Assessment of slope stability influenced by vegetation cover and additional loads applied

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Abstract: Assessment of slope stability influenced by vegetation cover and additional loads applied. The article presents the results of research conducted in order to create nomographs allowing assessment of slope stability. The proposed recommendations involve graphs and charts, where factor of safety (FOS) is computed in accordance to six different characteristics: slope height and angle, slope surface vegetation cover, applied surcharge, position of water table, soil mechanical conditions. For the purpose of the research several geotechnical models and approaches were used and became a basis for developing simplified method of predicting the failure of natural and engineered slopes. The advantage of the solutions presented is their simplicity of use; as further FOS calculations are not required during the complex assessment of slope stability.

Key words: slope failure, bio-engineering, charts, factor of safety

INTRODUCTION

Slope instability and slope failures are significant problems in geotechnical engineering, that engineers throughout the world are dealing with. There is a variety of slope failure types, all of them mainly caused by forces associated with ground water flow and gravity, and occur as the result of shear failure or soil liquefaction (Abramson et al. 2002). There have been a great number of slope stability analyses undertaken by engineers. All of these analyses are conducted using very complex calculation methods, which require time to achieve the expected results. Furthermore, the site investigation procedures required are very expensive. To avoid such issues throughout the last two centuries there have been developed several slope stability charts, including Bishop’s, Taylor’s or Spenser’s charts (Abramson et al. 2002). Those charts were developed mainly for high structures, however for small slopes that kind of research is innovative and could produce valuable results. The charts for slope stability assessment, prepared in the paper, will help to assess the factor of safety for slopes up to 10 m in height, in both natural and artificial stability conditions. The charts consider different soil and hydrological conditions, different slope angles and heights, and the influence of vegetation and surcharge applied. Nowadays, when economic factors are taken into consideration in an investment planning, it is important
to find new cost effective investigative tools or guides, which can help to reduce investment costs whilst giving reliable slope stability assessment.

MATERIALS AND METHODS

The proposed charts for assessment of slope stability in small earth structures, which are the final output of the study, were developed by considering several classic methods of slope stability analysis including Fellenius, Bishop, Janbu, and Taylor from which the factor of safety is obtained. The first three methods are based on the limit equilibrium technique, which is applicable in stability assessment by using the method of slices, whereas Taylor’s method is based on the total stress analysis. The reason for choosing these methods is that they present the most common techniques of calculating the stability of slopes (Smith and Smith 1998, Abramson et al. 2002, Craig 2004).

The factor of safety for the charts of this research was evaluated for six varying parameters. These are: slope height (\(H\)), slope angle (\(\beta\)), soil parameters (\(\gamma\), \(c\), \(\phi\)), groundwater table position, position and weight of surcharge and vegetation cover.

These parameters were chosen as they always occur as crucial ones during site investigations into the causes of slope failure (Abramson et al. 2002). As the guidelines were developed for small earth structures, the factor of safety was computed for several typical values of height (2, 4, 6, 8 and 10 m). It was assumed after reviewing the literature (i.e. Smith and Smith 1998, Abramson et al. 2002, Craig 2004, Koda 2011), that for small structures these values are most common, and vary within the proposed range.

The slope angles (\(\beta\)) used to develop graphs and charts are 30°, 40° and 50°. The proposed angles present the range of values which are very common design of cuttings, road embankments or levees, not exceeding 10 m in height (Smith and Smith 1998, Osiński 2010 and 2012). The next parameter for which the stability of slopes was evaluated is the soil-water condition. Parameters of soil are crucial to obtain the factor of safety (Zabielska-Adamska 2006), and they determine the earth mass movement as the soil structure is very sensitive to any kind of hydrological or stress changes. There are three fundamental soil characteristics required for calculating the stability of slope: unit weight – \(\gamma\) (kg/m³), cohesion – \(c\) (kPa), internal friction angle – \(\phi\) (°).

The soil used in constructing earth embankments has a typical range of unit weight values from 18 to 22 kg/m³, this range was used in the research to obtain the factor of safety. The next parameter is the cohesion, for which values were selected to be from 0 to 50 kPa, as this range is representative of the less stable slopes. The third parameter, which is necessary to obtain the factor of safety, is the angle of internal shear resistance (\(\phi\)). The values in the study varies from 0° (saturated cohesive soil) to 50° (compacted coarse soil), as this range is representative of small earth structures stability.

Another factor that influences the stability of the slope is the groundwater. Most existing charts describe the existence of groundwater as a pore water ratio (\(r_w\)), which is expressed as:
In existing stability charts the procedure to obtain the $r_u$ is complex, requiring a number of additional calculations. For this reason the nomographs were designed in according to the depth of the water table. There are two ranges of values for the depth of the groundwater table, 0.5–1 and 1.5–3 m. Below the depth of 3 m the presence of water has been found not to influence the factor of safety (Osiński 2010). To make the calculation as precise as possible, and to predict any scenario of groundwater flow, the GeoStudio computer programme was used. It allows the creation of groundwater flow models through the structure by using flow net method (Cholewa and Baran 2013), which provides answers for the pore water pressure at every point of the considered structure (Osiński 2010).

The next parameter considered was the surcharge (Figs 1 and 2). On field sites it often happens that additional loads are found on the slopes. This can be dangerous, but unfortunately is very common. In terms of this kind of situation, in the nomographs two positions of 9-meter-long surcharge of 15 kN in weight were considered on the top and at the bottom of the slope (Figs 1 and 2). The investigation conducted by the authors showed that smaller values of surcharge had little effect on the stability of slope. The proposed load of 15 kN at a length of 9 m (2.15 kN/m, which could be expressed as 200 kg/m) showed significant changes in the factor of safety ($FOS$) were evaluated for slopes with parameters which were initially in the range of values between 1
and 2. This is to show how the factor of safety varies in extreme conditions, when collapse of the slope is most probable.

Another parameter, which also has a significant impact on slope stability, is the vegetation cover (Fig. 3). By using the Slip4EX spreadsheet (Greenwood 2006), it is possible to assess how the distribution and type of vegetation can influence the factor of safety. In this study, slopes with low value of the factor of safety were considered and assessed.

FIGURE 2. Surcharge applied at the bottom of slope (GeoStudio computations)

FIGURE 3. Effect of vegetation cover (FOS calculated by using Slip4EX, the geometry of the failure surface computed by GeoStudio2007)
to see how vegetation cover affected the resulting stability. In Slip4EX the factor of safety can be calculated by using several equations developed by Greenwood (2006), however in this study the Greenwood General Method was used, as it presents similar characteristics to other methods used in this study. The model is described by equation where all the parameters indexed with “v” derives from changes caused by presence of vegetation cover on slopes:

\[
F = \frac{\sum [(c' + c')l + [(W + W_v)\cos \alpha - (U + \Delta U_v)l - (U' - \Delta U_{v})]\sin \alpha - D_v \sin \alpha (\alpha - \beta) + T \sin \Theta \tan \varphi]}{\sum [(W + W_v)\sin \alpha + D_v \cos (\alpha - \beta) - T \cos \Theta]}
\]

where:
- \(F\) (-) – factor of safety,
- \(c'\) – increase in cohesion (kPa),
- \(W_v\) – increase in weight of slice (kN),
- \(\Delta U_v\) – increase in water force (m),
- \(D_v\) – wind force (kN),
- \(T\) – tensile root force (kN),
- \(\Theta\) – angle between direction of \(T\) and base of slip surface (°).

Examples of the results obtained from the research are presented in Tables 1, 2 and 3. The factors were used as a basis for developing stability charts, for which an example is presented in Figure 4. To increase the value of the nomographs, the slope stability analyses were conducted by using different methods available in the literature, which were compared and assessed according to forces acting during the slope failure and the geometry of slip surface.

### TABLE 1. Results of factor of safety obtained from the Bishop method (change in height)

| Slope parameters | \(H = 10\) m, \(\beta = 30°\) | \(H = 6\) m, \(\beta = 30°\) |
|------------------|--------------------------|--------------------------|
| Soil parameters  | \(\gamma = 20\) kg/m³, \(c = 30\) kPa, \(\varphi = 10°\) | \(\gamma = 20\) kg/m³, \(c = 30\) kPa, \(\varphi = 10°\) |
| Depth of water table | non | 0.5–1 m | 2–3 m | non | 0.5–1 m | 2–3 m |
| \(FOS\)          | 1.574 | 1.270 | 1.403 | 2.180 | 1.865 | 2.003 |

### TABLE 2. Changes in factor of safety according to surcharge applied (the Bishop method)

| Slope parameters | \(H = 10\) m, \(\beta = 40°\) | \(H = 6\) m, \(\beta = 30°\) |
|------------------|--------------------------|--------------------------|
| Soil parameters  | \(\gamma = 18\) kg/m³, \(c = 30\) kPa, \(\varphi = 10°\) | \(\gamma = 20\) kg/m³, \(c = 20\) kPa, \(\varphi = 10°\) |
| Position of surcharge (15 kN) | no surcharge | top of the slope | bottom of the slope | no surcharge | top of the slope | bottom of the slope |
| \(FOS\)          | 1.439 | 1.330 | 1.532 | 1.626 | 1.456 | 1.823 |

### TABLE 3. Changes of factor of safety according to vegetation presence (the Greenwood method)

| Slope parameters | \(H = 10\) m, \(\beta = 40°\) | \(H = 8\) m, \(\beta = 40°\) | \(H = 6\) m, \(\beta = 40°\) |
|------------------|--------------------------|--------------------------|--------------------------|
| Soil parameters  | \(\gamma = 18\) kg/m³, \(c = 10\) kPa, \(\varphi = 20°\) | \(\gamma = 18\) kg/m³, \(c = 10\) kPa, \(\varphi = 20°\) | \(\gamma = 18\) kg/m³, \(c = 10\) kPa, \(\varphi = 20°\) |
| Presence of vegetation (veg) | no veg | no veg | no veg | no veg | no veg | veg |
| \(FOS\)          | 1.010 | 1.140 | 1.130 | 1.260 | 1.360 | 1.560 |
Slope parameters: $H = 6 \text{ m}$, $WT = 0.5–1 \text{ m}$, $\beta = 40^\circ$, $\gamma = 18 \text{ kg/m}^3$, $c = 20 \text{ kPa}$, $\phi = 20^\circ$

FIGURE 4. The example of slope stability chart
The employment of computer software, such as GeoStudio2007, AutoCAD and Slip4EX, were essential for the research. These programmes appeared to be very useful, moreover in some cases even crucial, i.e. computing the factor of safety for slopes with vegetation cover. Each of the software packages played a different role in the research development, however a combination of the three programmes was more efficient (Osiński 2010).

RESULTS OF THE RESEARCH

Evaluation of the methods used in the study

One of the objectives of the study was to select the method from which the charts would be developed. The Bishop’s method was selected to conduct further calculations. Table 1 presents examples of the calculations for the factor of safety for different slope parameters using Bishop’s method. Several methods were considered in this study to obtain slope stability results. All of them are numerical models, where the method of slices or total stress analysis is used. The comparison of methods was conducted to show differences in the computed results, to prove that different assumptions for vertical and horizontal forces influences the results, and finally to decide which method was the most accurate in terms of consideration of interslice forces and geometry of the failure surface. The advantages and disadvantages enable the authors to conclude that the Bishop’s (simplified) method is the most reliable and appropriate for the study, in terms of the interslice forces considered in the method, application to different geometry of the failure surface, the reliability of results, and application in different parameter of soil (no limitation for cohesive or granulated materials).

The influence of surcharge applied and vegetation cover on slope stability

The next objective of the research was the investigation of how the factor of safety changes when different natural and artificial parameters were considered. These parameters are: slope height, slope angle, soil parameters, position of water table, position of surcharge applied and slope vegetation cover. The influence of the first four factors has been already presented in Table 1 while the surcharge and vegetation cover is presented in the Tables 2 and 3, respectively. The complete presentation of results (graphs and charts) can be found in Osiński (2010).

The next factor considered in the research was the vegetation effect. The assessment of slope stability according to the presence of vegetation was evaluated by using the Greenwood’s method (Greenwood 2006, Osiński 2010). An example of the results is presented in Table 3.

Stability charts for the slope stability assessment

The slope stability charts were designed on the basis of the results presented in the previous section, where the factors of safety for different slope parameters were calculated. The slope height and angle, soil parameters (γ, c, φ), and position of water table were considered. To obtain the factor of safety from the slope stability chart (Fig. 4), steps listed bellow should be followed:
Step 1. Defining the problem. All required parameters of the slope \((H, \beta, \gamma, c, \phi, WT)\) have to be collected from site investigation.

Step 2. Appropriate stability chart has to be chosen.

Step 3. Soil parameters \((\gamma, c, \phi)\) has to be related to the supportive table.

Step 4. The soil property number (SPN) has to be read off.

Step 5. Soil property number (SPN) has to be related to the X axis.

Step 6. From the legend on the right side of the graph the adequate line, which refers to the height of slope considered, has to be chosen.

Step 7. Having chosen the soil property number (SPN) and the line presenting the slope height, the intersection of these two on the graph, enable the user to read the factor of safety for considered slope from the Y axis.

DISCUSSION

Stability charts

The existing slope stability charts presented in this study consider slope height and angle, different soil parameters \((\gamma, c, \phi)\), and hydrological conditions. As mentioned previously, slope stability charts have already been developed. However, the nomographs developed in the study consider additional parameters (surcharge, vegetation). They provide basic information as to how the stability can be improved and furthermore they do not require complex, additional calculations to obtain the final results.

Charts available in literature (Smith and Smith 1998, Abramson et al. 2002, Craig 2004, Osiński 2010) and stability charts, i.e. the Bishop’s and Morgenstern’s chart, are related especially to dams, and do not provide sufficient information of stability assessment for a wide range of values of soils parameters. To obtain the factor of safety, the calculation formula has to be used, and moreover the stability related to the hydrological condition can only be assessed if the pore pressure coefficient is known. The same condition is in Michałowski’s charts (2002). The \(r_u\) is the parameter which is difficult to obtain, as it requires knowledge of flow net method procedures (complex in drawing and calculating) or at least familiarity with geotechnical computer programmes. The nomographs presented in this paper enable users to obtain the factor of safety for saturated soil, by knowing the position of the water table, which can be assessed by borehole observations, without the need for expensive tools such as specially equipped piezometers. Worth mentioning is the values proposed in the nomographs could be easily interpolated. The flow net method, to define the position of the water table and find parameters of pore water pressure of saturated soil, was used by the authors. That is why the factor of safety is easier to obtain from the tools developed in this study. Another advantage is that any further calculations are not required. The same advantages apply compared with other existing charts. Spencer (Abramson et al. 2002) uses pore pressure coefficient to present hydrological conditions, just like Janbu (Craig 2004), but he additionally requires the depth and shape of
slope failure to be defined, which can be difficult to obtain, as this issue requires good geotechnical knowledge. It is crucial for obtaining reliable results and has to be done very carefully. Other existing charts are those developed by Hoek and Bray (1981). They are very useful but the results for the factor of safety can only be obtained after complex and time consuming iterative calculations, which make the charts difficult to use.

**Surcharge effect**

Most of the existing in literature stability charts do not refer to such parameters as slope vegetation cover or surcharge effect. There are only Janbu’s charts which are developed according to the additional load applied to the slope. Janbu in his charts introduces the reduction factor for surcharge which is not an appropriate expression. Statement of surcharge effect is provided to give the user an idea of how the stability of the earth structure can vary when overburden is applied in different position. It shows how the slope can behave when, for example, waste is deposited on top of it, or simply to give an idea of how to avoid instability by applying, for example, gabions at the toe of the structure.

**The effect of the presence of vegetation**

The presence of vegetation was the next parameter on which the research was conducted. It shows how in a basic way the value of the factor of safety can be increased, and how important it is to remember that vegetation can greatly influence slope stability (Greenwood et al. 2004, Koda and Osiński 2011 and 2012). For randomly chosen soil parameters (to avoid biased selection), with a bare slope surface the dimension of failure shape were measured and fed into the Slip4EX spreadsheet. The research was focused on distribution, weight and tensile root strength parameters of plants, rather than on selecting specific species of vegetation. The characteristics of the root system for the analysed cases were collected from Greenwood et al. (2004) and Koda et al. (2013). Research on the influence of vegetation showed that it can be one of the effective methods of slope stability improvement, in terms of cost and efficiency. However, this statement is very debatable (Greenwood et al. 2004). In some cases it is proven that the presence of vegetation can negatively influence slope stability.

**CONCLUSIONS**

The aim of the project was to develop charts and graphs to assist in the design procedures for building safe of small earth structures, such as dams up to 10 m in height, levees, road embankments and terraces. The existing charts are mainly focused on larger slopes (height more than 10 m), and furthermore their functionality can be improved. The tools developed in this study provide simplicity and accuracy in slope stability assessment. By using computer-aided methods it is claimed that the results are precise and reliable. Moreover, the methodology that has been developed made the charts simple to use, where making any further assumptions or calculations are excluded. This is why these nomograms are also aimed at engineers who are less familiar with geotechnics.
The essential part of the research is that the assessment was undertaken according to a variety of natural and artificial stability influencing factors, which significantly increased the value of the nomographs. The research conducted presents very useful information, such as how surcharge applied at the top or bottom of the slope can significantly change stability. It has also been shown that a simple activity, such as vegetation establishment, can increase the factor of safety by as much as 20%. All of these reasons make the presented charts unique and innovative. By using a simple method of presenting the results, creating simple graphs and tables, every user is able to explore these nomographs in a real and professional, geotechnical way.

REFERENCES

ABRAMSON L.W., SUNIL SHARMA T.L., BOYCE L.M. 2002: Slope Stability and Stabilization Methods. 2nd ed. John Wiley and Sons, New York.

CHOLEWA M., BARAN P. 2013: Modeling of permissibility flow in embankments formed from ash-slag mixture. Annual Set of Environment Protection 5: 479–491.

CRAIG R.F. 2004: Craig’s Soil Mechanics. 7th ed. Spon Press, London.

GREENWOOD J.R. et al. 2004: Assessing the Contribution of Vegetation to Slope Stability. J. of Geotech. and Geoenviron. Engin. 157 (4): 99–208.

GREENWOOD J.R. 2006: SLIP4EX – A Program for Routine Slope Stability Analysis to Include the Effects of Vegetation, Reinforcement and Hydrological Changes. Geotech. and Geol. Engin. 24 (3): 449–465.

HOEK E., BRAY J.W. 1981: Rock Slope Engineering. 3rd ed. Institution of Mining and Metallurgy, London.

KODA E. 2011: Landfill stability under reclamation and pollutant transport using the observational method. Warsaw Univ. of Life Sci. – SGGW. [Stateczność rekultywowanych składowisk odpadów i migracja zanieczyszczeń przy wykorzystaniu metody obserwacyjnej. Rozpr. Nauk. i Mon. Nr 384 (hab.). Wyd. SGGW, Warszawa] [in Polish].

KODA E., OSIŃSKI P. 2011: Slope erosion control with the use of fly-ash and sewage sludge. Ann. of Warsaw Univ. of Life. Sci. – SGGW, Land Reclam. 43 (2): 101–111.

KODA E., OSIŃSKI P. 2012: Improvement of slope stability as a result of combining diverse reinforcement methods. Acta Sci. Pol. Arch. 11 (1): 3–14.

KODA E., PACHUTA K., OSIŃSKI P. 2013: Potential of Plant Applications in the Initial Stage of the Landfill Reclamation Process. Pol. J. of Environ. Stud. 22 (6): 1731–1739.

MICHAŁOWSKI R.L. 2002: Stability charts for uniform slopes. J. of Geotech. and Geoenviron. Engin. 128 (4): 351–355.

OSIŃSKI P. 2010: Guidelines for assessment of slope stability in small earth structures. MSc Thesis, Cranfield University.

OSIŃSKI P. 2012: Ocena stateczności skarp małych budowli ziemnych. Inż. Mor. i Geotech. 4: 478–482.

SMITH G.N., SMITH I.G. 1998: Elements of Soil Mechanics. 7th ed. Blackwell Science, London.

ZABIELSKA-ADAMSKA K. 2006: Shear strength parameters of compacted fly ash – HDPE geomembrane interfaces. Geotextiles and Geomembranes 24: 91–102.

Streszczenie: Ocena stateczności skarp przy uwzględnieniu wpływu okrywy roślinnej oraz przyłożonego obciążenia. W artykule przedstawiono wyniki prac podjętych w celu stworzenia nomogramów służących ocenie stanu bezpieczeństwa skarp. W wyniku podjętych prac badawczych i obliczeniowych opracowano zestawy tabel i grafów przedstawiających zależność współczynnika stateczności od wybranych sześciu parametrów skarpy: wysokość i nachylenie, wpływ okrywy roślinnej, przyłożone dodatkowe obciążenia, warunki geotechniczne i wpływ wody. Zaletą nomogramów jest prostota ich użytkowania, gdyż ocena stateczności nie wymaga dodatkowych obliczeń.

Słowa kluczowe: osuwisko, bioinżynieria, nomogramy, współczynnik stateczności

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