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# Verification of Engineering-Geological/Geotechnical Correlation Column and Reference Level of Correlation (RNK) Method by Observations in the Slip-Plane Zone

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**Key words:** Plasticity index, Shear strength, Engineering-geological/geotechnical correlation column, RNK-method, Slope stability, Landslide.

## Abstract

The engineering-geological/geotechnical correlation column can be established in zones of limited extent using one or several characteristic layers, one of which is selected as the reference layer. The Reference Level of Correlation method, i.e. the RNK (*Referentni nivo korelacije* in Croatian) method, is a confirmed procedure enabling the establishment of such columns. In the engineering geological/geotechnical correlation column, the plasticity index is the most significant indicator of the peak friction angle, full-softening friction angle and residual friction angle for coherent soils and soft rock formations. As a rule, maximum plasticity index values correspond to the minimum values of such friction angles. This opens up the possibility of an exact engineering-geological/geotechnical model, with accurate differentiation of minimum shear strength zones, zones of different permeability, and zones of various degrees of natural compaction. This procedure was applied *inter alia* on the successfully improved Granice landslide located in the Zagreb area, where it was proven that elements for verification based on the RNK-method exist for all three areas of investigation: sliding body – drain trench section – detail in the central portion of the sliding zone. The procedure is recommended as a means for finding solutions to similar problems.

## 1. INTRODUCTION

When presenting results obtained during study of a landslide situated in the stiff and fractured diluvial clay in the zone of Prekrižje in Zagreb, NONVEILLER (1964) indicated that the low thickness of the sliding zone (from 1 to 10 mm) was established as late as in the course of subsequent observations made during improvement work. The zone is in fact composed of a very thin intercalation of light gray or bluish clay of high plasticity (CH), which was not discovered during the initial drilling operations. While describing the assumed sliding mechanism and results of stability analyses, he claimed that the shear strength of the lowest-strength material component is in fact relevant as a proof of slope safety. Over several past decades, such observations have proven to be quite useful and have served as guidance to many investigators all over the world in their efforts to explore this idea in greater detail. Furthermore, fully aware of the complexity of slope stability investigations and of the need to establish close cooperation between engineering geologists and geotechnical engineers, NONVEILLER (1979, p. 402) states: “Extensive research has shown that geological details that at first appear to be of secondary significance, are sometimes crucial for the stability and development of landslides on slopes, and may hence be relevant for safety calculations. Today, it is evident that such phenomena, occurring in the very complex geological medium of the Earth’s crust, can not be considered separately, i.e. as a purely mechanical phenomenon”.

The aim of precise engineering-geological and/or geotechnical modelling of relatively well-bedded media (soft rocks and all types of soil) is to establish complete correlation of formations i.e. to create a logical vertical sequence (engineering-geological and/or geotechnical correlation column) in which the lateral persistence of “layers” (and even very thin laminae) of uniform geotechnical properties can also be established. The detailed correlation of formations (in geological sciences by normal mapping “from layer to layer”) has revealed (ORTOLAN, 1990, 1996, 2000) that all geotechnical results (obtained both *in situ* and in the laboratory) may be interpolated, in zones of

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limited extent characterized by relative lithological homogeneity, into the appropriate part of a vertical sequence within the geotechnical correlation column, both in flat and inclined types of terrain. This is obtained by one or several characteristic layers, one of which is then selected as a reference layer. ORTOLAN (1996) named this a *Reference Level of Correlation* (*RNK – Referentni nivo korelacije* in Croatian). Here the emphasis is placed on the existence of one plane or a very thin but widely spread zone, which becomes crucial for all other harmonisation with this recognizable level. The selection of the above mentioned name may be explained by analogy with the definition for the reference level (niveau surface) in mathematics (theory of fields), geophysics and geodesy. In addition, this level or thin zone also alludes to the notion of a reference horizon.

A series of novel procedures was developed in the scope of the thesis (ORTOLAN, 1996) using the Podsused landslide in Zagreb as an example. Strict application of such procedures in the engineering geological and/or geotechnical modelling has become known as the Reference Level of Correlation Method (RNK-method).

The task of establishing a spatial engineering-geological/geotechnical model of a landslide may prove to be extremely delicate and complex, particularly in the case of deep multilayered landslides. In this respect, the following features must be defined with sufficient accuracy: geometry of sliding bodies, pore pressures along slip planes, and shear resistance parameters along zones with minimum shear strength materials.

Here, our attention is focused on the well known Granice landslide in Zagreb or, more precisely, on the segment that is of crucial significance for the accurate geotechnical modelling of landslides: the establishment and verification of the engineering-geological and/or geotechnical correlation column. This example is particularly interesting because investigations and analyses were carried out by experts from various complementary disciplines and professions and, in the end, the landslide was successfully improved.

## 2. RNK METHOD – FUNDAMENTAL NOTIONS AND BASIC DEFINITIONS

The plasticity index has proven to be a reliable strength indicator for coherent materials (ORTOLAN, 1996; ORTOLAN & MIHALINEC, 1998). Therefore, testing of Atterberg plasticity limits on point samples can reasonably be recommended for the identification of minimum shear strength zones. The sampling interval should not exceed 10 cm (sometimes it should be as little as several cm, and even several mm). However, sampling at every 0.5–1.0 m interval, always based on professional judgment, is generally considered sufficient. A diagram, usable in practice and showing correlation between the residual and peak friction angle and plasticity index, was proposed by ORTOLAN & MIHALINEC (1998).

The *RNK-method* or the *Reference Level of Correlation Method* (ORTOLAN, 1996) is a fully developed method for engineering-geological and/or geotechnical modelling. It is primarily destined for analysis of the slope stability of soils and soft rock formations.

The RNK (Reference Level of Correlation) 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 lithostratigraphic, i.e. engineering geological and/or geotechnical sequence (engineering-geological and/or geotechnical correlation column).

In the RNK-method, we mostly use visually recognizable layers, i.e. layers of striking colour and exceptionally high or low plasticity with respect to the underlying and overlying strata, or layers that are markedly fossiliferous, layers with marked grading, with high organic matter content, or layers characterized by some other distinguishing feature. However, the presence of visually recognizable reference layers is not a requirement. In case of lithological monotony, the position of the RNK may be defined at will by means of a graphical procedure, provided that there is a sufficient density of laboratory results (plasticity index). The procedure is carried out in such a way that results (obtained by laboratory testing of samples from boreholes, trial pits or outcrops) having at least one joint portion in a vertical sequence of layers, are drawn on oleates shown on the same scale (e.g. plasticity indices by depth). After that, oleates from individual boreholes (neighbouring boreholes must go through at least one part of the same package of formations) are overlapped so that test results are brought into a coincident position (position of maximum conformance) for portions of the same packages of formations. The RNK is defined at an oleate selected at will, and then the RNK defined in this way is transferred to the coincident positions of the remaining boreholes. Once the RNK depths are defined for every borehole, the results are united into a geotechnical correlation column. If we have the RNK position with at least three neighbouring boreholes of different extent, then the position of zones or layers may be determined by defining the plane with three points. Local deviations of layer positions between neighbouring boreholes can also be defined.

The *geotechnical correlation column* is a consistent engineering-geological and/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 reasonably be 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 we may in principle differentiate zones of minimum residual shear resistance, with their thicknesses and continuities, and also layers with different moisture, permeability, natural compaction, compressibility, etc. The engineering-geological and/or geotechnical correlation column of an analyzed area is the "key" to the interpretation of the overall engineering-geological and/or geotechnical relationships in a required number of profiles selected at will for 2D and spatial analysis, which is especially significant in 3D analysis of stability.

The following supporting documents are most often used in the study of landslides: general geological map of the wider area under study, geotechnical correlation column, engineering-geological map with slip-plane contour lines and with clearly delineated slip areas and hydro-isohypses or hydro-isopiestic lines at the slip-plane level (ORTOLAN, 1996, 2000). Previous definition of such features is the guarantee that the highest possible level of accuracy will be attained in the resolution of slip problems and/or in the definition of crucial slope safety factors. Such supporting documents provide all relevant information needed to develop a series of representative detailed profiles which is in turn indispensable in the three-dimensional stability analyses of slopes. Such documents were also provided for the Granice landslide which is presented below as a case study.

## 3. RESULTS OBTAINED BY THE RNK-METHOD

The consistent use of the RNK-method in the period from 1995 to the present day has resulted in the elaboration of three-dimensional geotechnical models for some thirty landslides. In all of these cases the following parameters were successfully defined: sliding body geometry, pore pressures along slip-planes, and shear strength parameters for materials along zones of minimum shear resistance. In combination with existing topographical documents, this enabled accurate stability analyses and definition of optimum improvement procedures. The Podsused landslide may be described as one of the most complex urban landslide projects in the world (ORTOLAN, 1996, 2000). It is precisely on this project that the RNK-method has been developed in full detail, and the reliability of the model was confirmed with photogrammetry measurements (ORTOLAN & PLEŠKO, 1992; ORTOLAN et al., 1995) as well as with three-dimensional stability analyses (MIHALINEC & STANIĆ, 1991; STANIĆ & NONVEILLER, 1996). As it meets all the relevant criteria (JURAK et al., 1996) it has been proposed for insertion in the WLI (World Landslide Inventory).

Most of the studied landslides have been improved, in all cases with great success, and the supervisory work conducted during realization of improvement activities provided positive feedback information about the correctness of the adopted engineering-geological and/or geotechnical landslide models (e.g. at the Frkanovec landslide near Čakovec and at the Granice landslide), and about reliability of the engineering-geological and/or geotechnical correlation column (design cross section). On some projects, such as the Čiritež landslide in Istria and Črešnjevec landslide in Zagreb, the reliability of the model was checked and confirmed by appropriate auscultation equipment: inclinometers, piezometers and benchmarks. On these landslide projects, inclinometer movements were registered at depths that corresponded well with forecast values obtained on the basis of the RNK-method. Landslide models were also confirmed by new samples taken during installation of auscultation equipment, e.g. on the Granice and Črešnjevec landslide projects. These samples were tested in the laboratory in order to establish new geotechnical correlation columns, but this effort only confirmed the model that had previously been accepted. In the case of the Črešnjevec landslide, the validity of the model was additionally confirmed by deep excavation for a water reservoir in the vicinity of the landslide. In fact, a number of samples were taken from the foundation pit and tested in the laboratory, and the results have shown good correspondence with the previously established geotechnical correlation column. Interpolation of the results obtained by samples from boreholes for installation of additional auscultation equipment, into the already prepared geotechnical correlation column was similar.

## 4. VERIFICATION OF THE ENGINEERING-GEOLOGICAL/GEOTECHNICAL CORRELATION COLUMN AND RNK-METHOD ON THE GRANICE LANDSLIDE PROJECT IN ZAGREB

One of the ways for checking the reliability of the engineering-geological and/or geotechnical column is presented using the Granice landslide in Zagreb as an example. Here, the validity of the geotechnical correlation column and three-dimensional sliding model was assesed by continuous monitoring during the realization of drain trenches, using three generations of samples that were systematically taken and tested in the laboratory. According to observations made by NONVEILLER (1964, 1979), special emphasis was placed on the study of "geological details seemingly of secondary significance". Results of these investigations and verification of the engineering-geological and/or geotechnical correlation column, all point to the high accuracy of the RNK-method, and are presented in the following section.

### 4.1. Properties of materials found in the landslide during the first investigation of 1995

The objective of the first investigative campaign conducted in 1995 was to establish a geotechnical report with a landslide improvement proposal. A general layout for

Fig. 1 General layout of the Granice landslide with the coordinates of an approximate centre of gravity.

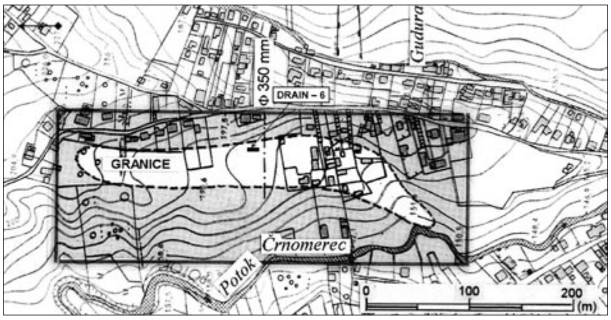

Fig. 2 Granice landslide with the position of the steel pressure pipeline forming part of the municipal drinking water supply system, which was for many years endangered by landslide activity.

the landslide is presented in Fig. 1. The topographic presentation of the neighbouring terrain with the contour of the landslide is given in Fig. 2. It can be seen that the landslide was activated on the plateau, slightly sloping (no more than 5°) from north to south, which is also the slip direction. The first geotechnical correlation column of the landslide was prepared by graphical procedure, i.e. by the overlapping of oleates. A portion of this column, with the geological and AC classification of materials, is presented in Fig. 3.

Formations found on the landslide date back to the Upper Pontian (*Rhomboidea* layers) and are characterized by their pronounced laminar texture. The formations slope slightly towards the southeast, and the slip-plane generally coincides with the position of the layers.

Samples from all three generations (1995, May and August 1998) are presented on the plasticity chart (Fig. 4) where they are classified on their plasticity according to the BSCS (British Soil Classification System – BSI, 1981; IAEG, 1981). Here, attention is drawn to the group of clay samples characterized by very high plasticity (CV) which is often typical for materials of pronounced colloidal activity and high expansivity. It is precisely these samples that come from the slip zone proper, about 10 cm in total thickness.

Results of laboratory and in situ investigations, presented in the form of a single geotechnical correlation column, are given in Fig. 5. The situation is very indicative and leaves little doubt as to the position of the slip-plane. In fact, several indicators are normally considered significant for the detection of potential slip-planes. Three such indicators are taken into account in our case: quantity of clay particles ($<2$ μm in size, $\geq 30\%$; coinciding with a reduction in the sand component), plasticity index (PI) as a derived variable ($\geq 50\%$) and natural compaction level of the soil.

In the interval presented in Fig. 5, the first two indicators show two very pronounced and coinciding "peaks" (which are in firm logical correlation to one another) at the same level. This clearly points to a weakening in the geotechnical correlation column and to the possible formation of a mechanical discontinuity. The third indicator (natural compaction or relative density) is indicative only in particular cases. Here we may say that it is indicative only to a certain extent, as a significant increase in the degree of compaction actually occurs below the slip-plane level. However, all the information points to a particular plane and to the following reference level of correlation: $RNK = KP = 0$ (Fig. 5).

The consistency state known as material "remolding" may partly be caused by significant displacements (total displacements of about 10 m were registered at the Granice landslide). However, this state should not be considered as definite evidence of the slip-plane position. In fact, displacements amounting to several metres were registered along slip-planes in the case of the Podsused landslide but the occurrence of "remolding" was not registered at any of the three slip-planes (ORTOLAN, 1996). It would be more plausible to explain the contrasts in the compaction level of materials through the history of terrain formation, including diagenesis. Of course, the position of slip-planes at the contact of contrasting features may also be purely coincidental. In this respect, it may be noted that the "Zagreb terrace" sediments, dating back to the Pleistocene, are lacking in the case of the Granice landslide as they were probably lost due to erosion. Slope wash sediments i.e. colluvium (cf. Fig. 3) dating back to the early Quaternary period (pebbles and poorly rounded fragments of quartz and rocks from Medvednica mountain, and frequent remains of vegetable matter) occur directly above the Upper Pontonian layers. These sediments were not (or at least not considerably) compressed with a thick overburden, nor are there any indications of the onset of lithification, which is why the natural compaction level is lower.

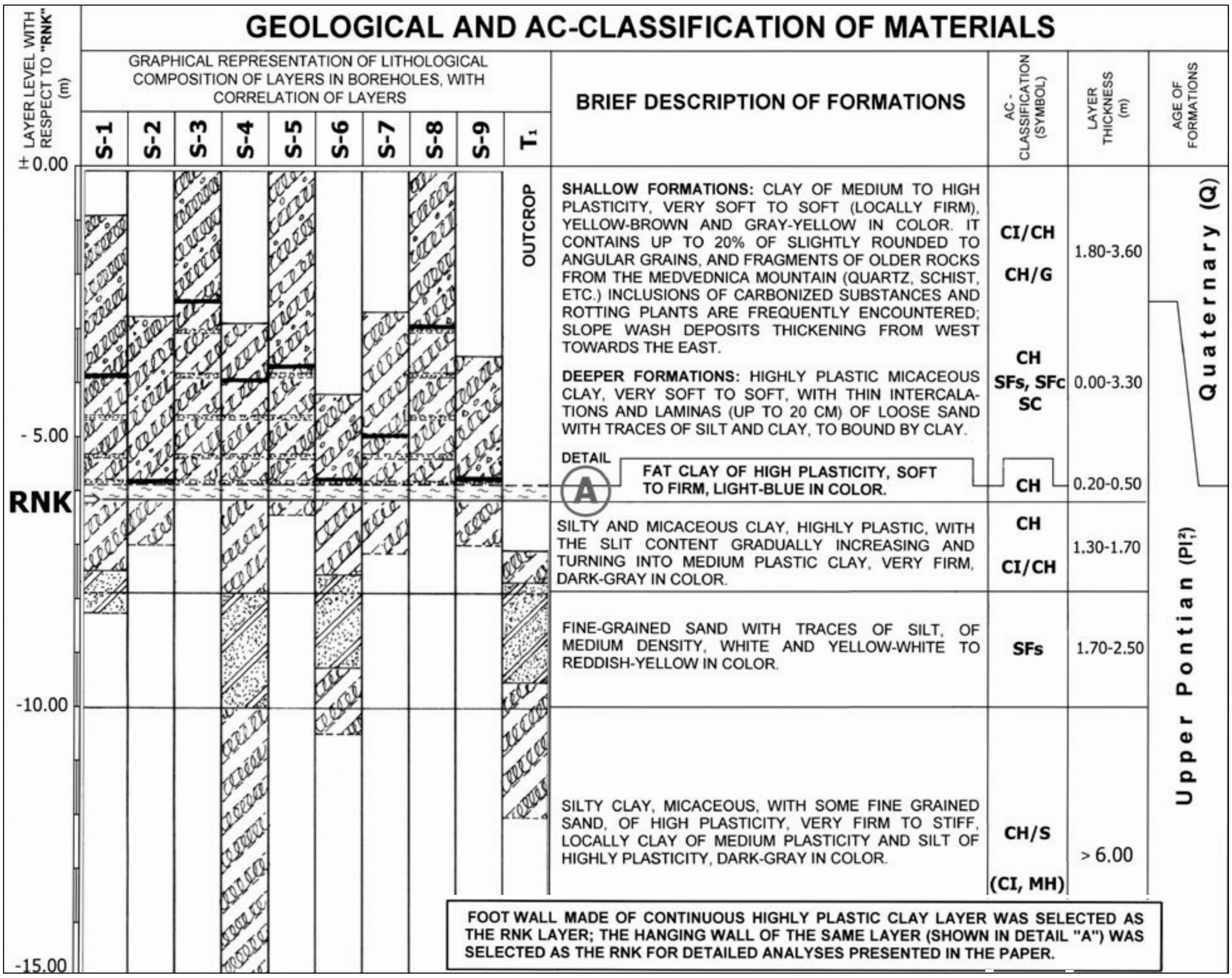

Fig. 3 Geotechnical correlation column of the Granice landslide (ORTOLAN, 1996) established using the visually recognizable reference level of correlation.

### 4.2. Data about landslide material gained by investigative campaigns undertaken in May and August 1998

The second campaign of systematic sampling in the narrow slip-plane zone was conducted during the realization of drain trenches protected with Krings struts (in drain "6"; cf. drain position in Fig. 2) on the occasion of field exercises for students of the Faculty of Mining, Geology and Petroleum Engineering (May 7, 1998). At that time, a small cylindrical sample was taken in the immediate vicinity of the slip zone (Fig. 6) and was then subjected to detailed testing. The third campaign of sampling and laboratory testing, related to the installation of inclinometers and piezometers, was conducted in August 1998.

Sample differentiation by grading, conducted in 1995 and 1998 (trench excavation for drain "6") is presented in the triangular grading diagram (Fig. 7). Three groups of fine-grained materials can clearly be differentiated: silty sand (III), clay (I) and a silt-dominated mixture (II). These groups are distributed as follows: silty sand is found in the continuous layer below the drain bottom, the silt-dominated mixture is equally distributed below and above the slip-plane, while samples with medium and high clay content (particles <2 μm) are either located in the slip-plane or in the zone immediately next to the slip-plane (about ten cm in thickness). The classification according to the content of clay size particles, i.e. low content (<20%) and high content (>40%) is based on a paper proposed by SKEMPTON (1985). The proportion of clay particles has a notable effect on the behaviour of the material.

Results obtained through determination of the plasticity index of clay samples during all three campaigns are presented in Fig. 8. The hanging wall composed of fat clay layer of high plasticity, soft to firm, light-blue in colour (shown in Fig. 3) was selected as the reference level of correlation (coinciding with the slip-plane position, i.e. RNK=SP) for the geotechnical correlation columns shown in Figs. 5 and 8. It is believed that this fat clay layer belongs to the non-eroded top portion of the Upper Pontian formations, although its genesis can also be explained differently, as indicated in the discussion.

Despite significant distances between individual sampling positions (often exceeding 100 m), all results

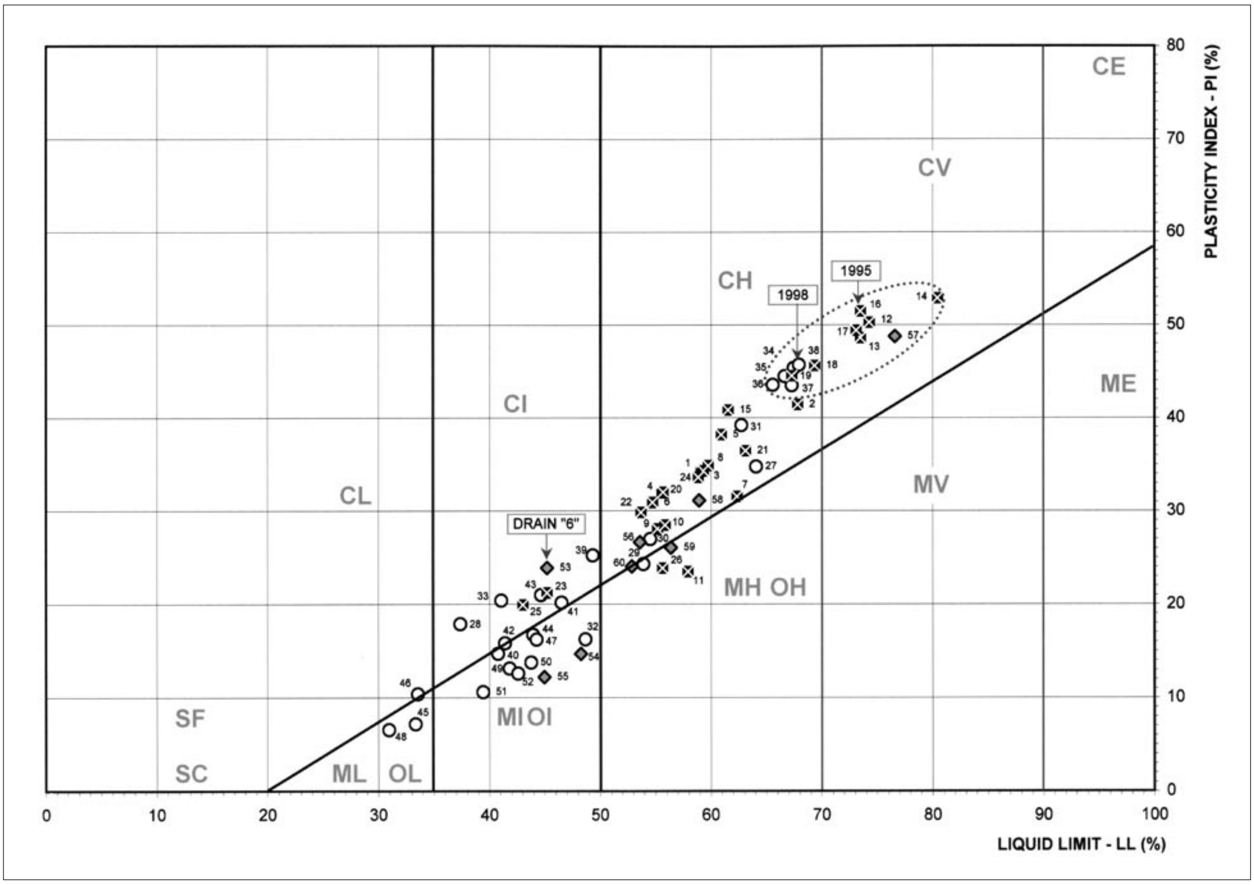

Fig. 4 Plasticity chart for all three generations of samples from the Granice landslide in Zagreb which served for verification of the engineering geological/geotechnical correlation column and RNK method. The encircled zone contains samples from the slip-plane.

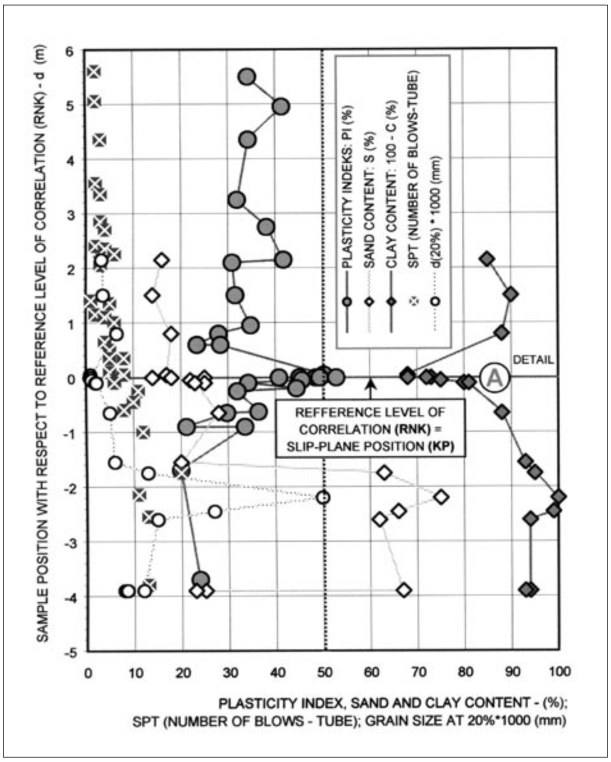

Fig. 5 Geotechnical correlation column for the Granice landslide (based on 1995 data).

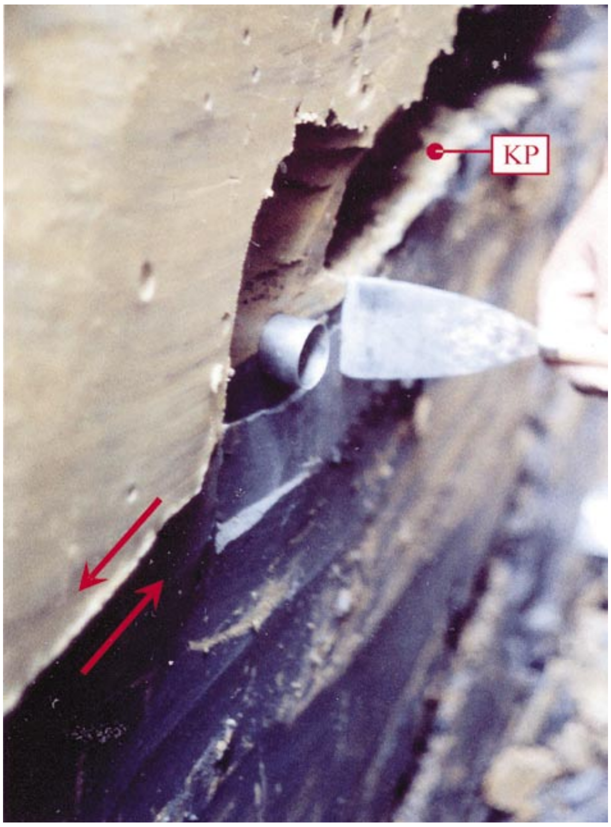

Fig. 6 Sampling in the immediate vicinity of the slip plane (KP) in drain "6" (Photo by V. Belošević, May 7, 1998).

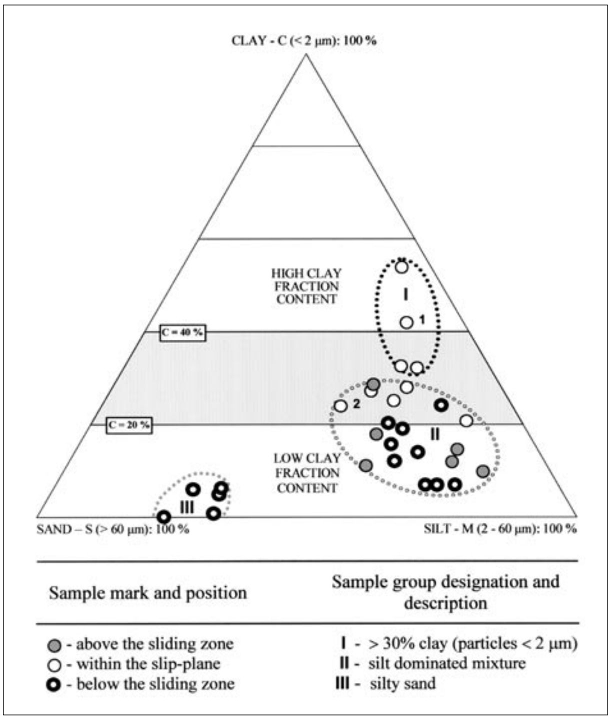

Fig. 7 Triangular grading diagram with grain size differentiation for samples taken in 1995 (cf. Fig. 5) and those from drain trench "6". Samples (1) and (2) are from the cylinder shown in Fig. 10 (detail A).

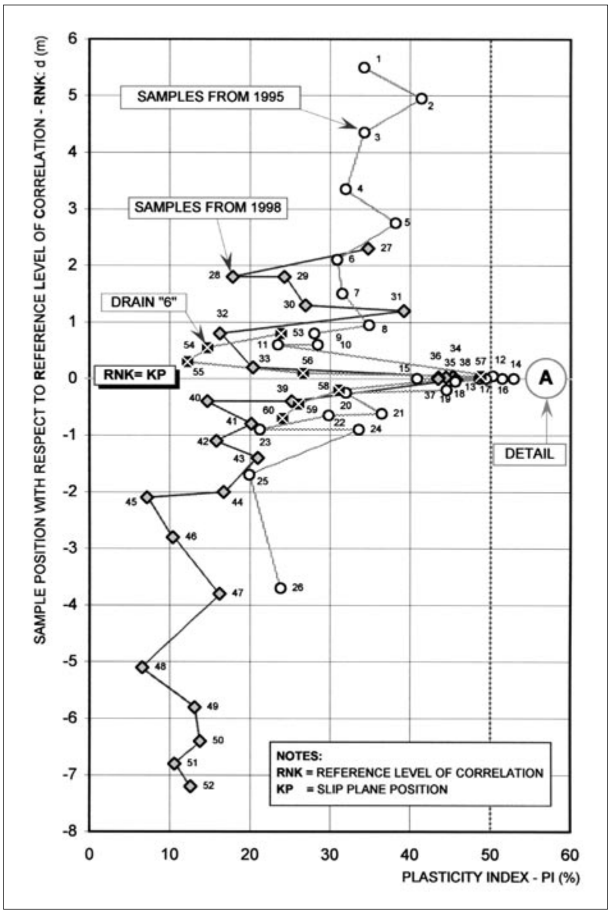

Fig. 8 Verification of the geotechnical correlation column presented in Fig. 5, based on the plasticity index from 1998 (samples from boreholes drilled for the installation of auscultation equipment and drain "6").

point to good correspondence regarding the slip-plane position, which was quite accurately estimated in the geotechnical correlation column prepared in 1995 (ORTOLAN, 1996), as well as being detected and confirmed by the continuous monitoring activities conducted during realization of subsequent landslide improvement work.

Results obtained by the determination of uniaxial compressive strength (by pocket penetrometer) and undrained shear strength (by light vane) in the slip-plane proper during realization of drain trenches (in drain "6"; drain position is shown in Fig. 2) are presented in Fig. 9. The same figure shows the content of the clay fraction (particles <2 µm) as determined on the same samples that were used for the definition of the Atterberg limits (plasticity indices are shown in Fig. 5). Fig. 9 also shows that the highest clay content was registered in the sample coming from the slip-plane. The accuracy of the slip-plane position was also confirmed by uniaxial compressive and undrained shear strength values. Of course, neither this, nor any other confirmation, can be considered significant in this case because the slip-plane position is clearly visible (Fig. 6). However, if we were to look for the position of a potential slip-plane on a slope whose stability we have to determine, then each of the above details would of course have an appropriate weight.

At this point, it would also be of interest to consider an obvious difference in the maximum content of the clay fraction, which can be seen by comparing Fig. 5 (CF=32%) with Fig. 9 (CF=53%). The difference is exclusively due to the use of different de-coagulants during the determination of grain size distribution. Thus water glass was used on samples taken in 1995, while sodium hexametaphosphate was used during sampling performed in 1998. In fact, the sodium hexametaphosphate was introduced as standard only after 1995, i.e. after MULABDIĆ et al. (1994) proved that the clay content may vary by up to 200–300%, depending on the previous preparation of soil samples for hydrometric analysis. Samples prepared in this way would probably put an even greater emphasis on the grading differentiation shown in Fig. 7. This is yet another proof of the claim about enrichment of a thin zone with clay particles, which has in fact oriented the reference level of correlation (RNK) precisely towards this lithological feature of the engineering-geological and/or geotechnical column.

All this shows that the validity of the engineering-geological and/or geotechnical correlation column has been confirmed on many occasions and in many ways, while also proving the correctness of basic notions of the RNK-method. The soundness of the method was also proven through stability analyses (ORTOLAN, 1996) as the factor of safety Fs≈1.0 had already been

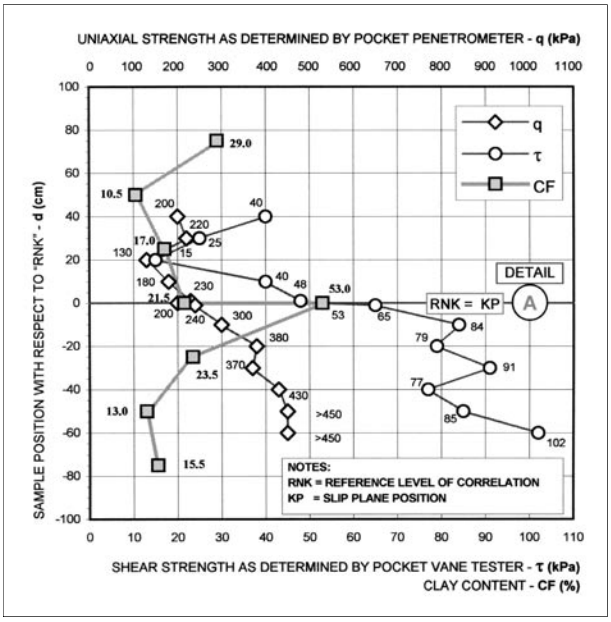

Fig. 9 Determination of uniaxial compressive strength, undrained shear strength and grading of material from drain "6" (detail A in Figs. 3, 5, 8).

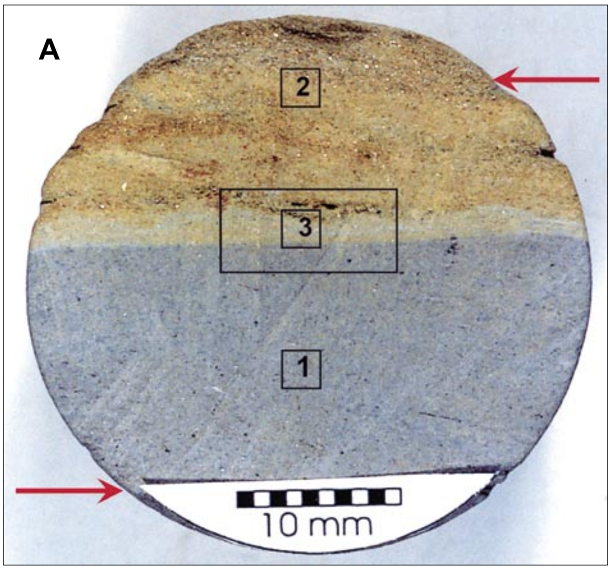

Fig. 10 Cross-sectional photograph of the cylinder from Fig. 6 (detail A: Figs. 3, 5, 6, 8 and 9). Shear stress zone is marked by arrows.

obtained on the representative prognostic geotechnical profile during the initial iterations of calculations. Such a level of accuracy was obtained on all projects on which the RNK-method has so far been used.

## 5. ANALYSIS OF DETAILS IN THE SLIP-PLANE ZONE

### 5.1. Sample physiography

The study of details in the narrow slip-plane zone (and immediately above and below it), was undertaken in the second systematic sampling campaign conducted during realization of drain trenches (in the drain "6"). At that time, a small undisturbed sample was extracted with a metal cylinder (Figs. 6 and 10). In this sample, the gray silty clay (1) can clearly be differentiated in the foot wall of the slip-plane and the yellow-brown sandy silt (2) in the hanging wall, with a contact lamina between them (3). The position of the slip-plane can clearly be observed in Fig. 6 because, soon after excavation of a portion of the drain ditch, the material was displaced, at a level of 4.70 m, from the sliding body (yellow-brown – in hanging wall) and passed via stable sediments (gray – in foot wall) and along the slip-plane, due to the markedly softer consistence of material in the sliding body. In this segment, the slip-plane is also the limit plane.

The sample extracted with the metal cylinder measuring 10 cm in length and 3.5 cm in diameter, was analyzed in detail using various methods and procedures, as shown below. Blown up detail of the cylinder cross section given in Fig. 10 is presented in Fig. 11. The presence of macropores can be noted in the yellow-brown sandy silt. These macropores enable a more intensive flow of ground water, while also contributing to better redistribution of pore pressures along the sliding plane. They also bear witness to the transport of fine particles.

### 5.2. Mineralogical and petrographical analyses

The material contained in the extracted cylinder was analyzed by (a) optical microscopy, (b) scanning electron microscopy (SEM) with an additional system for analysis in the energy-dispersive X-ray spectrum (EDAX), (c) by X-ray powder diffraction (XRD), and also included (d) determination of grading, and (e) chemical analyses. The yellow-brown material contained in one part of the sample was marked as "sample 2" while the gray material was marked as "sample 1".

The thin section was prepared in the zone perpendicular to the cylinder axis. The section included the contact between the yellow-brown and gray material (material 3 in Figs. 10 and 12). The following materials were identified by petrographical analysis:

1) gray pelite–sandy silt;
2) limonitic sand of graywacke type;
3) contact lamina composed of sand of fine-grained filo-arenite type.

As to the contact lamina in the cut zone, 2–3 mm in thickness, we should also take into account the mixing of particles from the foot wall and hanging wall, due to shear and displacement realized at the failure surface. It is known that the particle orientation and subparallel arrangement of grains occurs in the shear zone in accordance with the slip-plane (MORGENSTERN &

Fig. 11 Photograph of a detail from the rectangle shown in Fig. 10 (x16).

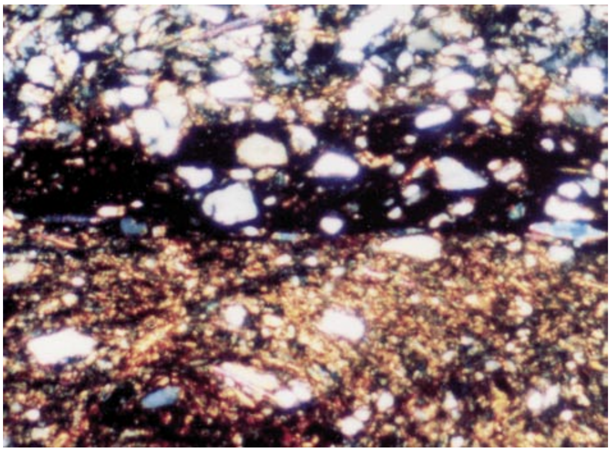

Fig. 12 Subparallel distribution of mineral grains along the slip-plane (N+, x50) in contact lamina (3) from detail A.

TCHALENKO, 1967; MITCHELL, 1993 – fig. 8.23b, p. 151), as can be seen in Fig. 12.

The SEM photomicrographs of yellow-brown and gray material are presented in Figs. 13 and 14. Minerals dominant in the yellow-brown material (2) are quartz and muscovite, and they range from 2 to 100 μm in size. The content of feldspars and goethite (grain size up to 40 μm) is also significant. Very small chlorite sheets, up to 3 μm in diameter, can be found in the base, but also on bigger muscovite sheets. Pores are up to 40 μm in width, and are partly filled with very small chlorite sheets. According to its composition, the gray material (1) is similar to the yellow-brown material, although its average grain size is much smaller and goethite particles are not present. Pores up to 30 μm in width are mostly filled with very fine sheets of chlorite and sericite. The clay content is much higher than in the yellow-brown material.

The grading analysis was conducted by wet sieving (particle fractions: >0.063 mm) and by sedimentation in cylinders (particle fractions: <0.063 mm) with Na-pyrophosphate as a decoagulant. The graphical presentation of results, with cumulative grading curves, is given in Fig. 15. It can be seen that the gray material (1) contains over 40 percent (by weight) of particles <2 μm, i.e. almost two times as much as the yellow-brown material (sample 2). According to the grading and mineralogical composition (Table 2) the gray pelite sample (1) represents silty clay, while the yellow-brown sample (2) represents sandy silt.

The amount of the main chemical components were determined by classic analysis, except for the Na and K contents which were determined by flame photometry. The corresponding results are given in Table 1. Concentrations of exchangeable cations after leaching of the global samples with 2M ammonium acetate solution for two days were determined: Na and K by flame emission spectrometry (FES), and Ca, Mg and Ba by inductively coupled plasma and atomic emission spectrometry (ICP – AES). The exchangeable cation concentrations (meq/100 g) are: Ca=6.7, Mg=5.5, Na=0.9, K=0.8, Ba=0.0 (sample 2); Ca=1.6, Mg=8.9, Na=0.6, K=1.4, Ba=0.1 (sample 1). According to these values, the cation exchange capacity (CEC) amounts to 13.9 meq/100 g (sample 2) and 22.6 meq/100 g (sample 1).

Fig. 13 SEM photomicrograph of the yellow-brown sandy silt. Chlorite sheets are situated among muscovite, quartz and limonite (?).

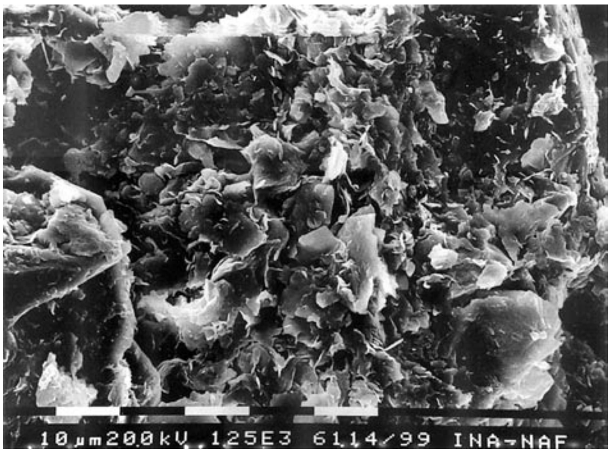

Fig. 14 SEM photomicrograph of the gray-coloured silty clay. Clusters of fine flaky chlorite surrounded by quartz particles are quite frequent.

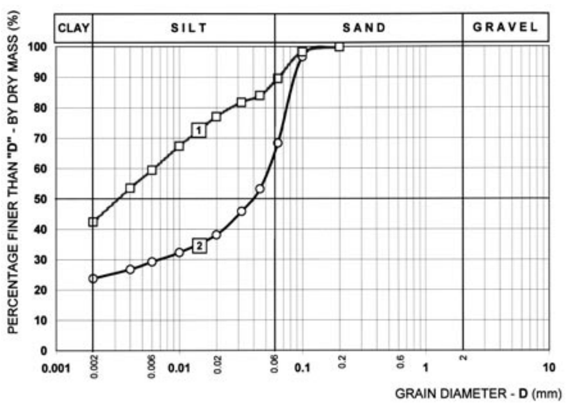

Fig. 15 Cumulative grading curves for the yellow-brown sandy silt (Sample 2) and gray silty clay (Sample 1) which are in contact along the slip-plane.

| Chemical component | Sample 1 (gray) | Sample 2 (yellow-brown) |
|---|---|---|
| $SiO_2$ | 59.22 | 65.95 |
| $TiO_2$ | 0.28 | 0.35 |
| $Al_2O_3$ | 20.98 | 14.70 |
| $Fe_2O_3$* | 4.15 | 6.90 |
| MgO | 2.65 | 1.65 |
| CaO | 0.57 | 0.62 |
| $Na_2O$ | 0.82 | 1.15 |
| $K_2O$ | 3.52 | 3.04 |
| LOI | 6.60 | 4.84 |
| $H_2O^{105}$ | 1.57 | 1.05 |
| **Total** | **100.36** | **100.25** |

Table 1 Chemical composition of samples 1 and 2 (% by weight). *Total Fe content expressed as $Fe_2O_3$.

| Mineral | Sample 1 (gray) | Sample 2 (yellow-brown) |
|---|---|---|
| Quartz | 23 | 38 |
| Plagioclase | 4 | 8 |
| K-feldspar | 1 | 2 |
| Goethite | – | 5 |
| Muscovite + Illitic material | 40 | 30 |
| Smectite | 12 | 5 |
| Chlorite | 15 | 10 |
| Kaolinite | 5 | 2 |

Table 2 Mineral composition of analyzed samples 1 and 2 (approximate weight %).

The mineral composition of the samples was determined by X-ray powder diffraction. Diffraction patterns of non-oriented global samples were registered after the following treatments: (a) air drying, (b) glycerol solvation, (c) heating to 650°C for one hour, and (d) dissolution in HCl (1:1).

Diffraction patterns of oriented samples (isolated <1 μm particle fraction) were registered after the following treatments: (a) air drying and (b) treatment with ethylene glycol. The proportion of quartz, plagioclase, K-feldspar and goethite was determined by semi-quantitative X-ray analysis (external standard method).

The mineral composition of the samples is shown in Table 2. An approximate proportion of minerals in the samples was determined by harmonization of the X-ray, chemical analysis and CEC data. It can be seen that samples from 10-Å minerals, as well as the muscovite, also contain an illitic material. Individual proportions of muscovite and illite could not be determined. For that reason, the sum of the proportions of these minerals is given in Table 2. However, according to the diffraction patterns of the separated clay-size fraction (particles <2 μm), the illitic material is the most abundant clay component in both samples. Quartz was not identified in the separated <1 μm particle fraction, which enabled X-ray identification of illitic material according to ŚRODOŃ (1984). Characteristic parts of the X-ray diffraction patterns of this fraction, separated from both samples, are shown in Fig. 16. According to ŚRODOŃ (1984), illitic materials from both samples are mixtures of pure illite and ISII-ordered interstratified illite–smectite, which contains less than 15% of smectite layers.

According to the data from Table 2 and considering the proportion of particles smaller than 2 μm in which illitic material is dominant, it can be concluded that the low-permeability gray clay in powder (sample 1) contains much more typical clay minerals than the yellow-brown sandy silt (sample 2). It should furthermore be noted that a significant quantity of this mineral component, characterized by swelling (smectite), is present in the gray pelite sample.

## 6. DISCUSSION

A possibility that the highly-plastic gray clay layer (CH) found in all boreholes realized in 1995 (Fig. 3), as well as in subsequent boreholes, may be of different genesis is noted in Section 4. There the thickness of this visible layer most often amounted to about 40 cm (i.e. it varied from 15 to 50 cm) while its thickness was about 10 cm in the drain trench ("6"). The slip-plane in contact with the hanging wall was registered on all occasions so that it is also a contact surface. As such, it was finally accepted as the reference level of correlation (RNK).

In fact, it can be assumed that the primary enrichment with clay particles occurred during deposition of the *Rhomboidea* layers, otherwise of pronouncedly laminated texture, which reduced the permeability in this horizon of the lithological column. Thus the

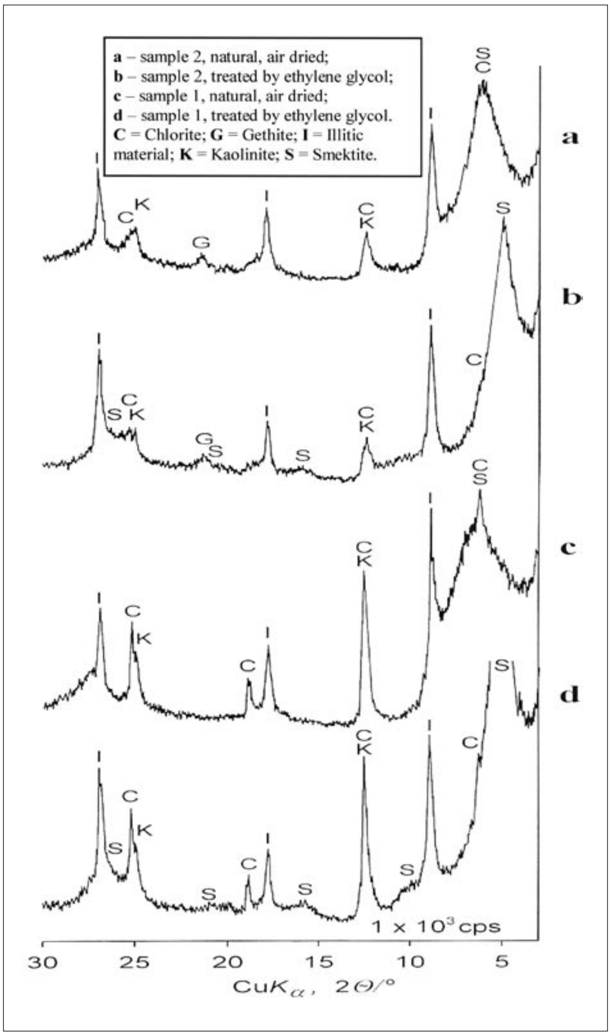

Fig. 16 Characteristic parts of the XRD patterns of samples with preferentially oriented particles of <1μm.

predisposition was created for the formation of the *secondary argillic zone*, as indicated by HRISTOV (1974). Environmental predispositions, i.e. relevant grading of the profile and hydrogeological circumstances, enabled subsequent enrichment with clay particles brought by water descending from the overburden.

Therefore, this is a continuous zone secondarily enriched with clay due to zonal differentiation of the soil crust due to weathering, which resulted in the formation of an argillic zone of gley type with spreading parallel to the surface of the terrain. Perhaps it is precisely by its formation that the grading contrast is so pronounced at the contact with the hanging wall (Figs. 10 and 11). As such, the zone has a specific hydrogeological and engineering-geological/geotechnical role. From the hydrogeological standpoint, it is a poorly permeable or almost impermeable layer, and in the engineering-geological/geotechnical sense, it is a zone of minimum shear resistance in a relevant stress field. Thus it can generally be described as a potential slip-plane, which was activated in the case under study.

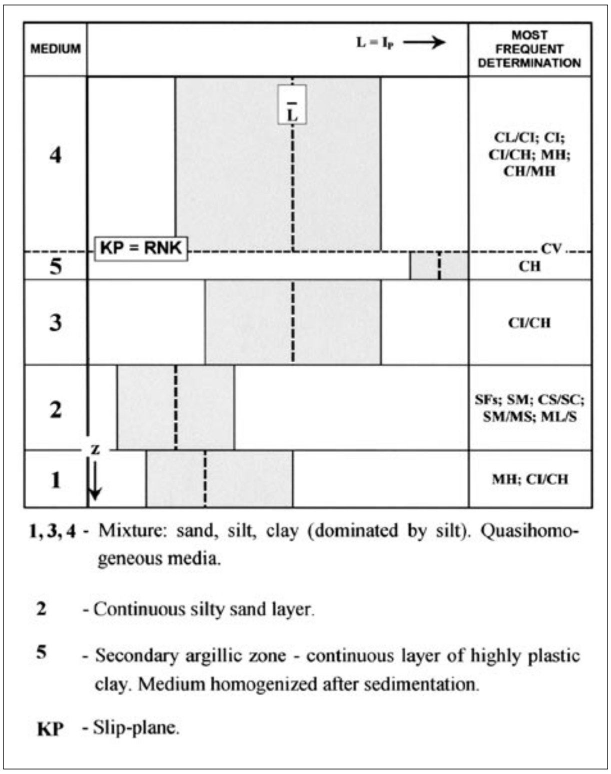

Fig. 17 Structural model according to RAC (1973) based on the variability of the selected indicator – plasticity index L=IP (not to scale, thickness relationships are relative). Legend: 1, 3, 4 – Mixture: sand, silt, clay (dominated by silt). Quasihomogeneous media. 2 – Continuous silty sand layer. 5 – Secondary argillic zone – continuous layer of highly plastic clay. Medium homogenized after sedimentation. KP – Slip-plane.

According to variable distribution (in this case it is a derived variable – plasticity index, L=Ip) changing with the depth (Fig. 17), we can clearly distinguish structural model elements of a stratified type (RAC, 1973 – Fig. 38, p. 129). In this case, this feature predetermines the landslide, which is of a translational type. The model presentation is valid for the sliding body in the *Rhomboidea* layers. A general correspondence of the investigated properties is obvious, as shown in Figs. 5 and 8, regardless of the distance in time and space. In the sliding zone, we obviously have clay of high to very high plasticity, and of minimum shear strength. It should be noted that some differences in the liquid limit and plasticity index values probably occurred due to the inadequate protection of samples against drying because, in fact, Atterberg limits must be determined on naturally moist samples. If this is not the case, significant deviations may be expected as to the liquid limit and plasticity index values (results are much lower). Some difference could also have occurred due to different levels of correctness during sample taking, because of the difference in drilling methods. The drilling made in 1995 was performed by hand augering with a pedological auger, while the drilling conducted in August 1998 was made by machine drilling with a single core barrel. Obviously, in the case of machine drilling with a single core barrel the correctness of sampling is higher, and the representativity of selected samples is better. When drilling is performed with a pedological auger, we are regularly faced with problems such as mixing with neighbouring soil layers and loss of information about the drilled interval.

## 7. CONCLUSION

In the study of landslides, stability levels of natural slopes, and artificially shaped slopes, unequivocal results can be obtained by the correlation of formations, and this by introducing the reference level of correlation (RNK-method) and by looking for the zone of minimum shear strength in the engineering-geological/ geotechnical correlation column through the plasticity index. Properly verified examples fully confirm significance of establishing engineering-geological and/or geotechnical correlation columns, particularly in the case of smaller areas. However, this column can sometimes be established for zones occupying as much as several kilometres in area. The slip-plane positioning logic is confirmed by all segments and details studied in the scope of this analysis. When applied strictly and accurately, the methodology can be used widely under appropriate geological circumstances in soft rocks and in all types of soil. Results obtained so far prove that the method is fully suitable for the preparation of exact engineering-geological and/or geotechnical models, and that such use of the method is highly recommended. Its qualities are best manifested in the case of lithologically monotonous pelitic sediment profiles (silt and clay mixtures and their alternations) or in cases when the limits between individual formations are or cannot clearly be distinguished.

The methodology has no sense if samples from longer intervals are selected by the “strip sample” method. All samples must always be selected by the point method, and extracted from the smallest possible intervals (up to 10 cm in length) as thicker intervals of materials of identical properties are very rare in nature (slip-planes are often formed along fine laminae about 1 mm in thickness, and sometimes even less), while only zones with materials presenting the minimum parameters of shear resistance are relevant and critical for exact geotechnical modelling. This was also revealed by detailed investigations in the very narrow slip-plane zone as undertaken in this case, which is in accordance with the assertions made in the introductory part of the paper.

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