimensions and geometry of this instability are:

- total length: $L = 425$ m;
- width of the displaced mass: $W_d = 200$ m;
- depth of the displaced mass: $D_d = 6\text{-}20$ m;

Figure 6. Active landslide on NE slope of the river valley, marked as C on Figure 2

This landslide is not a recent phenomenon, and data concerning mass movements have been registered during the entire 20th century. On December 1996 approximately 850 000 m^3 of material moved. Movement of isolated limestone blocks and opening of new fractures in a rock 'mega-block' at the top of the slope can be observed. Results of geodetic monitoring also indicate that the largest displacements are occurring on the top of the slope, involving isolated blocks as well as the limestone mega-block that is separated from the karst plateau (Benac et al. 2002). The larger part of the landslide body is saturated by underground water penetrating through the covering material in a zone where it is in contact with the underlying flysch bedrock. Unlike the limestone, the flysch rock mass is more prone to weathering and a clayey weathering zone has formed at the flysch bedrock surface, thus impeding drainage. According to accepted classifications, the described instabilities have characteristics of a retrogressive landslide that started to develop from the foot of the slope to the top due to river erosion and undercutting at the slope foot. As the position of the slip plane was predisposed by the slope geology, the landslide can also be considered as dominantly translational in character (Cruden & Varnes 1996).

CONCLUSIONS

A clear distinction is evident between the morphologies of the opposite slopes of the Rječina River Valley and the granulometric composition of the slope deposits. The south-western side is almost entirely covered by coarse grained, cohesionless rockfall/talus material, where blocks larger then 10 m^3 are common. At the top of the slopes, carbonate rock scarps define the edge of the karst plateau from the flysch complex rocks. Measurements of displacements and observed instability phenomena on the northwestern slope, are indicative of distinctive geodynamic processes related to stress relief (Benac et al.1999, Benac et al.2002). The described instabilities are atypical of karstified carbonate and flysch complex contacts in the wider area of Rijeka and are more typical of those observed in the Alps (Moser 2002).

Only in the central part of the Rječina River Valley are instabilities on both slopes formed. Basic geohazard events could involve the movement of slope deposits towards the Rječina River channel (Figure 2 and 3), which may give rise to two groups of secondary effects (Erismann & Abele 2001). The first is the potential damming of the Rječina river channel and formation of landslide-dammed lakes. The second is the possible formation of a flooding wave caused by destruction of the natural landslide dams and consequent flooding of the lower central zone of the city of Rijeka.

Since both slopes are close to the limiting state of equilibrium for stability, preparatory factors already exist. Heavy precipitation or earthquake events, separately or in combination, may become efficient triggers of rock-falls and rockslides. Daily precipitation in excess of 100 mm is frequent in the area. The Rječina River Valley is part of Rijeka's epicentral seismic area, in which earthquakes with magnitude greater than M= 6 have been recorded during the last two millennia (Herak, Herak & Markusic 1996).

Further investigations of mass movements on the slopes, including quantitative geohazard assessment, will be needed. For this reason, a monitoring system for the observation of further events on both slopes of the valley should be initiated. The investigations should also include simulation of a potential river channel blockage (Clerici et al. 2002, Raghvendra, Debasis& Sudhir 2005) and assessment of a flooding wave following destruction of this natural barrier.

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