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PROBABILISTIC PROGNOSIS OF CLIFFSLIDE ALONG BALTIC SEA COAST IN POLAND

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Summary: In recent years in Poland an increasing activity of sliding process in many parts of Polish cliff coast has been observed. It has created a serious danger for all structures located nearby. In order to explain the mechanisms governing sliding process as well as to elaborate calculation stability methods appropriate for these mechanisms comprehensive investigations have been undertaken. Slope stability is usually analysed by means of deterministic approach. However, such methods are insufficient for determination of stability of cliffs and dangerous zones along the cliff coastline. In the paper a probabilistic method of cliff sliding prognosis is presented. In the method proposed soil strength parameters are assumed to be random values. Abrasive sea activity is simulated by changes of cliff profile. Numerical calculations based on the method allow for verification of cliff stability and evaluation of the range of failure zone in the inland part of cliff.

Streszczenie: W ostatnich latach obserwuje się zwiększenie aktywności osuwiskowej polskich wybrzeży klifowych. Zagrożonych zostało wiele obiektów zlokalizowanych na koronie klifów. Od kilkunastu lat prowadzi się obszerne badania zagadnienia stateczności w celu wyjaśnienia mechanizmów rządzących zjawiskami osuwiskowymi oraz opracowania metod obliczeń stateczności odpowiadających tym mechanizmom. Zazwyczaj do analiz stateczności zboczy stosowane jest podejście deterministyczne. Jednakże, taka metoda jest niewystarczająca do określenia stateczności klifów oraz stref zagrożonych utratą stateczności. W pracy przedstawiono probabilistyczną metodę prognozowania osuwisk. W proponowanej metodzie zakłada się, że parametry wytrzymałościowe gruntów budujących zbocze klifowe są zmiennymi losowymi. Abrazyjna działalność morze symulowana jest poprzez zmianę geometrii brzegu klifowego. Obliczenia numeryczne oparte na takich założeniach pozwalają na sprawdzenie stateczności zbocza oraz określenie stref na koronie klifu zagrożonych utratą stateczności.

Resume: Une activité creasante des éboulements de terre est observée dans des années récentes dans de plusieurs éndroits sur la côte polonaise. Ce processus implique des consequences serieuses pour toutes les constructions situes au voisinage. Pour expliquer le mécanisme des éboulements et établir une méthode de calcul de la stabilité appropriée à ce mécanisme une récherche a été réalisée. D'habitude, la stabilité de talus est calculée avec une approche déterministique. Cette approche reste quand même insuffisante pour la stabilité de la falaise et des zones en danger situées le long de côtes. Une méthode probabilistique de la prognose des éboulements de terres est présentée dans cette comunication. Dans la méthode proposée les paramètres de la résistance du sol au cisaillement sont assumée comme des valeurs casuelles. L'activité abrasive de la mer est simulée par les changéments de la forme de la falaise. Les calculs numériques effectués sur la base de la méthode proposée permettent une vérification de la stabilité de la falaise et aussi une évaluation de l'extent de la zone de rupture dans sa partie haute.

1. INTRODUCTION

Along almost 500 kilometres of Polish coastline one can distinguish two main forms of coast: cliffs and dunes. Cliff coast spreads out over a total distance of 100 km. Long term investigations have revealed that average rate of withdrawal of cliff coastline amounts 1 m per year reaching at some places even 2 m a year.

In recent years it has been observed a significant growth of the activity of many of Polish cliffs. It is mainly caused by abrasive sea activity and landslide processes which are strictly related to the characteristic geological profile and hydrological conditions. It resulted in serious danger for buildings and roads at some seaside resorts.

Intensive cliff landslide processes created a need to carry out detailed stability analysis for most active parts of cliff coastline together with elaboration of the method of prognosis. Such a prognosis should allow for determination of zones of potential stability loss. Subsequently, it should serve for optimal regional planning and operation within areas located nearby the cliffs.

2. MAIN FACTORS INFLUENCING CLIFFS STABILITY

The comprehensive studies of stability processes and abrasion of cliffs have shown that they are influenced by various factors among them one can distinguish the following, namely (see Fig. 1):

- ① – Hydrodynamic Baltic sea activity such as: wave generation and oscillations of sea state causing intensive scouring of cliffs toe together with sediment transport, mainly during storms.
- ② – Inconvenient geotechnical profile of cliffs with clayey courses of various thickness along which slip of soil mass takes place (roofs of clays are usually inclined towards the sea),
- ③ – Seepage forces caused by intensive groundwater flow that increase the overturning moment,
- ④ – Surface erosion of cliff slopes generated by heavy rains, winds, icing and freezing,
- ⑤ – Groundwater flow and rain waters which in terms of seepage streams increase the erosion process and saturate a zone initiating the slip.
- ⑥ – Humans activity in the urban areas located nearby causing surcharge load from buildings, influence of vehicle traffic or leakage from water supply installations.

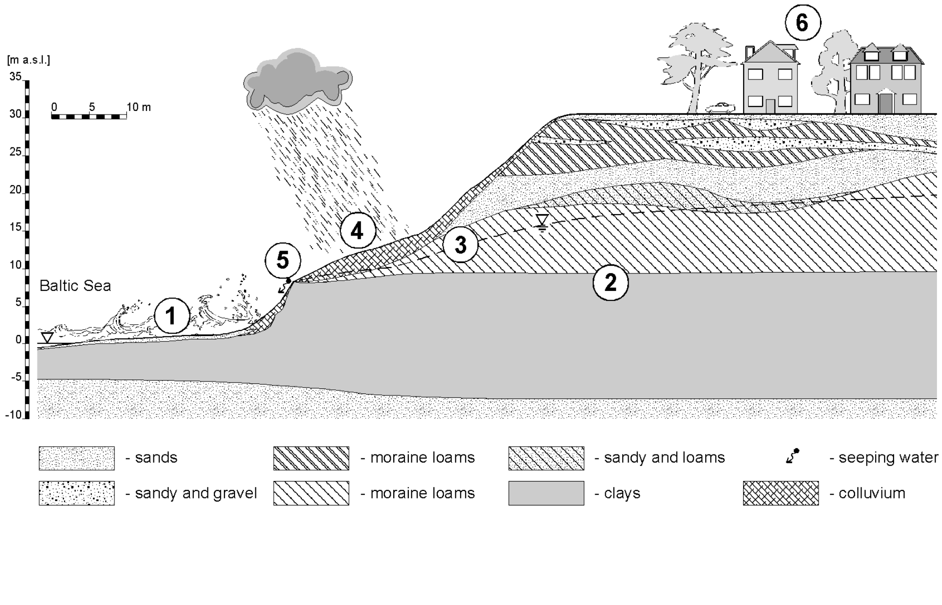

Fig. 1. Factors influencing landslide processes and abrasion of cliffs

On other hand there is also a group of factors that can improve stability of cliff slopes such as e.g. tree roots reinforcing and protecting cliff surface.

It should be clearly stated that does not exist the universal general method of the analysis of cliff stability that would comprise all mentioned factors. However, due to the fact that some of the influences are unpredictable and unmeasured, the calculation method should consider most important factors.

3. METHOD OF ANALYSIS

There are several methods of stability analysis which make use of probabilistic techniques. First of them have been developed in early thirties. However, majority of the methods regards scarps and slopes built of homogeneous soil what makes these methods of small usefulness for the stability analysis of cliffs which are usually characterised by complex geological structure.

Among proposed methods for layered slopes one can distinguish two main groups based on Bishops approach:

– groups based on the procedure assuming a deterministic geotechnical profile with statistically uniform layers the physical and mechanical parameters of which are described by random characteristics. Such method has been developed by Baker and Horne (1977) and later improved by Tobutt and Richards (1979),
– solutions taking into account variability of layer thickness resulting in variable geotechnical profile.

The procedure proposed in this paper has its roots in the first group of the methods. In the stability analysis the following assumptions has been implemented:

– the calculations are made for deterministically determined plain profile obtained on the basis of geological analysis of *in situ* investigations and laboratory tests,
– stability analysis is based on Bishop's and Nonveiller's simplified approaches for circular and arbitrary slip surfaces, respectively,
– at least one of the layers is described by random strength parameters in terms of two-dimensional correlative random variable for (ϕ,c), where ϕ and c denote angle of internal friction and cohesion, respectively.

The analysis has begun from choosing the most active and typical parts of Polish cliff coastline. In order to recognise the geometry and geology of cliffs and to determine the values of physical and strength parameters, very comprehensive and detailed *in situ* and laboratory investigations have been carried out.

The results of laboratory tests have been next subjected to statistical analysis. It has been assumed that strength parameters i.e. angle of internal friction ϕ and cohesion c are dependent correlative random variables

In the slope analysed several layers can be described by random parameters which in turn can be presented in terms of random field in the form of two-dimensional random variable **W[Φ,C]** where **Φ** and **C** denote random variables of friction angle and cohesion, respectively. The numerical realisation of random variable **W** was based on the procedure proposed by Wilde (1981) which makes use of pseudo random generators.

Data regarding cliff geometry, properties of soils building the slope together with generated files of random variables are the basis for stability calculations.

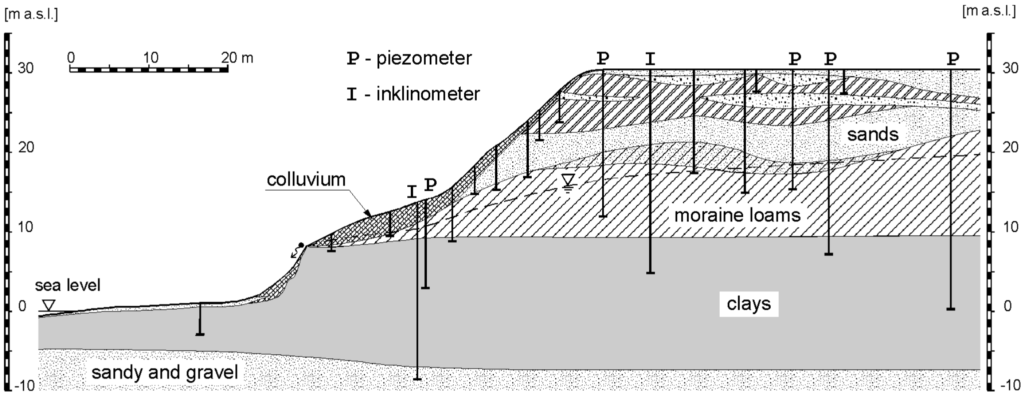

Fig. 2. Scheme of borings for characteristic cliff profile (Jastrzębia Góra cliff, km. 134.2)

As it was already mentioned the analysis is based on simplified method of slices. Calculations were carried out in terms of numerical codes which were searching for minimum stability factor taking into account the randomness of strength parameters. The calculated minimum stability factors corresponded to critical slip surfaces.

For every generated couple of random variable **W** the calculated minimum stability factor F_{min} was related to one realisation of random variable $\mathbf{F_{min}}$.

During searching for critical slip surface corresponding to minimum stability factor it has been assumed that subsequent analysed circular surfaces run through a given point located on the top of cliff. The point was next being moved with the assumed step ΔK, inland. For subsequent positions of the point the computer was calculating subsequent realisations of random variable $\mathbf{F_{min}}$. As a result of calculations sets of minimum stability factors for a given position of the point were obtained.

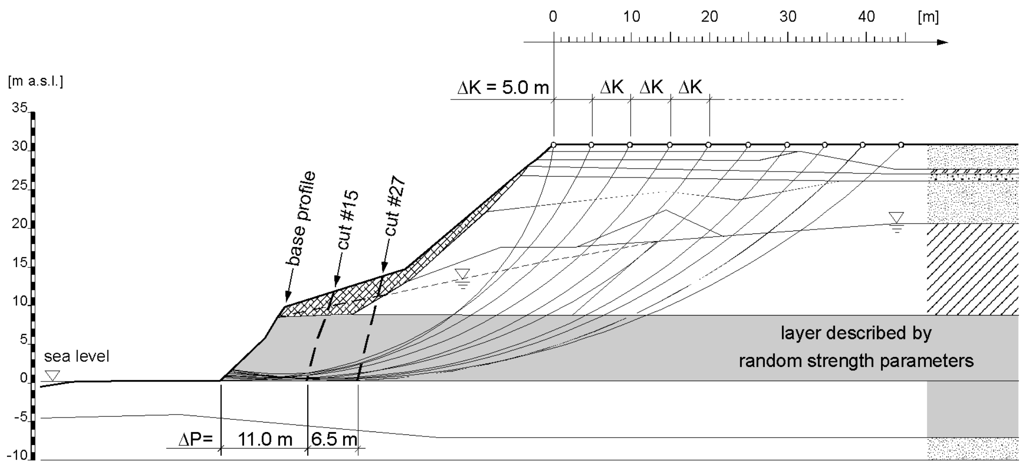

Fig. 3. Calculation scheme for the ΔK step assumed and changing cliff geometry

In order to model the abrasive character of sea activity the calculations have been repeated for changing geometry of cliff toe corresponding to progressive shortening of the abrasive threshold. It has been simulated by successive cutting of cliff toe in the form of slides of the width ΔP (Fig. 3).

Change of the cliff geometry allowed for stability calculations for subsequent phases of progressive abrasion of the cliff due to destructive sea activity. Confrontation of changing geometry with the average rate of abrasion based on long term observations (Subotowicz, 1982) resulted in the prognosis of the development of landslide processes for the analysed part of cliff.

The calculations enabled the determination of failure probability p_f for specified points the critical slip surfaces were running through. The failure probability can be expressed by the following formula:

$$p_f = P(F < N) = \int_{-\infty}^{\infty} \left[\int_{-\infty}^{F=N} f(N)\, f(F)\, df \right] dN \,.$$

Due to difficulties in determining a joined probability distribution described by Eq.(1) it has been assumed that F_p will be determined in terms of deterministic values varying between 1 and 1.5 with step 0.1. Particular values of F_p reflect various safety criteria. In Fig. 4 are shown some results of calculations of cliff failure probability as a function of a distance from cliff crest edge.

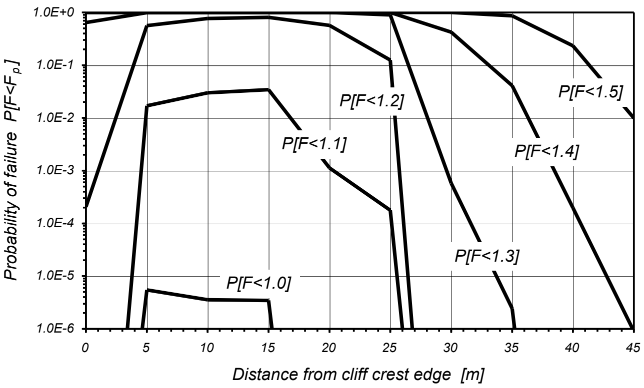

Fig. 4. Probability of stability loss as a function of a distance from crest edge (example)

4. CALCULATION RESULTS

In the case of probabilistic analyses of stability more rational estimation of slope stability can be performed including scatter of geotechnical parameters, randomness of the system of layers or other random factors.

However, as in the deterministic approach it is required to establish ultimate values. The range of postulated values is quite wide (see Wu and Kraft, 1970; Alonso, 1976; Matsuo and Asaoka, 1976). They propose to take values of probability of stability loss between 10^{-6} to 10^{-1}

whereas Meyerhof (1970) and Harr (1977) suggest one single value 10^{-3} and Schultze (1979) $p_f = 10^{-2}$.
Taking into account the following:

– calculations based on Bishop's method, for which the minimum ultimate stability factor $F_u = 1.3$,

– specified procedure of stability calculations in which the random variable of F_{min} corresponds to slip surfaces running through the specified point located on the top of cliff,

– comparison of the field observations with stability calculation results,

– suggested in the literature ultimate values of failure probability criterion,

it has been proposed to take the value of ultimate stability factor to be $F_u = 1.3$ and the probability level $p_f [F<F_p = F_u = 1.3] = 10^{-3}$.
For specified ultimate values the analysis of probability plots in a function of a distance from the crest edge (see Fig. 4) reduces the problem to searching for zones of potential stability loss.

Practical procedure to determine such zones has been presented for Jastrzębia Góra cliff geotechnical profile (km. 134.2) for base profile and two cuttings of cliff toe (Fig. 5).

Stability calculations have been carried out assuming constant thickness of colluvium. Subsequent cuttings of cliff toe do not influence the geometry changes in any other part of cliff.
In general, both geometry of colluvium mass as well as its physical and mechanical properties vary in time. However, consideration of these changes into more general analysis is a very difficult task due to the following factors:

– spatial heterogeneity of physical and mechanical properties of soil building the colluvium,

– frequency and intensity of rainfalls influencing the changes of colluvium moisture content,

– influence of vibrations due to sea waves motion (particularly during heavy storms).

Some studies on this problem did not give convincing solutions. In order to verify the problem regarding the estimation of the influence of colluvium thickness on stability calculations based on probabilistic approach additional analysis has been carried out. This problem seems to be important due to direct impact of thickness changes on the equilibrium of shear and weight forces.

The analysis concerned stability calculations for two extreme cases:

– full colluvium thickness corresponding to base profile – denoted as "1k",

– the lack of colluvium – denote as "0k".

Changes of geometry of Jastrzębia Góra km 134.2 cliff profile have been shown in Fig. 6. whereas corresponding calculation results in Fig. 7.

As it can be seen from Fig. 7 the maximum increase of the range of a zone of potential failure due to changes of colluvium thickness amounts 15%. Several cases analysed have shown that these changes can cause the increase of the range of such zone even 40%.

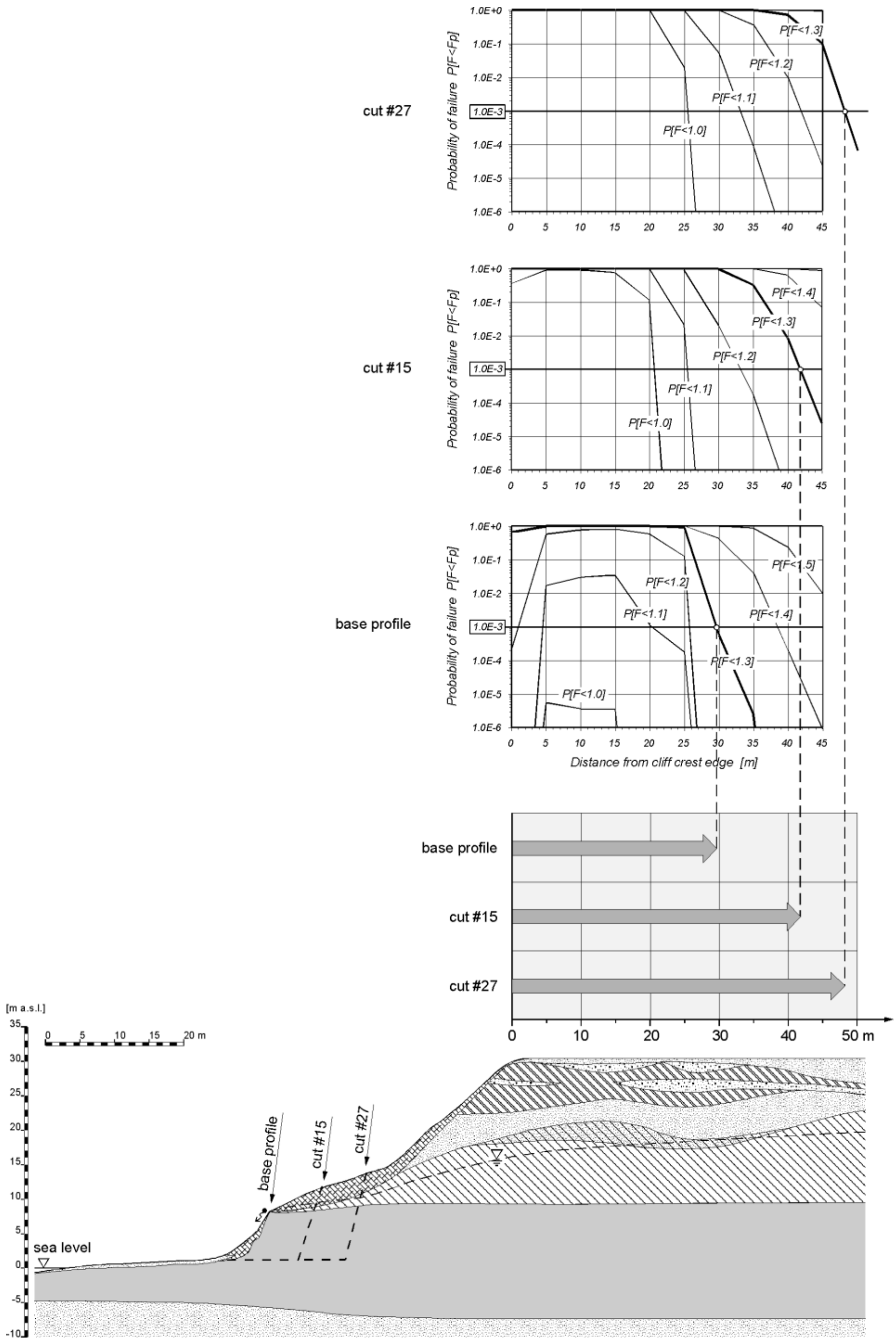

Fig. 5. Determination of zones of potential failure for Jastrzębia Góra cliff, km 134.2

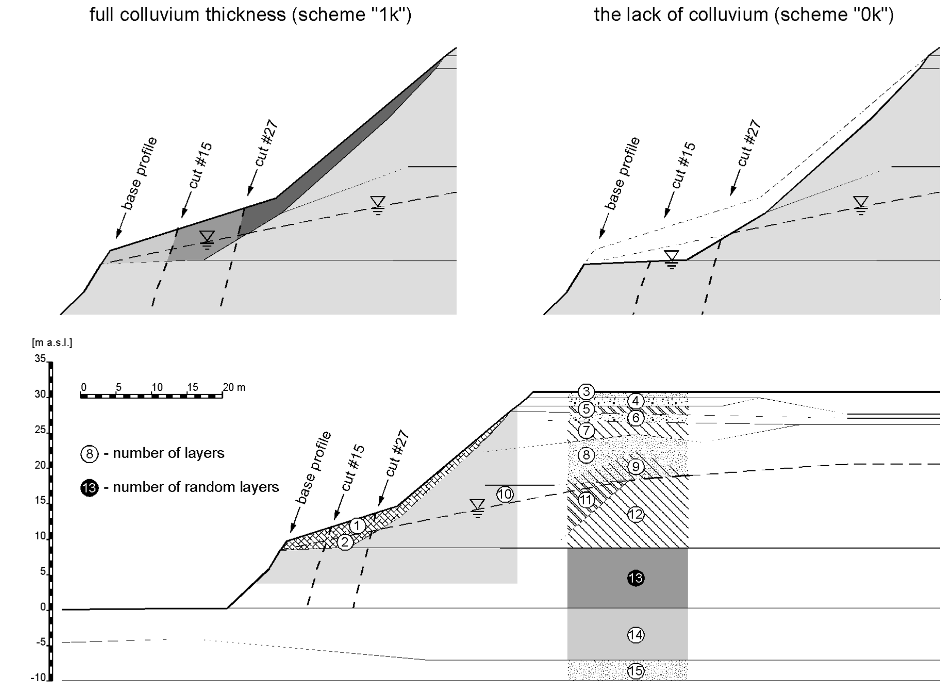

Fig. 6. Assumed schemes of geometry changes caused by decreasing thickness of colluvium (Jastrzębia Góra km 134.2, random layer – 13).

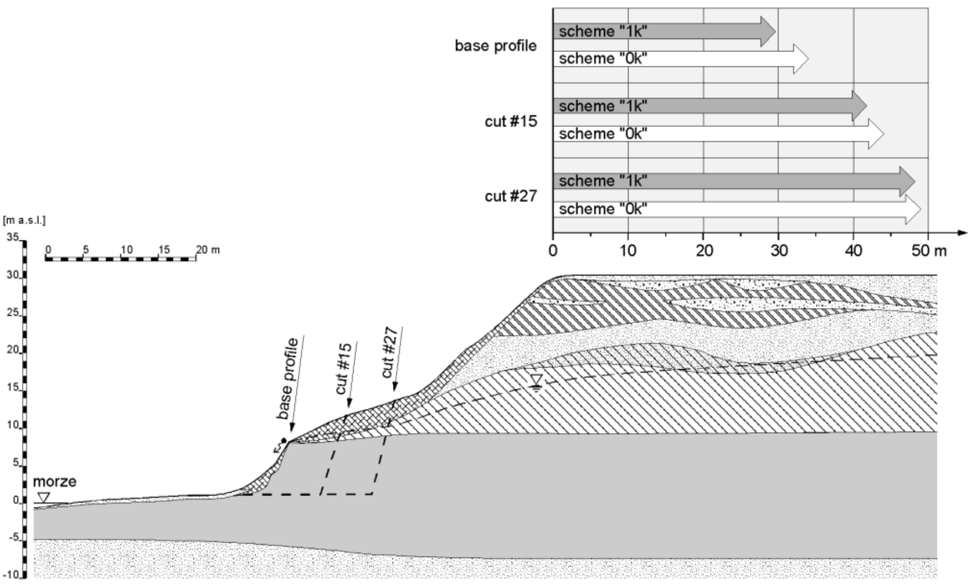

Fig. 7. Determination of zones of potential failure in Jastrzębia Góra, km 134.2 for changes of colluvium thickness.

5. CONCLUSIONS

In the paper the method of stability calculations with probability elements has been presented. The method has been developed for stability analysis of Polish cliffs that in recent years were subjected to intensive landslide processes. Probability method proposed enables stability prognosis significantly increasing the possibilities of Bishop's deterministic method. In the analysis it is necessary to assume various schemes of the cliff geometry which take into account abrasive sea activity and changes of colluvium thickness. Including the influence of this thickness revealed the change of zone of potential stability loss even 40%.

The methods allows for reliable estimation of stability when one can assume the failure probability criterion higher than 10^{-5}. For lower probability criteria ($p_f \leq 10^{-5}$) other probabilistic methods should be applied.

The analyses performed show that simulations of destructive sea activity can be carried out using 2 to 4 cuts of the abrasive threshold.

The method proposed is particularly effective in the stability analysis of cliffs with clearly formed abrasive threshold built of cohesive soil (mostly clay) of several meters thick. In the case of little thickness (below 1m) of layer responsible for initiation of landslide phenomenon the analysis should be complemented by calculations for arbitrary slip surface.

The possibility of determination of zones of potential failure makes the analysis appropriate for development of cliffs and design of protection system of coastline and cliffs itself.

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