RATIONAL IMPROVEMENT OF LANDSLIDES IN CLAY

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Abstract

The possibility of using data bases based on a combination of acceptable methods is described in the paper. The nonlinear dependence between technical solutions expressed by normalized coefficients, k_1 and, k_2, on the one side and landslide zones, Fk, on the other, has been established based on the analysis of 80 landslides, 50 of which already improved. The analyzed landslide zones ranged in size from F_k^{min}= 600 m² to F_k^{max}=60.000m².
The analysis of data-base results has revealed that there is no linear correlational dependence between expressions F_k~k_1, F_k~k_2, C_u~k_1, C_u~k_2, C_u~k_1/k_2 for each of the analyzed zones ranging in size from F_k^{min}=600 m² to F_k^{max}=60.000 m². In addition, as the relationship between small, medium--sized and large landslides amounts to 1:5:23, respectively, the only reliable correlational dependence, applied jointly to medium-sized and large landslides, can be expressed as $\ln F_k$~k_1, $\ln F_k$~k_2, k_1~ $\ln C_u$, k_2~ $\ln C_u$, k_1/k_2 ~$\ln C_u$.
Correlational dependences established in this way provide designers and clients with a reliable basis for transparent estimation of technical solutions k_1 and k_2 and prediction of the total landslide improvement cost C_u. According to information available to the authors, no similar proposals have so far been given in international literature.

1 Introduction

Considering the extent and magnitude of damage that has been caused by landslides in many developed countries, the UNESCO formed a working group whose task was to prepare a worldwide cadastre of landslides (WP/WLI) in order to provide assistance in the creation of national landslide cadastres. At the level of former Yugoslavia (Committee for Hydrogeology and Engineering Geology), a Commission was formed to prepare instructions for the registration and study of unstable slopes and landslides [14]. Guidelines provided by this Commission were used in the establishment of the landslide and debris-fall data base [1] and [9].

2 Establishment of land slide data base

2.1 Establishment of data bases for designed and improved landslides

During more than three decades of study of landslide occurrences, mostly in northern and western Bosnia, it has been established that natural slopes are mostly formed of thin diluvial younger Quaternary cover formations, neogenic sediments of overconsolidated, fissured or relatively intact clay of high plasticity (CH). Deeper underground, the soil is formed of clayey marls and marly limestones, sometimes in combination with sandy and gravely formations. Structural and tectonic relationships are not complex and bedding planes are mostly well aligned, with low values of shear resistance parameters. These bedding planes are mostly

parallel to the ground surface, and may be regarded as potential slip planes. An appropriate engineering-geological landslide map has been produced on the basis of engineering-geological mapping data, precipitation measurements, ground water level measurements in piezometers and existing wells, and according to permeability coefficient calculations. This landslide map enables differentiation of engineering-geological models (IGM) and geotechnical models (GM) which in turn are the basis for creation of calculation models (CM).
The following limit values have been defined based on results obtained by laboratory testing of highly plastic clays: $\gamma = 18\text{-}19$ [kN/m³], $w_L = 40\text{-}85$ [%], $I_p = 25\text{-}50$ [%], $c = 10\text{-}40$ [kN/m²], $\varphi = 10\text{-}25$ [°] and $k_v = 10^{-7}\text{-}10^{-9}$ [cm/s].
In most landslides covered by the analysis, the ground water level is situated close to the ground surface. Furthermore, in most landslides the slip plane is located at 5 to 7m under the ground level. New landslides are formed and old ones are activated mostly on slopes with an inadequate precipitation and waste water drainage. Many landslide occurrences have been noted on roadways, where about 85 percent of all landslides are situated. Main culprits for landslide occurrence are: underlying ground surface not prepared for embankment construction, poor quality material placed as embankment material, inadequate drainage of surface and ground waters, inadequate inclination of cutting or embankment slopes, and inappropriate maintenance of gutters and culverts situated along the road.

2.2 Rational procedure for landslide improvement

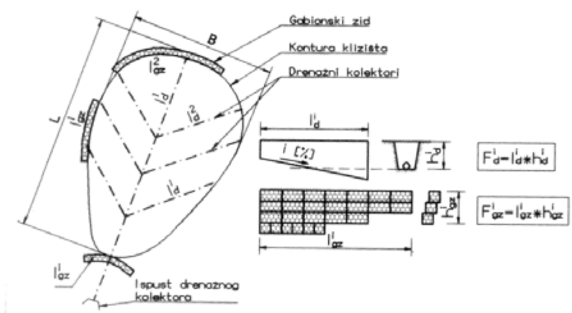

Figure 1 Schematic view of landslide improvement solution by means of drainage and support structure (gabions)

A rational landslide improvement method (RSK), requiring selection of a relationship between the drainage system and retaining structures (gabion walls, reinforced-concrete walls, and piling structures), has been developed following many years of investigation and research work, mostly presented in papers [15] and [21]. After determining the area affected by the landslide (Fk), which is calculated from the topographic and engineering-geological maps on which landslide traces are registered, and following on site inspection, the initially collected data are analyzed and synthesized, and the length (l_d^i) and depth (h_d^i) of drainage collectors, as well as the length (l_{pk}^i) and height (h_{pk}^i) of retaining structures, are selected (estimated) (Fig. 1). The values F_{pk} and F_d obtained in this way are then used to calculate – based on expressions (1) and (2) – the values of normalized influence coefficients for technical solutions k_1 and k_2.
Normalized influence coefficient of the drainage system:

$$k_1 = \frac{\sum_{i=1}^{n} l_d^i \cdot h_d^i}{F_k} = \left[\frac{m^2}{m^2}\right] \tag{1}$$

Normalized influence coefficient of the retaining structures:

$$k_2 = \frac{\sum_{i=1}^{n} l_{pk}^{i} \cdot h_{pk}^{i}}{F_k} = \left[\frac{m^2}{m^2}\right] \qquad (2)$$

3 Comprehensive statistical analysis of data base for medium and large land slides, and a joint analysis of medium and large slides

3.1 Medium-sized landslides 1700 m² ≤ F_k ≤ 5280 m²

The total of 17 landslides were analyzed and the analysis results (Figs. 2, 3, 4, and 5) are presented as the relationship between the landslide area F_k and landslide improvement cost C_u on the one side, and influence coefficients k_1 and k_2, on the other. Results obtained by the study of landslides prior to 2003 are marked with rhomboid, while results obtained after 2003 (Table 1) are marked with a triangle.

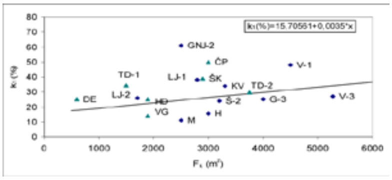

Figure 2 Fk~k1 dependence

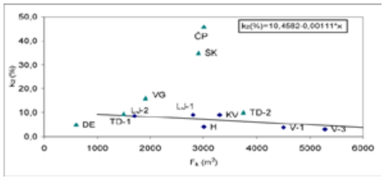

Figure 3 Fk~k2 dependence

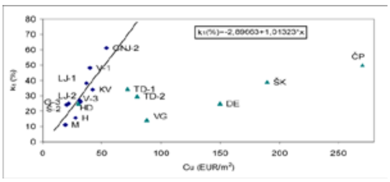

Figure 4 k1~Cu dependence

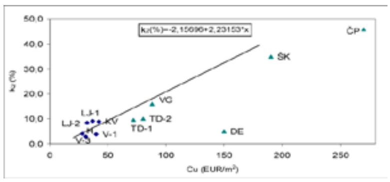

Figure 5 k2~Cu dependence

3.2 Large landslides 5280 m² ≤ F_k ≤ 60 000 m²

The total of 10 landslides were analyzed and the analysis results (Figs. 6, 7, 8, and 9) are presented as the relationship between the landslide area F_k and landslide improvement cost C_u on the one side, and influence coefficients k_1 and k_2, on the other.

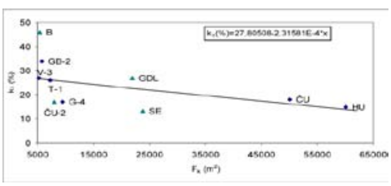

Figure 6 F_k~k_1 dependence

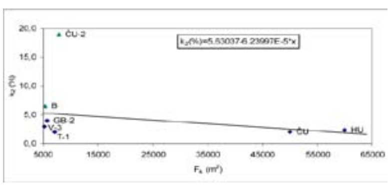

Figure 7 F_k~k_2 dependence

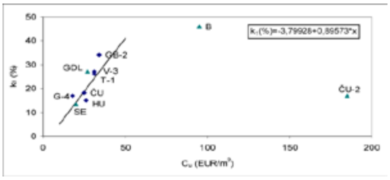

Figure 8 $k_1 \sim C_u$ dependence

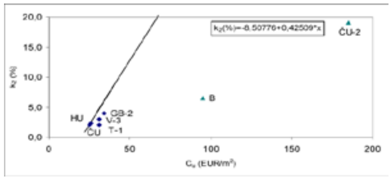

Figure 9 $k_2 \sim C_u$ dependence

3.3 Joint analysis for medium-sized and large landslides

The total of 27 landslides were analyzed and the analysis results (Figs. 10, 11, 12 and 13) are presented as the relationship between the landslide area F_k and landslide improvement cost C_u on the one side, and influence coefficients k_1 and k_2, on the other.

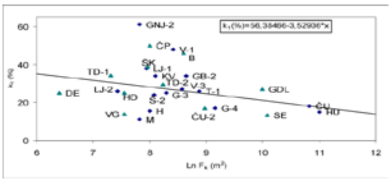

Figure 10 $F_k \sim k_1$ dependence

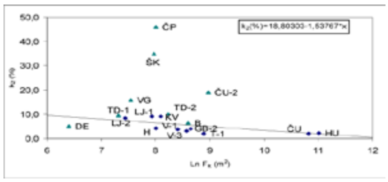

Figure 11 $F_k \sim k_2$ dependence

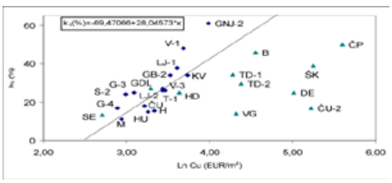

Figure 12 $k_1 \sim \ln C_u$ dependence

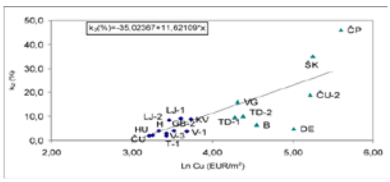

Figure 13 $k_2 \sim \ln C_u$ dependence

As the data bases are relatively small, the decision was made to increase the data base by linking the landslide groups under study. The data base for small + medium + large landslides comprises 30 data (Figures 14, 15, 16 and 17). The correlation coefficient R_2 ranges from the minimum of 0.35 to the maximum of 0.92.It may be stated that the point of intersection of tangents for the part of the curve situated within the small, medium and large landslides is located in the point corresponding to $F_k \approx 2000\ m^2$ (Fig. 14), and so it has been established that one correlation dependence is valid for the area $F_k \leq 2000\ m^2$, while an another correlation dependence - corresponding to medium and large landslides - is valid for $F_k \geq 2000\ m^2$.

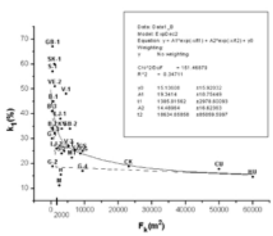

Figure 14 $F_k \sim k_1$ dependence

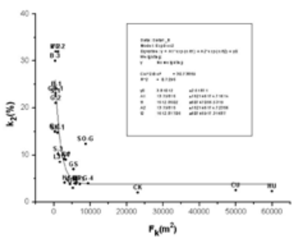

Figure 15 $F_k \sim k_2$ dependence

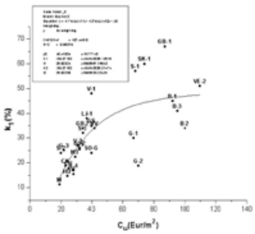

Figure 16 k_1~C_u dependence

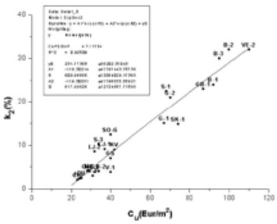

Figure 17 k_2~C_u dependence

4 Analysis of statistical diagrams for the studied correlation dependences as related to the RSK procedure

In the scope of the RSK procedure, the data bases formed separately for medium-sized and large landslides are used, based on statistical analysis presented in diagrams F_k~k_1, F_k~k_2, C_u~k_1, C_u~k_2, as a basis for selecting rational improvement measures because of great difference in price between retaining structures and drainage systems, which greatly influences the total landslide improvement cost "C_u". The RSK procedure is an iterative system in which technical solution coefficients k_1 and k_2 are selected for a particular landslide that is to be improved, and then the total landslide improvement cost C_u [EUR/m²] is read from the corresponding diagrams. The RSK procedure is then used to select the solution that, depending on "k_1" and "k_2", provides the lowest landslide improvement costs "C_u", taking into account local engineering-geological conditions, geotechnical properties, and the depth of the assumed critical failure surface.

Table 1 Results from statistical diagrams with correlational dependence between technical solutions and improvement costs

Mark	Landslide name - roadway	Landslide area	DESIGN SOLUTION				PRICE (EUR/m²)			NOTE	
			Drainage area	Retaining structures area	Drainage coefficient	Retaining structures coefficient	Drainage	Retaining structures	Total	Improvement method	Time period
		Fk (m²)	Fd (m²)	Fpk (m²)	k_1 (%)	k_2 (%)	C_d	Cpk	$C_u=C_d+C_{pk}$		
ČU-2	Čukovići-Zagreb (residential area)	7.920	1.350	1.500	17	19	35	150	185	Anchored pile structure + drainage	Designed 2005 Improved 2006
VG	Road Vugrovec-Goranec Zagreb	1.900	250	310	14	16	28	60	88	Reinforced concrete wall + drainage	Designed 2007 Improved 2008
ČP	Road Čabar-Zamost	3.000	1.500	1.400	50	46	35	235	270	Anchored reinforced concrete wall + drainage	Designed 2003 Improved 2004
DE	Road Dedići-Šestine Zagreb	600	150	300	25	5	30	120	150	Micropiles + drainage	Designed 2007
SE	Sesvetska cesta Planina Gornja Zagreb	23.800	3.176	0	13,3	0	20	0	20	Drainage	Designed 2007 Improved 2008.
GDL	Road Gornji Dragonožac -Lipnica, Zagreb	21.900	5.850	0	27	0	27	0	27	Drainage	Designed 2007
HD	Road Havidići, Velika Gorica	1.900	350	0	25	0	30	0	30	Drainage	Designed 2007 Improved 2008
ŠK	Road - shopping mall LIDL-Rijeka	2.900	1.140	1.020	39	35	70	120	190	Drainage + gabion walls	Designed 2007 Improved 2009
TD-1	Road Skokovi - Vrnograč - Bihać	1.500	516	144	34,4	9,6	32	40	72	Drainage + gabion walls	Designed 2005 Improved 2007
TD-2	Road Skokovi - Vrnograč - Bihać	3.750	1.280	380	29,7	10,1	40	40	80	Drainage + gabion walls	Designed 2005 Improved 2007
B	Road Jezero - Sanica Bihać	5.400	2.520	350	46	6,5	50	45	95	Drainage + rock toe	Designed 2004 Improved 2006
Average		*6.779*	*1.644*	*491*	*29*	*13*	*36*	*74*	*110*		

Some regular patterns have been established in the analysis of the above diagrams, with correlational dependences between technical solutions and improvement costs for medium-sized and large landslides. Table 1 gives comparison of all significant results from statistical diagrams, with correlational dependences between technical solutions and improvement costs, for the 2003 – 2009 time period, and for various retaining-structure design solutions.

5 Examples of designed and realized landslide improvement projects

5.1 Landside improvement by drainage system

Sesvetska ulica landslide

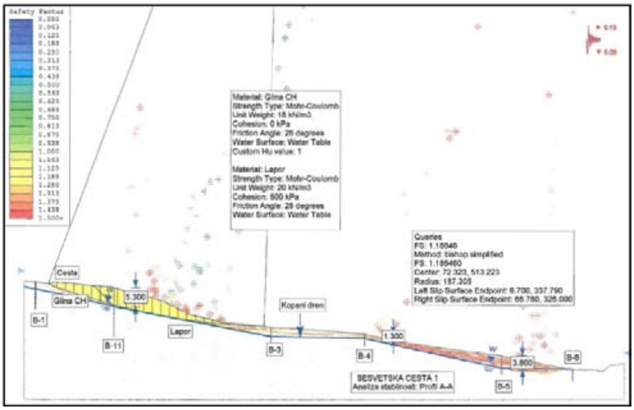

Figure 18 Stability analysis – landslide improvement by drainage system

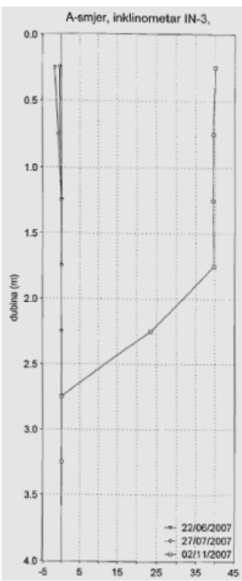

Figure 19 Inclinometer measurements

Figure 20 View of an improved landslide

5.2 Improvement of deep landslides using the anchored piling structure

Practical experience in landslide improvement has shown that two improvement methods are the most effective: drainage and retaining structures. In recent times, piles are increasingly used in many countries for the improvement of deep landslides. When piles are used, the designer is faced with some theoretical difficulties relating to the pile distribution geometry, pile positioning, and dimensioning of such structures. Active forces of soil in movement are brought into balance by reactive resistance of the non-moving mass beneath the failure surface, i.e. by increasing resistance to sliding via a pile structure, in which piles are linked together by means of a head beam. Tie beams, anchored into the stable soil or into a nearby reinforced structure, are used as a means to reduce the pile structure head movement, and to appropriately distribute pressure exerted on the retaining structure.
In the real-life example of the Sljeme foothills zone in Zagreb, the drainage system and the anchored pile structure were designed, with ties anchored into the reinforced concrete foundation slab (Fig. 21), so as to enable urban villa construction at the site of an active landslide. According to calculations, this improvement would increase the total gross price of residential space by 7 to 10 percent, which is in the concrete case quite acceptable considering the high quality and natural advantages of the locality.

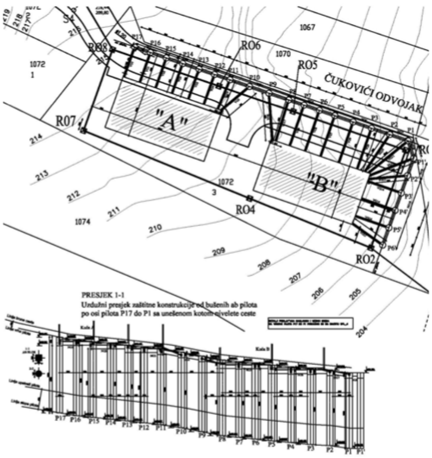

Figure 21 Plan view and cross section of the anchored pile reinforced-concrete structure as used during construction of urban villas in the Sljeme foothills zone in Zagreb

5.3 Anchored reinforced concrete wall

Road at the Čabar-Zamost Section

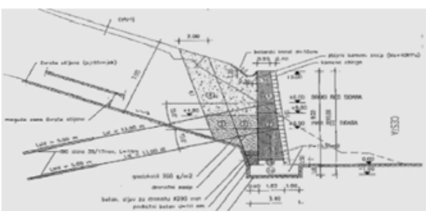

Figure 22 Design solution of an anchored reinforced-concrete wall

Figure 23 Anchored reinforced-concrete wall with the installed bottom row of anchors

6 Conclusion

A data base with 80 landslides, 50 of them already improved, was formed. Our personal experience (more than 30 years of practical work in this field) has shown that two stabilization methods should be used: drainage and retaining structures. Considering the adequacy of retaining structures in the construction and remedy of transport facilities, the emphasis is placed on retaining structures (gabion walls, reinforced-concrete walls, and piling structures) as they are one of the most appropriate landslide improvement techniques, in addition to drainage which is also regarded as a highly effective improvement method.
The rational landslide improvement method (RSK) presented in this paper enables a simple and transparent selection of rational landslide improvement solutions for medium-sized and large-sized sites; the solution is given for the level of conceptual design, and needs to be further elaborated.
It can be seen from the diagram of correlational dependences F_k~k_1 and F_k~k_2 (Figs. 14. and 15.) that over 90 percent of data are situated in the zone up to $F_k \leq 10.000$ m².
Separate schematic presentation of medium and large landslides, and joint presentation of medium and large landslides, unequivocally point to the similar character of correlational dependences established; which confirms the standpoint that the data bases can only be formed and analyzed separately, i.e. a distinct analysis for small-sized landslides, and a joint analysis for medium-sized and large-sized landslides.
The total cost of landslide improvement (Table 1) by means of drainage system and retaining structures roughly amounts to 110 €/m² for medium and large landslides. Out of the total landslide improvement cost, an average cost of improvement by drainage system amounts to 36 €/m². The proportion of landslide improvement by drainage system in the total cost of improvement roughly amounts to 33 percent. An average cost of improvement by retaining structures amounts to as many as 74 €/m², which is 67 percent of the total landslide improvement cost.

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