Landslides and Engineered Slopes – Chen et al. (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-41196-7

Landslide "Granice" in Zagreb (Croatia)

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ABSTRACT: Landslide "Granice"in Zagreb is an example of a shallow translational landslide formed on a gentle slope (6–7°). It is extremely elongated in shape, i.e. 300 m in length and 50 m in an average width. Although most of this landslide is on an undeveloped land, its lower part passes a developed area with some ten housing units. First movements registered in this locality date back to 1963/64. Investigations for landslide improvement were undertaken in 1995. Landslide improvement activities were completed in 1998. During ten years after the improvement works no displacements were observed and the life for the people on the landslide area has normalized.

1 INTRODUCTION

The north part of the Croatian capital Zagreb is settled on the lower part of mountain Medvednica, which highest peak Sljeme is 1033 m in height. In this, for living very attractive part of town, a number of landslides were formed. It was the result of urbanization and natural conditions. Some of these landslides have been known for a long time and some of them have activated recently. One of the landslides which has been active for a long period of time is the subject of this paper.

2 GEOTECHNICAL INVESTIGATIONS AND INTERPRETATIONS

Landslide "Granice" was first recognized during the basic geotechnical investigations of a wider area, which were performed in 1987 to define terms for urbanization planning. One borehole with double piezometer was made on the landslide. In contact with local citizens it was found that the first movements in the area took place about years 1963/64. The contour of the landslide was defined and it was established that its length is about 300 m, the average width is about 50 m and the area of landslide is about 1.4 hectares (Fig. 1). It was formed on a gentle slope (6–7°). General direction of movement was north to south. North part of the landslide was on an undeveloped land, while its lower part was on a developed area with some ten housing units. By comparing older topographic plans, from 1962, and the situation in the field, it was estimated that the horizontal movements have already reached about 3.5 m. The amounts of movements were visible on passages between the houses. The passages and stairs leading from the street Granice down to the houses were originally built along straight lines (Fig. 1). The lower parts of the stairs and passages were obviously moved south.

All houses built on the lower south part of landslide suffered damages as the result of landslide activities and were "traveling" together with the landslide. It was concluded that thorough geotechnical investigations and improvement measures are necessary. But a lack of funding delayed further actions.

More intensive activity of the landslide was observed after the rainy season in 1989. Finally, in 1995 detailed geotechnical investigations of the landslide with the objective to establish a landslide improvement proposal were conducted. New topographic plan and eleven boreholes, most of them with piezometers, were made to establish a correct geotechnical model.

Comparisons of the old topographic plans from 1962 (Fig. 1) and the new plan from 1995 (Fig. 2) were made for estimating horizontal displacements of landslide. It was established that during thirty-three years the displacements of most points that could be compared on the landslide exceeded approximately 5 m. The house which is positioned the most south, on the steeper part of landslide, was moved about 10 m.

As a result of geotechnical investigations (field and laboratory), a geotechnical model of the landslide was formed. The RNK-method was used for forming a landslide model of good quality based on relatively small quantity of investigations.

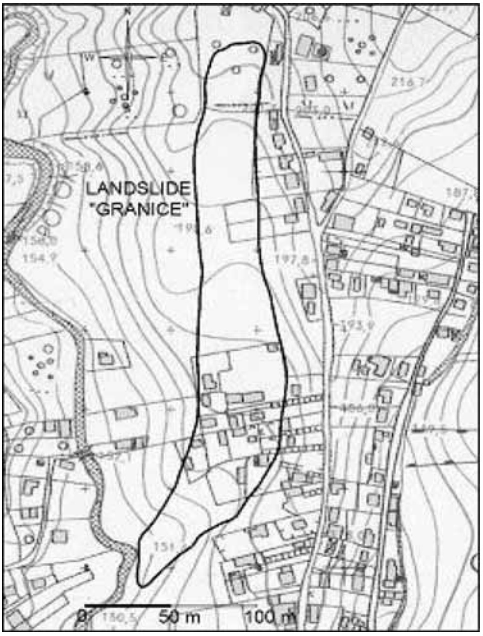


Figure 1. Landslide "Granice"—the contour on the old topographic plan from 1962. The passages and stairs by the east side are in straight lines.

The RNK-method, or the Reference Level of Correlation Method (Ortolan, 1996, 2000), is a fully developed method for engineering-geological and/or geotechnical modeling. It can be used for both soils and soft rock formations. The RNK is defined as an unequivocally recognizable and visually identifiable (or graphically defined) bedding plane or any other reference plane within a structural feature, in relation to which the altitude of all studied profiles can be unambiguously defined, with individual point analysis of any material property. Such a plane is a part of a single vertical geotechnical correlation column.

The geotechnical correlation column is a consistent engineering-geological or geotechnical soil model (design cross section) in which adequate parameters (defined in the laboratory or *in situ*, either by the point method or continuously), can be reasonably allocated to every defined layer (and portions of such layers) along the entire height of the vertical sequence of formations covered by the study. From such a geotechnical correlation column one may in principle distinguish zones of minimum residual shear resistance, with their thicknesses and continuities, and also layers with different moisture, permeability, natural compaction, compressibility, etc.

Geotechnical column of landslide "Granice" is shown in figures 3 and 4. The hanging wall of a fat clay layer of high plasticity, soft to firm, light-blue in colour, was selected as the reference level of correlation (RNK) for the geotechnical correlation column. In this case the RNK coincided with the slip surface position.

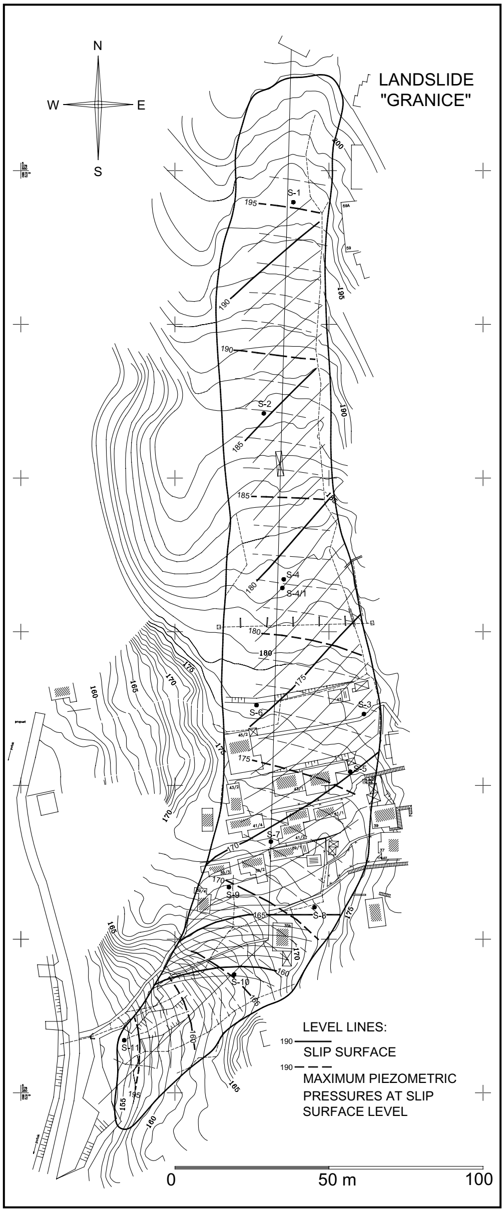


Figure 2. Landslide "Granice" on topographic plan made in 1995. The passages and stairs beside east side are not in straight lines any more.

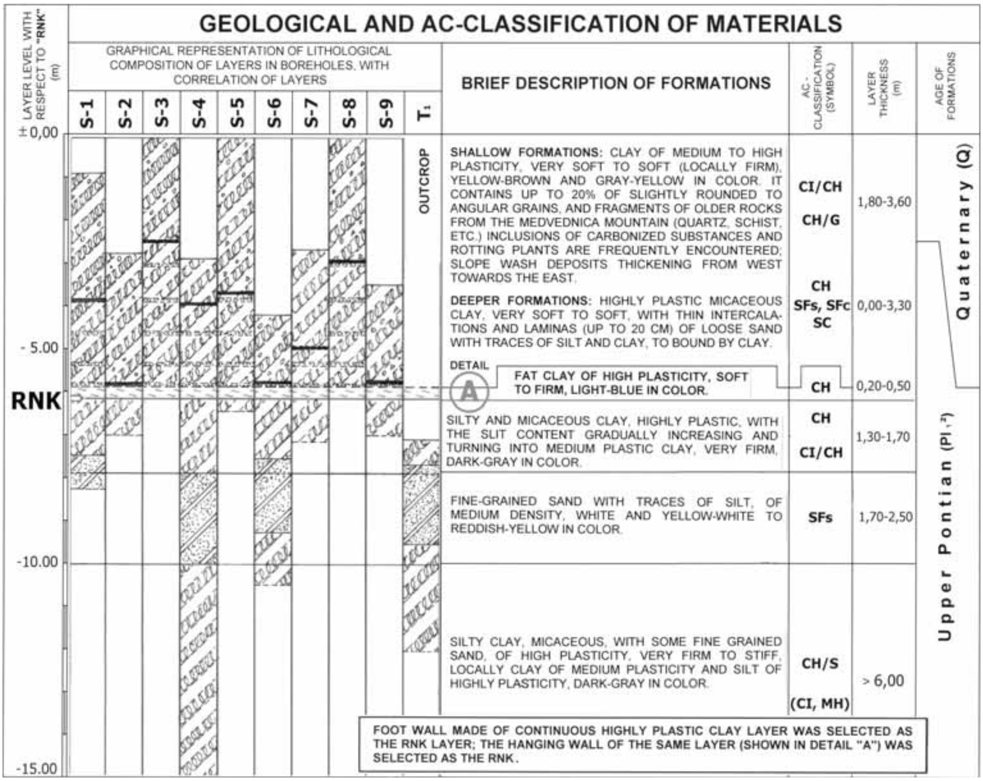


Figure 3. Geotechnical correlation column of the landslide Granice (Ortolan, 1996) established using the visually recognizable reference level of correlation.

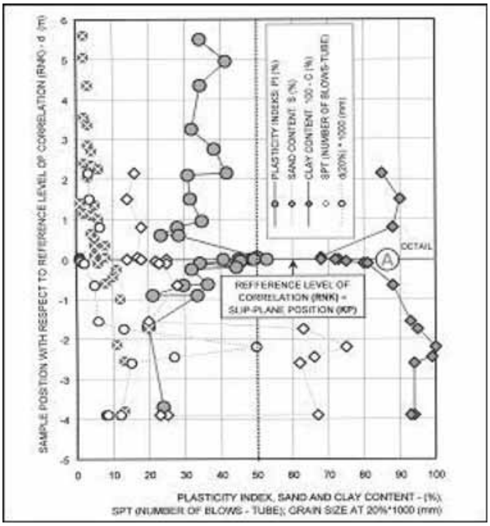


Figure 4. Some geotechnical characteristics of materials in geotechnical correlation column of the landslide “Granice” (Ortolan, 1996).

All boreholes were positioned in the correlation column. The absolute height of the RNK was defined at the position of every borehole.

The interpolation of the absolute height of the RNK level between the boreholes was made and lines connecting equal absolute heights of the RNK were constructed (Fig. 2). The depth of the RNK and the geotechnical correlation column enable the extrapolation of geotechnical characteristics of materials established for one position on the landslide on any other position on the landslide. This interpolation also yields the absolute height of the slip plane on the complete area of the landslide. The slip plane is almost parallel with the ground surface in the direction of movements, i.e. north to south. It is 3.5–4.5 m deep along the central profile (Fig. 2). In the perpendicular direction, i.e. west to east, the depth increases from 2 to 7 m.

The interpolation of the maximum absolute heights of piezometric pressures at the level of slip surface was also made, and the level lines were constructed (Fig. 2) on the basis of monitoring of installed piezometers.

Established geometry of the slip plane and the maximum piezometric pressures at the slip surface level, are the basic data for stability and seepage analyses.

3 STABILITY AND SEEPAGE ANALYSES

3.1 *Stability analyses*

After defining the geometry of the slip plane and the maximum piezometric pressures at the slip surface level stability analyses were performed.

It was adopted that the strength of the material along the slip surface is represented by its residual strength, because the landslide was active for a long period and movements that already occurred were large (Skempton 1985).

The assumptions for the stability analyses were: the strength of the material along the slip surface is equal at all points and when piezometric pressures exceed maximum measured values factor of safety falls to $FS = 1$.

Stability analyses were performed on the central profile, whose position is shown in figure 2. Only the part from the north edge to the break point of the profile was considered as relevant for landslide behavior. After the break point, sliding mass was just pushed by movements in the upper part in the south-west direction as a result of surface configuration. Analyses were performed using Spencer's method (Spencer 1967).

Factor of safety $FS \approx 1$ (0.984) was found for the residual friction angle $\varphi_R = 11°$ (with $c = 0$, $\gamma = 19\ \mathrm{kN/m^3}$). This result is considered realistic on the basis of the plasticity index established for the material on the slip surface (Fig. 4) and known correlations between the plasticity index and the residual friction angle (Ortolan & Mihalinec 1998).

It was concluded that the best improvement measure for the landslide would be to install drain trenches. Further stability analyses were performed to determine how much piezometric pressures should be lowered for assuring an acceptable factor of safety. The installation of the drain trenches was only possible on the north undeveloped part, so in the analyses the lowering of piezometric pressures was assumed in the first 200 m. A satisfactory factor of safety $FS = 1.319$ was obtained for lowering the piezometric pressures for 2 m.

After the improvement design was already completed three more samples from the slip zone were examined in the laboratory (Table 1). The established residual friction angle, with an average value $\varphi_R = 13.7°$ (Table 1), was slightly greater than calculated in previous analyses. It was concluded that the difference appeared because the samples were contaminated with sand which underlies the fat clay layer (Table 1, 15–19% sand particles).

Table 1. Laboratory results for the samples from the slip zone.

Bore-hole	Depth (m)	LL (%)	PL (%)	PI	SF (%)	CF (%)	φ_R (°)
S-2	3.1–3.2	73.5	22.0	51.5	19	36	13.9
S-3	6.8–7.1	73.1	23.7	49.4	18	34	13.7
S-8	6.4–6.7	71.7	26.6	45.1	15	36	13.5

On the other hand, the difference could mean that the piezometric pressures were underestimated (particularly along the east side which was under the influence of unsolved sewerage in the Granice street), but if that was the case the improvement measures were designed on safe side.

3.2 *Seepage analyses*

Seepage analyses were performed to define the distance between the drain trenches which would provide the necessary lowering of piezometric pressures.

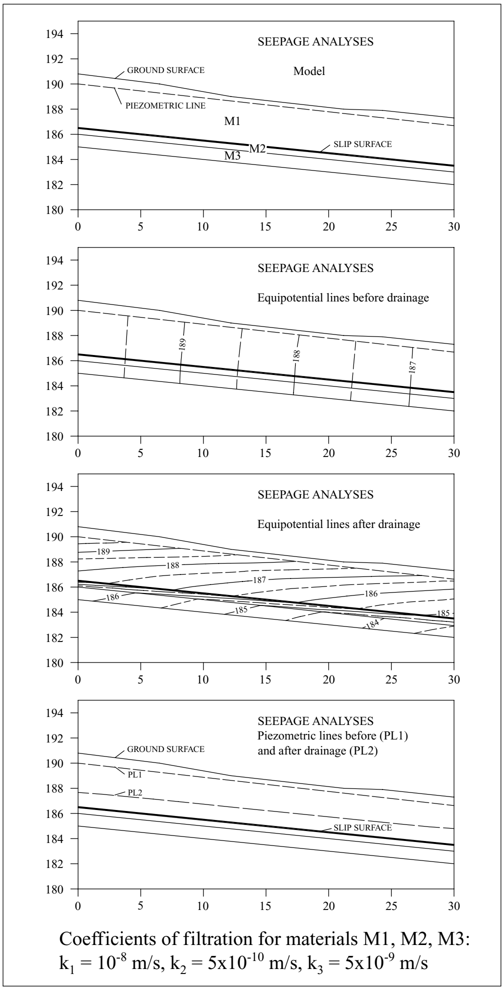
The fact that conditions along the whole central profile are very similar allowed that analyses could be performed on a smaller simplified model. The seepage analyses model is shown in figure 5.

Seepage analyses were made with computer program which enables 3D analysis by defining seepage conditions in parallel planes (Jović & Radelja, 1981). For this problem four planes were adopted: the first was through the drain trench and the fourth was on half distance between the trenches, while the second and the third were positioned so the distances between successive planes were equal.

The results were the pore water pressures in the points of four planes, and the average pressures from which new PL was constructed (Fig. 5).

The analyses have shown that the distance between the drain trenches should be $s \leq 6$ m for the adopted model, or generally $s \leq 1.8\ h$ (where h is the height from the slip surface to the PL). In that case average piezometric pressures at the slip surface level would be 2 m lower than established maximum piezometric pressures.

After these calculations, the positions of drain trenches were adopted as shown in figure 5. A factor of safety was then controlled for the adopted disposition of drain trenches for local conditions on different parts of the landslide. It was done because the depths of the slip surface and the pore water pressures were different from the west to the east side (Fig. 2). Factors of safety for infinite slope models and the influence of drain trenches on different parts of the landslide were calculated using diagrams (Stanić, 1984). These simple calculations proved that local factors of safety on all



Coefficients of filtration for materials M1, M2, M3:
$k_1 = 10^{-8}$ m/s, $k_2 = 5\text{x}10^{-10}$ m/s, $k_3 = 5\text{x}10^{-9}$ m/s

Figure 5. Seepage analyses. Model was formed from central profile, between 100 and 130 m from its north edge (Fig. 2).

parts of the landslide would be satisfactory (FS >1.3) and that the improvement in the FS would be 20–30% compared with those before the drainage.

4 IMPROVEMENT MEASURES AND MONITORING

The landslide was improved by the drain trenches, which seemed to be an appropriate solution already at the initial stage of investigation works, because of the landslide geometry.

The system of seven parallel drains was installed in the north undeveloped portion of the landslide. The distances between the drain trenches were, from the west to the east side: 4, 4.5, 5, 6, 8 and 8 m. The lengths of the drains were from 50 m for drain 1 to 182 m for drain 3. The drainage system ended north of the residential structures.

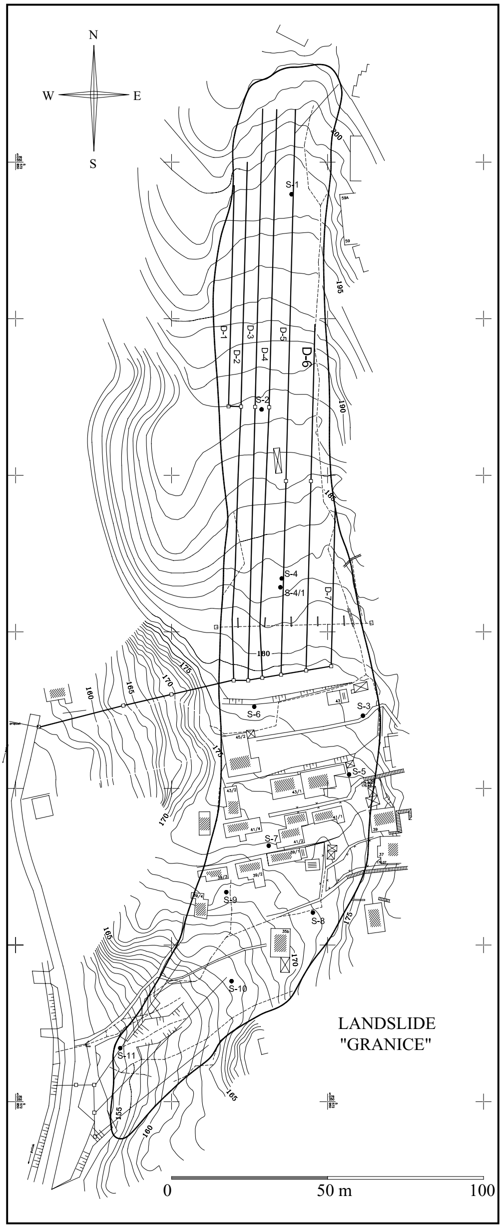


Figure 6. Landslide "Granice" — the positions of the drain trenches realized as main improvement measure.

Three additional drains were installed to the south of the residential structures. This constructive measure was needed because the material in this part of the sliding body was very soft and wet. Indeed it was so soft that it was partly replaced with drainage material on a large part of this surface.

According to the landslide improvement design, the problem of sewerage for residential structures situated in the Granice street, which is positioned above the landslide surface along the east side of the landslide, was to be solved simultaneously with the landslide improvement activities. Unfortunately, construction of the sewerage system was prevented by administrative and financial problems. Even so, the improvement was successful which was confirmed by monitoring.

Landslide monitoring activities were performed during one year after the landslide improvement. They revealed that the improvement works were successful. This was established by displacement measurements using inclinometers and geodetic benchmarks, which showed that no displacement occurred on the landslide after the improvement works. Piezometric monitoring revealed that the piezometric pressures were significantly reduced with respect to the prior situation on a greater portion of the zone covered by the drainage system. Next to the eastern edge of the landslide, which remained affected by the unsolved sewerage in the Granice street and in the populated portion of the landslide, the piezometric level did not change significantly when compared to the situation prior to the improvement works.

Improvement and monitoring activities were used to collect additional geotechnical data on the landslide in order to verify the adopted geotechnical model (Jurak et al. 2004). The data gathered in this way (Fig. 7) confirmed that the geotechnical correlation column based on 1995 data (Fig. 3) was fully reliable.

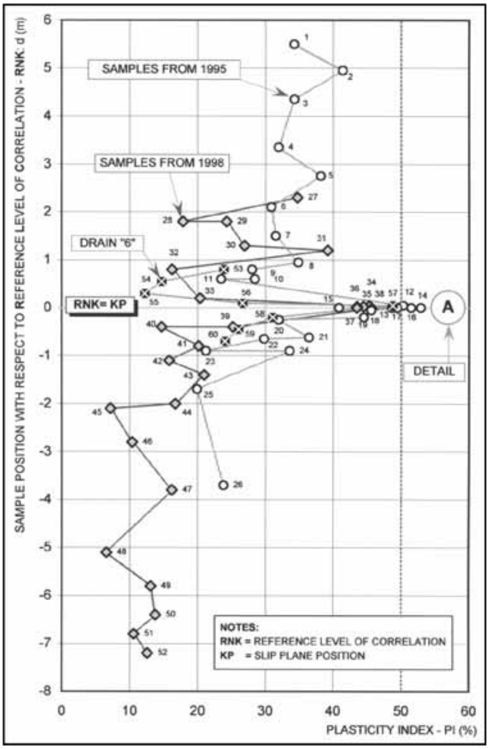


Figure 7. Verification of the geotechnical correlation column presented in Figures 3 and 4, based on plasticity indexes from 1998 (samples from boreholes drilled for the installation of monitoring equipment and from drain 6).

5 CONCLUSION

Landslide "Granice" in Zagreb was active more than 30 years. The displacements of the objects on the landslide exceeded approximately 5 m and one house positioned the most south, on steeper part of landslide was moved about 10 m.

Geotechnical investigations were conducted in 1995 and the result was a landslide improvement project.

The RNK method (Ortolan, 1996) was used to define a geotechnical model of the landslide. Contoured map of the slip plane with the sliding surface clearly delimited, contoured map of the maximum piezometric pressures at the slip surface level and the geotechnical column were provided so appropriate stability and seepage analyses could be done and appropriate improvement measures defined.

Geotechnical correlation column constructed on the basis of geotechnical investigations was verified by the data collected during improvement and monitoring activities (Jurak et al. 2004).

The landslide was improved in 1998 by installing the drain trenches. Landslide monitoring activities revealed that the improvement works were successful.

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