PREDICTION OF SLOPE FAILURE USING SEISMIC REFRACTION AND NUMERICAL MODELLING

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Introduction

Slope stability depends on many factors like weight and properties of materials. Ground water saturation and its pressure produce stresses, which have major impact on the loss of slope stability. Under such circumstances, prediction of any slope movements must involve analysis of disturbing forces from gravity, water pressure and strength of rock mass. The widely used numerical modelling and seismic surveys have been employed for this purpose. However, one has to remember that modelling is not a trivial process, as the mass sliding may result from various failure mechanisms. Seismic interpretation should also be verified by survey excavations: drillholes or trenches. The numerical modelling allows determining the factor of safety and pointing out the probable failure surface. The seismic surveys are used to confirm localisation of failure surface with its complexity.

Theoretically, according to the Mohr theory, orientation of failure surface depends on direction of the principal stresses. However, directions of these stresses and their distribution depend on stress history of a particular geological process, which led to slope formation (Ducan and Dunlop 1964; Lo and Lee 1973). Water pressure reduces effective stress and shear strength, as well. Increase of saturation in the zone of discontinuity may trigger mass movement. Under such circumstances, significance of numerical models depends on the actual situation and quality of input information such as forces due to gravity, water pressure, development of the failure process and the level of the forming sliding surface. Often, numerical modelling should anticipate a learning process, in which determination of the stress field should be compared with the actual values. Developing a method for empirical assessment of the rock sliding is needed for this purpose. It seems that seismic measurements in the landslide region may provide valuable information to be used for correction of modelling rock mass movement. Parameters describing any factor possible, including the compressive P-wave, S- wave and surface waves, are valuable in this context.

The slope movement in clay and silts is described in the following text. The subject matter of the survey and stability analysis is the embankment of the national road.

Geological conditions

The survey area in its surface part is made up of the Quaternary layer, called hereafter the overlay, and the Tertiary, Miocene formation, called hereafter the basement. The Quaternary overlay has developed in the form of clays and silts in plastic and hard-plastic state [6]. The thick of this Quaternary layer varies from 2.0m to 7.5m. The Tertiary basement is lithologically shaped in the form of dusty silts in the semi-consistent state [6]. The Miocene structures conform to the terrain morphology. The layers are inclined at the angle of about 20°. There are local changes of boundaries course in both Quaternary and Tertiary formations.

Numerical modelling

The analysis was aimed at assessing the mechanical condition of the system of road embankment – slope in the landslide area. This analysis has explained the nature of the failure process in the soil medium, indicated the course of the slide surface and described the FS factor of safety.

The calculations were made for the model constructed on the basis of the geological cross section along the longitudinal axis of the landslide in the direction close to perpendicular to the road centreline. The FS was calculated for the observed conditions and for the medium saturated with water. The effect of watering was obtained by entering depth-dependent porosity pressure in the model frame. The numerical calculation of the FS was based on the method of reducing strength parameters in the given sections (*the bracketing approach*) given by Dawson et al. (1999). FLAC v. 4.0 software based on the finite differences method was used for calculations (Flac Manual 1999). The calculations were made in the plain strain conditions. The medium model fulfilled the Coulomb-Mohr criterion. The failure process was described with the associated flow law. The assumed boundary conditions took into account the state of stress and deformation resulting from the gravitational load.

Before setting the road embankment, balance of forces was obtained in the medium. Due to the difficulties in measuring material constants of the road embankment, resulting from its inhomogeneity and varied properties, the "back analysis" was used. As a result of the observed correlation and the calculated vertical displacements, the strength parameters were determined. The other material constants were assumed on the basis of laboratory tests and correlation relationships based on the plasticity index determined with the screwed probe [7].

Results of calculations are illustrated in the following figures, under the observed and watered conditions, respectively (Fig.1).

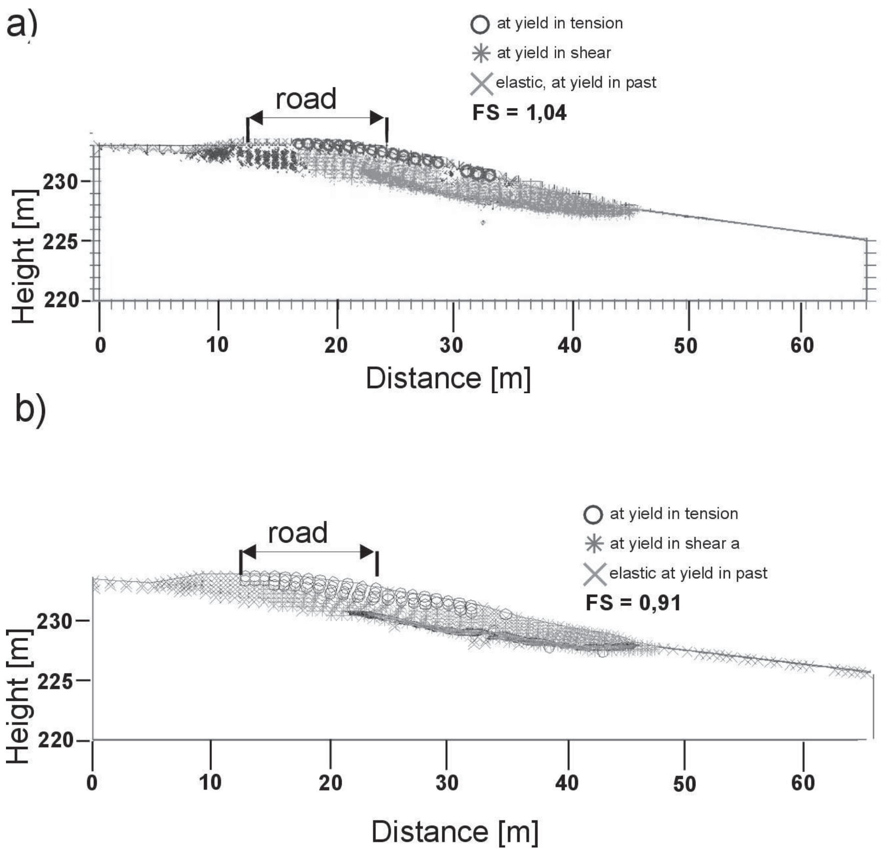

Fig. 1. Distribution of the plasticity indicators a) for the observed medium, b) for the watered medium.

Figure 1 shows the forming sliding surface from the surface below the embankment base to the embankment surface. At the pavement level, in the top part of the road embankment and locally in the slope, tensile stresses appear. This stresses intensify when the medium is watered. The failure process occurs mostly in the road embankment and in Quaternary formations. Under watering conditions of the medium, the sliding surface develops also in contact with the Tertiary basement.

The obtained results of calculations show that for the observed conditions, the model is in the ultimate state, with the FS of 1.04. With the medium saturated with water, the FS decreases to the value of 0.91. Under such conditions, the landslide occurrence is very probable.

Seismic surveys

Seismic surveys were aimed at localisation of the slide surface. Five profiles were made, of which profiles I-I’ and II-II’ ran along the landslide axis, and profiles III-III’, IV-IV’ and V-V’ were perpendicular to it. Seismic surveys were conducted with the refraction profiling technique with the 24-channel Geode (USA) seismic equipment and 14 Hz geophones. In the stage of processing and interpreting seismic data, a three-layer medium model was assumed.

The overlay showed two layers due to their different mechanical state. The calculated P wave velocity in the first overlay layer varied from 170 m/s to 540 m/s. On the basis of own experience, we can assume that this layer is made of loose soil formations, loosely compact clays and road embankment material. The depth of this layer is about 1.0 m on the average, locally increasing to 3.6 m in the basement lowering areas. The second overlay layer characterises of small variability of P wave velocity, in the range from 650 to 950 m/s. These are typical values for Quaternary formations like consistent clays and loosely consistent dusty silts. The depth of this layer varies along the longitudinal landslide axis, from ca. 1.0 m to ca. 3.0 m, locally increasing to 7.0 m in the basement lowering areas. In the third layer, the P wave velocity varies from 1550 to 1850 m/s. Locally, higher velocity occures, up to 2400 m/s. This anomaly may be related to more favourable basement consolidation. The third layer corresponds with the roof of Tertiary formations, which are formed in this area as grey dusty silts and clay slates. The interpretation is resulted in the seismic surfaces in Quaternary formations and in the Miocene roof basement showed in the figure 2.

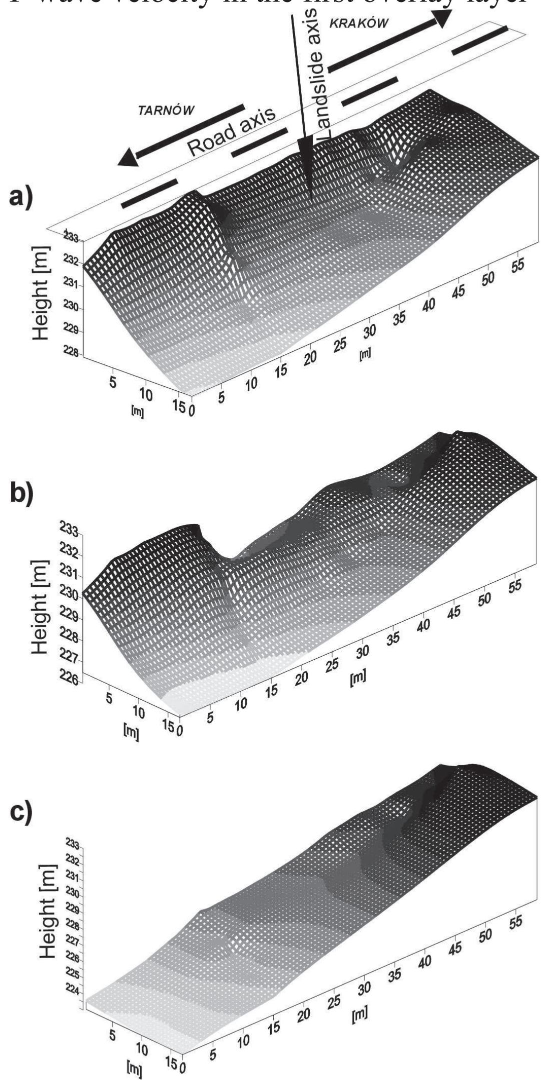

Fig. 2. The seismic surfaces a) morphology of the surface, b) within the Quaternary formations, c) within the upper part of Tertiary formations.

These surfaces were charted on the basis of the course of the boundaries determined in particular profiles. The kriging method was used to average the results. These surfaces represent the qualitative spatial picture of seismic anomalies. Local lowerings and upthrows in the direct neighbourhood of the embankment, visible in the course of the boundary between the first and the second layer may create slide surfaces (Fig. 2b). Other slide surfaces may be formed from the boundaries describing the course of the Miocene roof formations (Fig. 2c).

The seismic boundary between the second and third layers describes the boundary of the consolidated, less weathered in the upper part of Miocene formation. Significant length of the landslide suggests that the sliding surface may be located deeper and may partly run along the Miocene boundary.

It has to be noted here that the error of determination of the boundary depth under measuring conditions in the landslide area amounts up to ca. 1m.

Summarising, we have to say that the seismic boundary between the first and the second layers in the Quaternary formations separates zones of the medium with different consolidation values. It may also constitute a boundary between saturation and aeration zones in the soil medium. In the landslide area, this boundary may form the main slide surface.

Resume

On the basis of the conducted surveys, it was found out that slide surfaces develop in the road embankment, in the weakened zones of the Quaternary formations and over contact areas between the weathered and consolidated Miocene formations. The depth of the lowest surface in the Miocene formation along the embankment base is from 4.5 m to 5.5 m. Periodical activation of the slide surface is mostly due to watering.

The determined slide surfaces result from the analysis of the surface landslide forms, stability analysis made with the numerical modelling, seismic measurements and geological recognition. The results obtained provided enough information to prepare a project for securing the road embankment. These surveys confirmed the use of the methods applied and their economic effectiveness.

References

[1] Dawson E.M., Roth W.H., Drescher A., 1999, Slope Stability Analysis by Strength Reduction. Geotechnique 49(6), 835-840.

[2] Flac 4.0 Manual, 1999. Itasca Inc. Minnesota.

[3] Cruden D, Varnen D.J. 1996, Landslide types and processes of landslide investigations and mitigation Eds. Special Report 247

[4] Ducan J, Dunlop P.P 1969, Slopes in fissures stiff clays and shales. Int. Journal Soil Mechanics and Foundations Engineering . ASCE, Vol95, 467-492

[5] Lo K.Y ,Lee C,F 1973 Analysis of progressive failure in clay slopes. Proceedings 8th ICSMFE Moscow vol 1.1, 251-258

[6] Polish Norm PN-81 B-03020. Building soils, foundations bases, static calculation and design.

[7] Polish Norm PN-74 B-04452. Building soils, site investigation.