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History and present state of the Slano Blato landslide

J. Logar[1], **K. Fifer Bizjak**[2], **M. Kočevar**[3], **M. Mikoš**[1], **M. Ribičič**[4], **and B. Majes**[1]

[1]University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia
[2]Civil Engineering Institute, Ljubljana, Slovenia
[3]Geoinženiring, Ljubljana, Slovenia
[4]University of Ljubljana, Faculty of Natural Sciences and Technology, Ljubljana, Slovenia

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Abstract. The Slano Blato landslide is more than 1290 m long, 60 to 200 m wide and 3 to 11 m deep with a volume of about 700 000 m^3. It is located in the Eocene flysch region of western Slovenia with a limestone overthrust in the direct vicinity, above the landslide. The landslide moves mainly as a viscous earth flow with occurrences of rapid mud flows. In dry periods or in freezing conditions it behaves as a group of several slow to moderate landslides. The landslide follows the course of the Grajšček stream and is presently only 220 m away from Lokavec village. The landslide was first mentioned about 200 years ago. In 1887 it flowed as a liquid flow and reached and destroyed the main road in the valley 2 km away. The Austro-Hungarian monarchy sent one engineer to the site and 17 years later the slide was remediated with a series of torrential check dams. The monarchy prohibited any construction works in the influence area of the landslide. During the 20th century the region changed from Austrian, Italian, Yugoslav, and finally to Slovenian government in 1991. The relevant Austrian measures and decisions were forgotten during the course of the years, and building permits were issued after the World War II to local people who populated the part of the landslide influence area. Simultaneously, regular maintenance of the excellent past engineering works was neglected. In November 2000 a large landslide of mud and debris was triggered again and it still presents a danger to the relatively new residential houses today. At present, the village is protected against mudflows by a small rockfill dam and by the regulation of the stream bed. In rainy periods removal of mud is necessary to maintain safe conditions for the village. The paper discusses the geological, hydrogeological, hydrological and geotechnical conditions for the occurrence of the Slano Blato landslide. The primary reasons for the Slano blato landslide are the geological and hydrogeological conditions just beneath the overthrust of a Triassic limestone plateau over the Eocene flysch of Vipava valley. The direct reason for triggering the earth flow in 2000 was the intensive precipitation. During the course of years the precipitation threshold for earth flow movements has diminished. The landslide has to be remediated for two main reasons – (1) the village below the landslide is endangered, and (2) the landslide is still advancing retrogressively and laterally. The foreseen permanent remediation measures that are currently under construction are briefly presented.

1 Introduction

Even though Slovenia is a small country that occupies 20 252 km^2, more than 2500 active landslides are registered and more than 1500 have been put into a GIS database (Ribičič, 1999). The majority of them are smaller earth slides and earth slips to the order of 1000 to 10 000 m^3. In the last decade of the 20th century, four large landslides occurred with a total mass of the order of 1 000 000 m^3 or more (Fig. 1). The oldest one among these landslides is the Macesnik landslide triggered within a fossil landslide mass in 1990 (Majes et al., 2005[1]). The Stože landslide occurred in November 2000 in morainic material overlaying calcareous formations (Mikoš et al., 2004). The Strug landslide occurred in December 2001 on the contact between scaglia and flysch as a complex landslide with a combination of different slope instability phenomena (Mikoš et al., 2005[2]). The fourth large landslide is the Slano Blato landslide that occurred in November 2000 in an area geologically characterized by the overthrust of Triassic limestone over the Eocene flysch. Landsliding of rocks and soils in flysch formations can be observed elsewhere in Europe as well: an overview of landslides associated with the meteorological events in the

Correspondence to: J. Logar
(jlogar@fgg.uni-lj.si)

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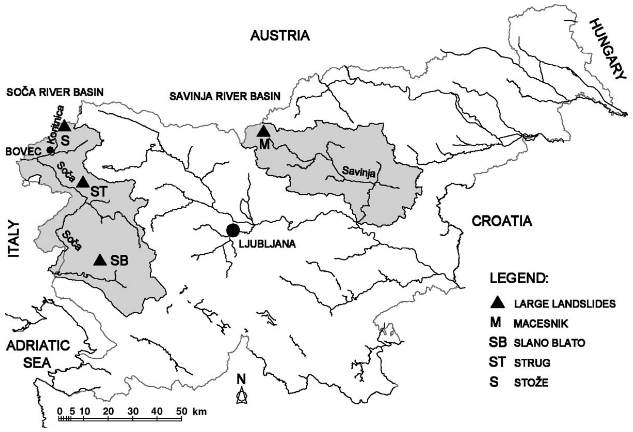

Fig. 1. Map of Slovenia with active large landslides.

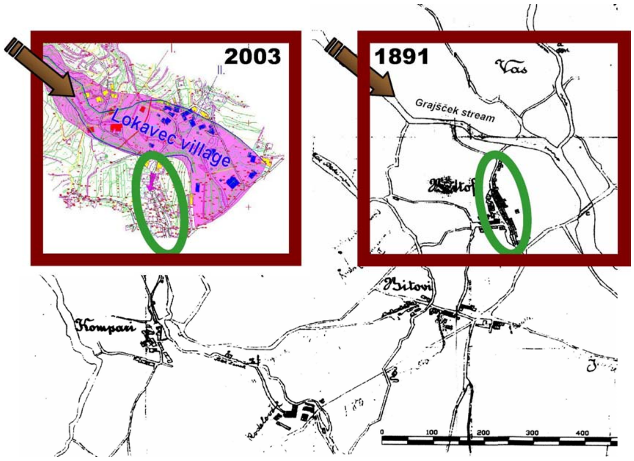

Fig. 2. A map of Lokavec village and its surroundings from 1891 compared with the map from 2003 (top left). Many houses (marked in red, blue and yellow) were built in the area with high landslide risk (hatched area on the map from 2003) after World War I.

European areas with flysch sediments is given by Krejčí et al. (2002), local situations are given i.e. for Switzerland by Lateltin et al. (1997), for Poland by Margielewski and Urban (2003), for Czech Republic by Krejčí et al. (2002) and for Greece by Christaras (1997).

2 History of the Slano Blato landslide area

The first landslide on this slope was mentioned about 200 years ago. The original local name Slano Blato in the Slovene language means "salty mud". An article published in the local newspaper Soča, No. 10 from 4 March 1887, reveals that during heavy rain on October 20, 1885, the Grajšček stream (Fig. 2) flooded and destroyed the main road, which is 2 km away from Lokavec village, in the length of 30 m and filled the streambed with mud.

The Austro-Hungarian monarchy sent one engineer to the site, who in the early 20th century managed to remediate the slide with mostly torrential remediation measures – a series of small check dams (Fig. 3a). These retention dams built on the Grajšček stream and its tributaries retained mud and debris and reduced the energy of stream water. On the top of the landslide the engineer found and regulated a water spring. The main remediation works were completed in 1903 and cost 49 857 crowns, which corresponds to 6 250 000 EUR (for the conversion, the comparison of teacher's salaries were used, as suggested by historians). Figure 3b shows only the top of one of these structures buried by Slano Blato landslide in 2001.

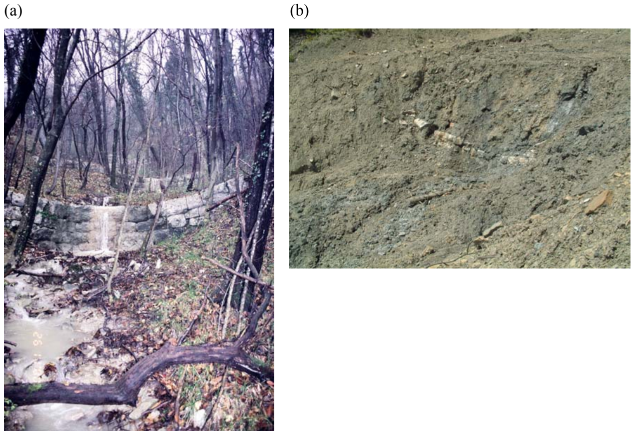

Fig. 3. The series of check dams on the tributary of the Grajšček stream before the landslide **(a)**, and the remains of a similar check dam covered by slided material in 2001 **(b)**.

Already more than 100 years ago, prevention was equally important as the execution of the described remediation works on the landslide. Therefore, any construction of new houses in the influence area of the landslide was prohibited by a decree. During the 20th century this area faced a series of political changes and came under the rule of four countries:

- before World War I: Austro-Hungarian monarchy,
- after World War I: Italy,
- after World War II: Yugoslavia,
- From 1991 onwards: Slovenia.

During the course of years the relevant Austrian measures and decisions were forgotten. After World War I, under the Italian rule, a church was built in the influence area followed by some houses. New building permits were issued after World War II to local people who populated the lower part of the Slano Blato landslide influence area. Towards the end of the 20th century regular maintenance of supporting check dams (Fig. 3a) was largely neglected.

Figure 2 shows a map of the Lokavec area in 1891. A large number of new houses that were built in the area after World War I in the hatched area, which indicates the influence area of the Slano Blato landslide. All old buildings from the 19th century lie outside this area (within the ellipse in Fig. 2).

Fig. 4. A far and a close view of the Slano Blato landslide.

Fig. 5. The photo taken on 23 November 2000, at the location later on referred to as the "Lake of Mud" just before the vegetation was ripped off. Note the pronounced heave in the centre due to the pressure caused by the soil sliding.

The water spring that was regulated during the remediation works at the beginning of the 20th century in the upper part of the old Slano Blato landslide, was in bad condition a few years before the new initiation of the Slano Blato landslide in 2000. We suggest that, as a consequence of infiltration and deep seepage of spring waters, the clayey gravel soils slowly became fully saturated with water and initiated a landslide after a period of strong precipitation in autumn 2000 (Figs. 16 and 18). The initial sliding was triggered on 19 November 2000, during a heavy rain period. Its initiation was nearly simultaneous with the large Stože debris landslide and debris flow in Log pod Mangartom (Mikoš et al., 2004), 60 km to the northwest.

After November 2000, in the upper part of the Slano Blato landslide, wide cracks allowed a large amount of rain water to penetrate into the ground. Together with ground water and water from the Grajšček stream and its tributaries, the rain water triggered a viscous flow of mud and debris. The earth flow (according to the landslide classification of the flow type; Hungr et al., 2001) moved along the Grajšček stream towards the Lokavec village with weather-dependent rates, reaching a maximum of 100 m/day. At the end of 2004 the landslide area reached a length of 1290 m and a width between 60 and 200 m. It is located at altitudes between 270 m and 640 m above sea level. The landslide affected an area of approximately 15 ha. Having a thickness from 3 to 11 m, the volume of the sliding mass was estimated as 700 000 m^3. Figure 4 presents two views on the landslide. The landslide presents a serious hazard for a part of Lokavec village. In order to plan effective remediation measures, field geological and geotechnical investigations were performed.

The following five stages of the Slano Blato landslide development can be distinguished:

1. The landslide was triggered on 19 November 2000, probably at an altitude of 570 m a.s.l. The continuous geological observations of the landslide started on 21 November. Therefore, the location of the initial event was deduced from the situation encountered during the first visit, taking into account the original state. The date of landslide occurrence was determined according to the witness, who noticed the mud in the Grajšček stream on 19 November. Due to continuous rainfall in that period, the sliding mass soon became liquid and found its way downwards along a narrow channel. A few days later, a large retrogressive rotational slide occurred above the initial scarp. This retrogressive sliding continued slowly until the present day resulting in the formation of several cracks above the main scarp, which is presently at the altitude of 640 m a.s.l. The liquid mud and debris flowed from this landslide area towards the village of Lokavec, causing high pressure on the slope below (Fig. 5), and it took a few days before the viscous earth flow removed the grass and trees. The deformation pattern with pronounced heave in the centre of Fig. 5 shows the enormous pressure increase in the soil layers below the surface. The mudflow stopped temporarily 400 m downward at the altitude of 460 m a.s.l. in the area referred to as the "Lake of Mud". This first phase lasted 5 days until 23 November 2000.

2. During the second phase, a large amount of mud and debris accumulated in the "Lake of Mud". The rate of advancement of the head of the earth flow dropped from the initial 60 to 100 m/day to only a few meters a day. The head of the earth flow reached a sandstone outcrop and split in two parts. On 18 December 2000, the front stopped at the altitude of 380 m a.s.l., further 300 m downwards of the outcrop. The photographs in Figs. 6a and 6b show the same area when the "Lake of Mud" formed and after the earth flow found its way further downstream.

3. Increased rainfall amount in March 2001, along with accumulation of a critical mass in the "Lake of mud", caused a new advancement of the earth flow on 20 March 2001. The head of the earth flow moved again at a rate of more than 10 m/day and traveled a distance of 330 m until it stopped on 25 April 2001. On its way

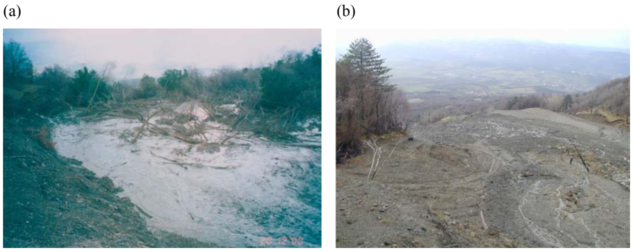
(a) (b)

Fig. 6. The “Lake of Mud” before **(a)** and after **(b)** the mud broke the barrier and flowed further downstream.

Fig. 7. Several minor mudflows occurred in October 2001.

Fig. 8. The rockfill dam that can retain up to 5000 m^3 of mud and debris was constructed to protect the village of Lokavec from extremely rapid mud flows generated at the surface of the stopped earth flow masses.

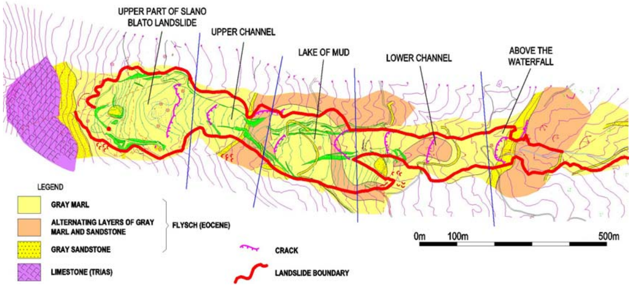

Fig. 9. Engineering geological map of the Slano Blato landslide area.

   the earth flow covered the 16 m high waterfall of the Grajšček stream. From the top of the landslide most of the material flowed downwards and a 50-m-long and 50-m-wide lake of water formed in a depression that remained. While the front of the earth flow stayed at the same position for some months, movement of wet soil masses continued on the surface along the entire length of the earth flow. Each time that sufficient material was accumulated in the “Lake of Mud”, intensive flowing was observed in the lower part of the earth flow.

4. In October 2001 several minor, very rapid to extremely rapid mudflows (according to Cruden and Varnes, 1996) generated from the lower part of the earth flow and followed the Grajšček stream bed through the village of Lokavec (Fig. 7). The mudflows were different in volume, density, and in the rate of advance.

5. At the beginning of 2002 a small rockfill dam with a bottom outlet was constructed in the Grajšček stream bed some 280 m from the village of Lokavec to protect it against the potential mudflows. Up to 5000 m^3 of debris could be retained behind the dam (Fig. 8). During the autumn and winter 2001—2002, up to 200 000 m^3 of mud and debris were mechanically removed from the area of the front of the earth flow and deposited on a dumping site in the valley bottom outside the village of Lokavec. The aim of this remediation measure was to protect the rockfill dam and the village of Lokavec in case of a sudden new fast advancement of the earth flow. The situation in the lower part of the earth flow stabilized after spring 2002, partially due to the fact that 2003 was rather dry (Figs. 17 and 20). Due to some technical measures, which are discussed later, the situation improved also along the rest of the landslide.

3 Geological conditions

The Slano Blato landslide is located exactly at the border of Triassic limestone and Eocene flysch, as shown in the engineering geological map (Fig. 9). The whole area consists of larger synclines and anticlines. The Eocene flysch consists of layers of marl and sandstone few centimeters up to few meters thick.

Limestone was overthrusted on the flysch over a very large distance. It is known as a Trnovski overthrust. The consequence of big tectonic movements in the past was a highly tectonized rock in that region. The flysch rock is strongly folded and ruptured.

The contact between limestone and flysch has the Dinaric orientation with a dip of 10° in NE direction. Based on the sediment texture, the inverse position of layers was es-

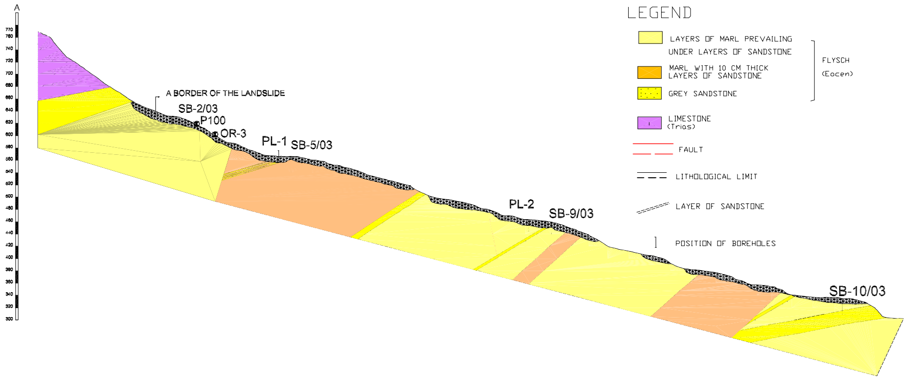

Fig. 10. Geological longitudinal section along the Slano Blato landslide area. The symbols have the same meaning as in the legend to Fig. 9.

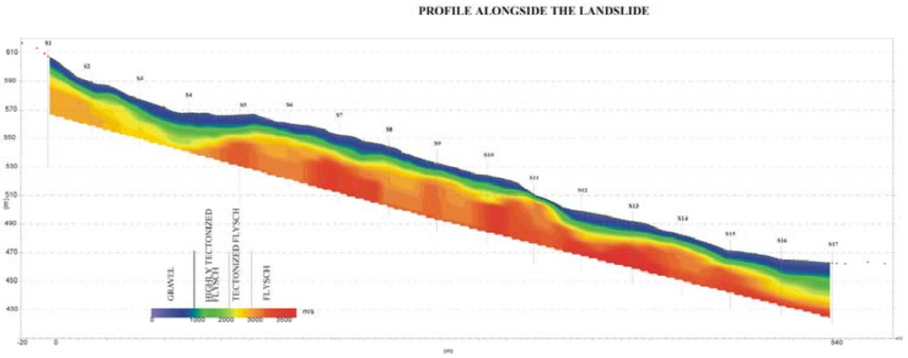

Fig. 11. The longitudinal seismic refraction section along the landslide.

tablished in the upper part of the landslide. Several faults with Dinaric orientation (330–345/55–75°) were observed throughout the whole landslide area.

Flysch, in the region of the landslide, is divided into three regions:

- layers of predominant sandstone in the thickness of at least one or several meters
- region with alternation of marl and 10 cm thick layers of sandstone
- region with predominant layers of marl.

The water inflow was observed in fissured layers of sandstone at several depths, during the borehole drilling, almost as a rule. The dip direction of layers is NE, which is, from the point of view of global stability, favourable with respect to the direction of the slope. The main part of the landslide finishes at the outcrop of a several meters thick layer of sandstone forming a 16-m-high waterfall before the earth flow.

The flysch rock is covered by heterogeneous clayey gravel with blocks of Triassic limestone, sandstone and marl. The thickness of this gravely layer is 3 to 11 m, and was determined by borehole logging (Fig. 10) and geophysical investigations, in particular the seismic refraction method (Car, Stopar, 2003) with one longitudinal section (Fig. 11) and several cross sections was applied.

The in situ investigations were performed in several steps from 2001 to 2003. Altogether 21 boreholes were made. Samples taken from these boreholes were investigated in the laboratories to obtain relevant material properties.

4 Material properties

4.1 Flysch bedrock

The strength characteristics of flysch bedrock were determined empirically according to the Hoek and Brown failure criterion (Marinos and Hoek, 2000, 2001) using the basic parameters GSI, UCS and m_i value of 7 as suggested by Hoek as an average value for marl. The Geological Strength Index (GSI) (Hoek, 1994; Hoek et al., 1995; Hoek and Brown, 1997; Hoek et al., 1998) for the marl flysch layers was between 15 and 25 for different locations. The uniaxial compressive strength (UCS) of flysch marl was very low, between 155 and 323 kPa, which classified these layers from the landslide area into the group of soft rocks. Based on these data, the angles of internal friction φ and cohesion intercept c were determined (φ between 22° and 26° and c between 80 and 110 kPa). Similar values were measured by direct shear tests on five marl samples: angle of internal friction between 22° and 27° with cohesion intercept between 0 and 52 kPa. Mea-

Table 1. Main material properties of the Slano Blato landslide material.

Property	2001	2002	2003
Number of samples	12	4[1]	18
Unit weight γ (kN/m^3)	18.5–20.7	20.6–22.1	19.0–21.8
Liquid limit LL (%)	40–52	45–51	37–53
Plastic limit PL (%)	19–24	20–23	21–24
Plasticity Index PI (%)	20–32	25–28	16–31
Natural water content w_0 (%)			
- natural material	20–41	20–24	12–27
- grains <2 mm		27–30	
Angle of internal friction φ (°)	17–30	24–27	21–24
Cohesion (kPa)	5–22	0–5	18–20

[1] Four large samples were taken from trial pits (together several 100 kg of soil mass).

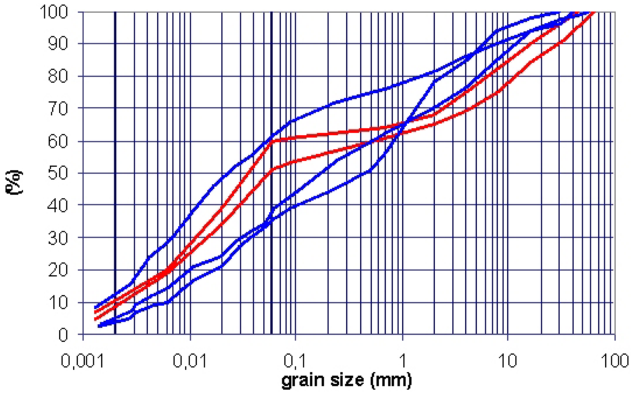

Fig. 12. Grain size distribution for selected samples from the landslide material.

sured water content on samples of marl varied between 8.6 and 13.7%.

On four samples from rare sandstone layers only the UCS was determined in laboratory, and values from 11 do 40 MPa were obtained. Through the established GSI=45, high strength characteristics were empirically estimated (Hoek, Marinos, 2000): $\varphi'=46°$ and $c'=0.8$ MPa.

4.2 Landslide material

The samples of the landslide material were taken from boreholes and from the trial pits near the surface in each of the investigation stages. 12 soil samples from boreholes were tested in 2001, in 2002 four samples of mud flow material were taken from trial pits and in 2003 29 samples from boreholes were tested in laboratory. The basic tests (water content, grain size distribution, liquid and plastic limit, unit weight) were performed and supplemented by triaxial and direct shear strength tests. The summary of test results is given in Table 1. Additionally the fractions of soil samples passing the 0.063 mm sieve were tested in viscometer to determine the viscosity and limit shear stress under flow conditions.

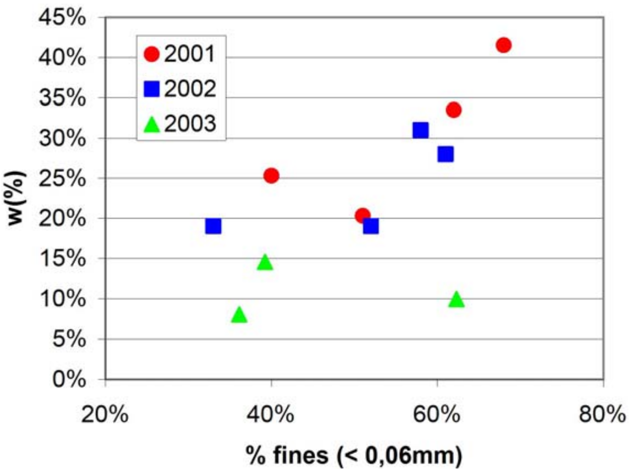

Fig. 13. Water contents of samples of mudflow material in three investigation campaigns with regard to the fines content.

The grain size distribution was analyzed for 20 samples. The results for 5 selected samples are presented in Fig. 12 (2 samples were tested in 2002 and 3 in 2003). The presented grain size distribution curves represent the whole range of measured grain size distributions. The majority of samples can be classified as silty clays with up to 45% gravel and sand particles. In other samples gravel and sand particles dominate (60%) over the silt and clay (40%). Such samples are found in the upper part of the landslide and at the locations where fractions of fines were partly washed away.

Figure 13 presents measured water contents as a function of the percent of fines in samples from the mudflow material. It can be seen that the water content decreases from 2001 to 2003. It appears that the landslide materials were drying out, however, it has to be emphasized that most of the field investigations in 2003 were performed in a relatively dry period.

Other characteristics of the landslide material are given in Table 1. Atterberg limits were determined on soil grains passing the 0.08 mm sieve. Shear strength characteristics were obtained on reconstituted specimens from the soil grains passing the 2 mm sieve by standard undrained consolidated triaxial tests (in 2002) and in direct shear tests (in 2001 and in 2003).

A test in a large oedometer cell (250*120 mm=D*H) was performed on a liquid landslide mass with initial water content of 31%, at which the fine matrix was in liquid state. Only one such test was performed on the samples with maximum grain size of 20 mm with the aim of investigating the influence of the consolidation on the reduction of water content. By loading the specimen up to 320 kPa, the water content was reduced to 19%. Figure 14 shows the result as a graph of water content vs. depth, assuming the unit weight of deposited sliding mass γ=21 kN/m^3. This result proved that the deposition of the sliding mass at locations where it can consolidate and partly dry up will cause an important increase in shear strength. At the same time, lower water contents obtained on site in 2003 mean that the material dries up eas-

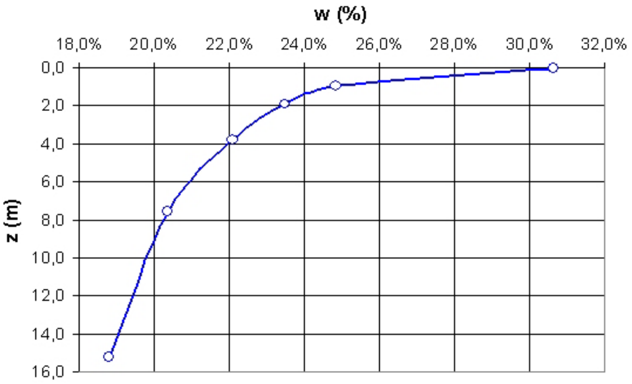

Fig. 14. Oedometer curve (void ratio e vs. vertical pressure σ') plotted as depth (z) vs. water content assuming that $z=\sigma'/\gamma$ and $w=e\gamma_w/\gamma_s$.

ily. Evidence from the field showed that after relatively short dry periods an up to 1.0-m-thick crust formed, which additionally contributed to the stabilisation of deposited landslide mass.

The viscosity (Fig. 15) and limit shear stress (Fig. 16) were measured in viscometer on fines with grain size $<63\,\mu$m. It was established that the limit shear stress dropped rapidly with increasing water content, from 100 kPa at 40% water content to only a few hundred Pa at 60% water content. The coefficient of viscosity decreased from 10^8 to 10^5 Pa.s for the same increase in water content.

5 Hydrogeological investigations

The coefficients of permeability were determined by 8 slug tests and 1 pump test. The saturated conductivity, k, varied in the following intervals:

1. 10^{-7}–10^{-8} m/s, for the marl and massive sandstone (flysch layers) and dense gravely clay as a part of the landslide material
2. 10^{-6}–10^{-5} m/s for tectonized marl and fissured sandstone, and
3. 10^{-4}–10^{-3} m/s for clayey gravel with pieces of limestone and siltstone as a part of the landslide mass.

The most important underground flow was found in the gravely layers. The water, which supplies the landslide, infiltrates into the ground in the catchment in the landslide's hinterland. Then water slowly seepaged into the landslide area through the layers of clayey gravel of intermediate and low permeability.

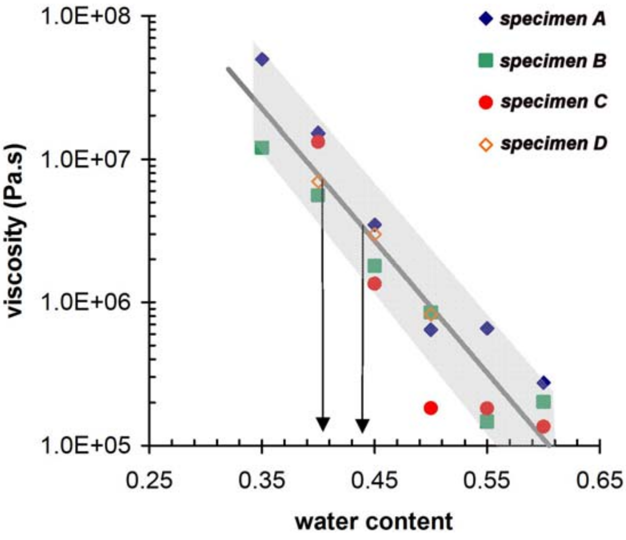

Fig. 15. Viscosity vs. water content as measured in viscometer on four specimens.

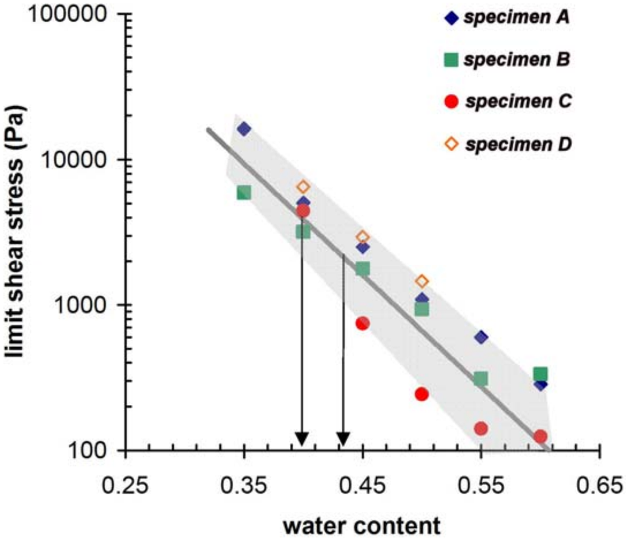

Fig. 16. Limit shear stress vs. water content measured in viscometer on four specimens.

Material with intermediate permeability existed even within the layers of flysch at a depth of more than 20 m, usually in fissured layers of marl and sandstone. Based on this result and on other field observations (locally the surface soil was in a liquid state even after longer dry periods; heave of the ground shown in Fig. 5, indicating that the ground became soft due to the water emerging from the bedrock and not from the surface) it was suggested that an important influx of water to the sliding mass came also from the lower flysch layers. Later on this was confirmed when the first two large hollow concrete shafts with a diameter of 5 m were made as a part of remediation actions. Up to 15 m^3 of water per day can be collected in one shaft.

Based on the measurements of springs, it was calculated that on the rainy days a water influx of 260 to 2600 l/day on the 100 m^2 area is possible from fissured layers of sandstone. Those inflows are not continuous. The position of individual pervious layers allowed for local water accumulation. The most pronounced water accumulation was in the depression area in the upper part of the initial landslide.

Table 2. Results of chemical analysis of 5 water samples.

location	Sample 1 spring above upper channel	Sample 2 stream above the Waterfall	Sample 3 upper part – center	Sample 4 upper part – west	Sample 5 upper channel
pH	7.15	7.88	7.50	7.68	8.01
electroconductivity (μS/cm)	1550	1695	688	679	1369
NO_3 (mg/l)	3.2	7.5	9.6	3.4	35.6
SO_4(mg/l)	584	753	121	124	569
Cl (mg/l)	71.0	62.1	4.44	1.78	5.33
PO_4 (mg/l)	<1	<1	<1	<1	<1
Ca (mg/l)	108.1	106.6	166.9	107.4	92.4
K (mg/l)	9.39	9.22	2.60	2.48	4.57
Mg (mg/l)	77.1	49.2	111.1	18.5	34.0
Na (mg/l)	149.3	200.1	18.4	21.0	193.9
HCO_3 (mg/l)	74.8	98.3	41.2	26.9	23.5

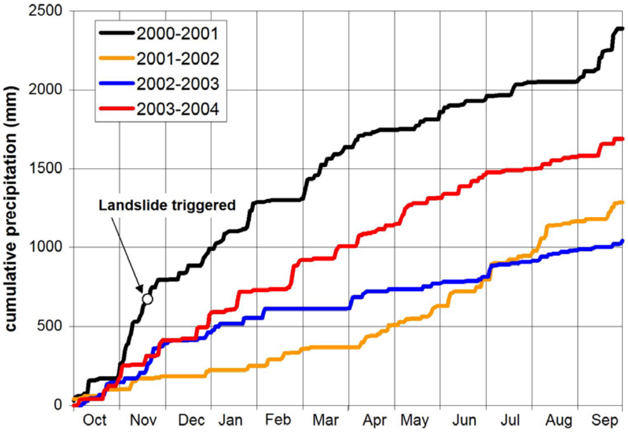

Fig. 17. Cumulative precipitation measured in the rain gauge in the village of Lokavec for four years.

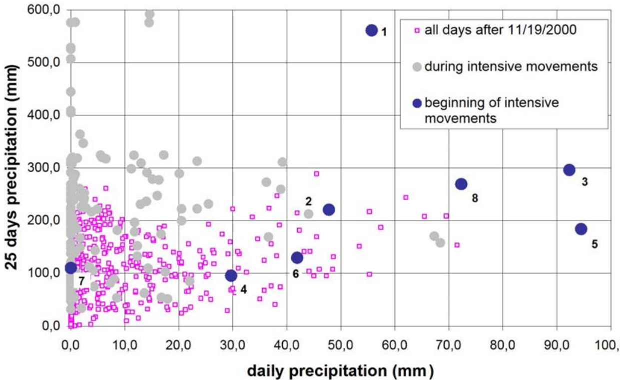

Fig. 18. 25-day cumulative precipitation vs. daily precipitation with triggering of 8 major sliding and/or earth flow events.

The discharge measurements of the Grajšček stream were done at different locations in the landslide area. The discharges depended on the amount of precipitation and ranged from 0.2 l/s up to the 50 l/s or more. During the period of strong precipitation the stream rose in two hours from 1 l/s to 50 l/s. In dry periods the flow of the Grajšček stream decreased very rapidly.

Due to the interesting name Slano Blato (Salty mud) and the indication from the local newspaper Soča from 1887, which documented the old saying that “when water from Slano Blato had flooded the grass, the grass withered”, chemical analyses were performed on five water samples from different locations within the landslide (see Table 2). It was found out that the water is slightly mineralized with increased concentrations of sulphates and sodium (samples 1, 2 and 5). The fact that the increased concentrations of salts were found along the upper channel and above the Waterfall, but not close to the scarp (samples 3 and 4), confirms an important contribution of underground water from a flysch aquifer to the sliding process.

Literature review showed that the salt content slightly influences also the flow properties of fine-grained soil if the salinity is above the flocculation threshold (Perret et al., 1996). Both limit shear stress and viscosity increase due to the increased salinity. So far no such tests have been performed for the materials from the Slano blato landslide.

6 Precipitations and landslide movements

Figure 17 shows the cumulative rainfall from October 2000 to July 2004. The data are presented for one-year periods starting from October to September of the next year. November 2000 was by far the most rainy month in the observed period with 591 mm of rainfall. Then follow March 2001 and September 2001 with 335 mm of rainfall, whereas during all other months less than 250 mm of rainfall was measured. The maximum daily precipitation in November 2000 did not exceed 67 mm, but daily values up to 95 mm were observed a few times in the following years. However, daily rainfall amounts did not correlate well with the observed rates of the

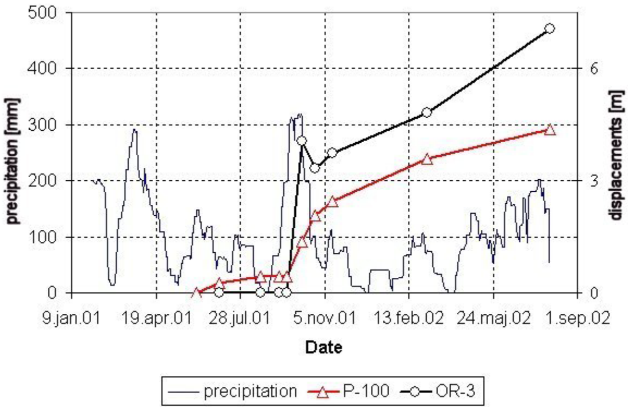

Fig. 19. 25-day cumulative rainfall and measured displacements of two points. (see Fig. 22 for the location of the measuring points).

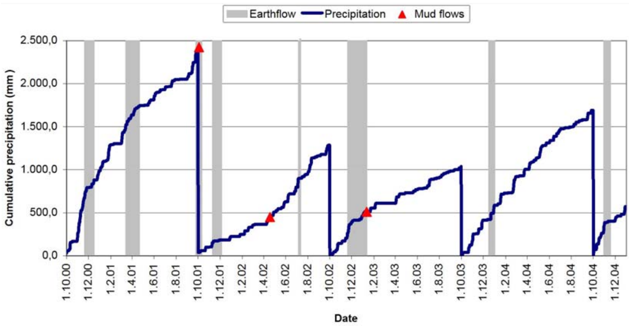

Fig. 20. Cumulative annual rainfall and the periods of intensive mass movements.

advancement of the front of the earth flow. Figure 18 shows the diagram of 25-day cumulative precipitation vs. daily precipitation. Large dark dots mark the eight days when significant earth movements started, grey dots show all days during intensive movemets, whereas small dots show all other days after 19 November 2000. The eight triggering events are numbered consecutively, showing that an extremely intensive precipitation had been necessary to provoke the first sliding. Each of the next triggering events happened after less rainfall.

In 2000, a temporary system of measuring points was set up. Displacements of the earth flow were followed, using GPS technology and with classical geodetic measurements. The displacements of some points reached the values of 150 m until they were lost from the measuring system. The majority of the measuring points was destroyed during the works on the drainage system in the part of the landslide. Until that time the largest displacements were observed in the upper part of the landslide, e.g. points OR-3 and P-100 (see Figs. 19 and 22).

Figure 20 presents cumulative annual rainfall (zeroed each 1 October to keep the reasonable scale) and the periods of intensive sliding mainly connected with the progression of the earth flow towards the village of Lokavec.

Fig. 21. The area of Grajšcek stream cross-section under the bridge is important for the flood and mudflow safety and therefore needs constant maintenance. The photo shows the cross-section partly filled with mud, which needs intervention.

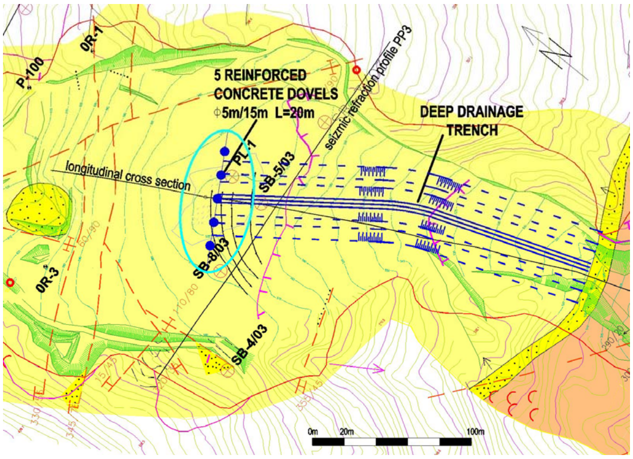

Fig. 22. Plan view of the upper part of the Slano Blato landslide with 5 reinforcing and dewatering shafts-dowels and deep drainage trenches.

In the years 2003 and 2004 some geodetic measurements were done for the upper part of the landslide. Although the period from November 2003 to April 2004 was dry, the top of boreholes moved by 16 m. Measurements indicated ongoing moderate movements of the landslide.

In some boreholes the inclinometer casings were placed to allow the monitoring of horizontal displacements. The measurements in the upper part of the landslide indicated that the sliding plane was not limited only to the contact between clayey gravel and flysch, but it could be even deeper. A borehole from that region showed the thickness of the gravely layer of 5 m, but the horizontal movements were measured up to the depth of 9.5 m. Another two inclinometer measurements, located at the edges of the landslide, ascertained the slip surface on the contact between gravely and flysch layer.

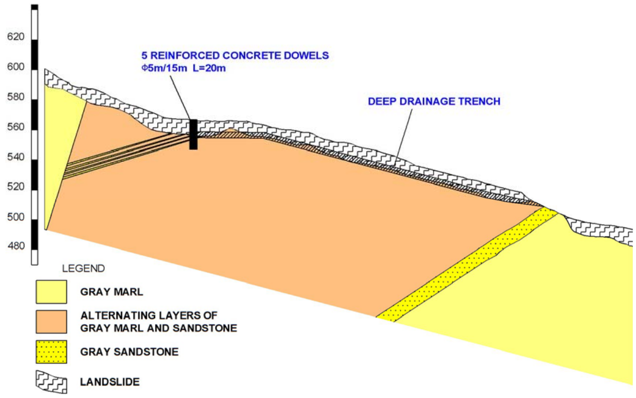

Fig. 23. Longitudinal section of the Slano Blato landslide with reinforcing and dewatering dowels at the top and deep drainage trenches along the landslide.

7 Risk reduction and remediation measures

Soon after the landslide had been triggered, a geological observation started. The intensive retrogressive enlargement of the landslide behind the original scarp and the earth flow progression from the landslide initiation area towards the village of Lokavec urged for the implementation of risk reduction measures. The landslide mass behaviour in the field and the results of the laboratory investigations showed the possibility of moving at least some nearly liquid landslide material from the central part to the stable sides of the earth flow course. Once there, the mechanically moved material would dry up and get stabilized. Due to the terrain morphology and the presumed potential instability of nearby dumping site locations in the vicinity of the landslide area, this was not the solution for large soil masses. The following measures have been implemented so far to reduce the risk for the village of Lokavec:

- Several drainage trenches in the upper part of the landslide were put in function in 2002, and were destroyed in 2003 due to retrogressive sliding. They were rebuild in 2004,
- Removal of 200 000 m^3 of the earth flow masses in the area of its front, for which a remediation of the local road was necessary,
- A small rockfill dam against fast mudflows,
- The Grajšček streambed was enlarged, made concave and protected by rip-rap to withstand fast flowing mudflows (Fig. 21).

Remediation measures planned for the future are the following (see Figs. 22 through 24):

- A drainage system in the upper part of the landslide.
- Construction of a set of 5 reinforced concrete shafts, which should act simultaneously as a dewatering wells and retaining structure (dowels).

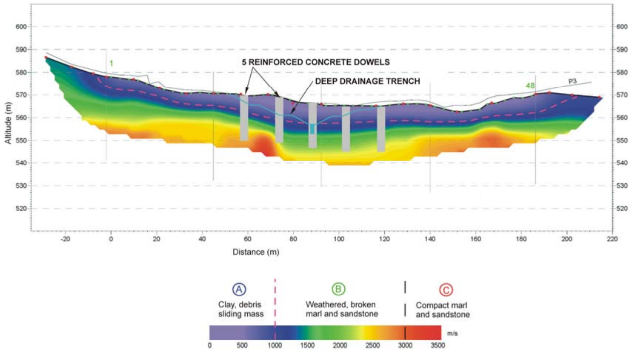

Fig. 24. Cross section across the future reinforcing and dewatering dowels together with geoseismic refraction profile (see Fig. 22 for the location of the geoseismic profile).

- Deep drainage trenches will be constructed along the earth flow course.

8 Conclusions

From the field and laboratory investigations the following conclusions can be drawn:

1. Even though the Slano Blato landslide was already remediated in the past, it was reactivated partially due to the bad condition of spring regulation works carried out at the beginning of the 20th century at the top of the landslide. The omission of maintenance of Grajšček and its tributaries stream courses intensified the progression of the earth flow later on. The intensive political changes in the region during the 20th century were therefore partly the reason for the landslide reoccurrence and for the potential damage to the village that spread during last century to the area influenced by the Slano Blato landslide.

2. The primary reason for the landslide on this particular location is the overthrust of a Triassic limestone plateau over the Eocene flysch of Vipava valley. This overthrust caused significant fracturing and consequently weathering of the flysch layers. Along the entire overthrust line numerous evidences of old landslides can be observed and have been confirmed by the ground investigations and earthworks for the new motorway.

3. Unfavorable hydrogeological conditions are also connected with this general geological feature. The specific position of water-bearing limestone behind and above the flysch formation with lower conductivity assures the constant water inflow to the fractured and weathered flysch.

4. The direct reason for the earth flow that was triggered in November 2000 was the increased water inflow due to intensive precipitation.

5. Periods with intensive earth flow movements correspond with higher precipitation. During the course of years the precipitation threshold for earth flow movements diminishes.

6. Earth and mud flows have occurred at the same location in the past. The main difference is that the landslide influence area was not populated before World War I. The presence of the village in the landslide influence area today, calls for the implementation of risk reduction and remediation measures.

7. Dewatering shall be the main remediation measure. Furthermore, the soil masses behind the present scarp have to be kept stable in order to minimize the earth flow volume.

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