ANALYSIS OF THE DIFFERENCES OF THE RESULTS OF CALCULATIONS OF THE STABILITY COEFFICIENT OF THE LANDSLIDE SLOPE

**Purpose.** Improving the accuracy of determining the stability of landslide slopes in some cases requires the use of several methods to find the coefficient of stability. Therefore, it is necessary to analyze the discrepancy between the results of the calculation of the coefficient of stability of landslide slopes. **Methodology.** The solution to the problem of finite element slope modeling in the LIRA-SAPR 2016 software package is based on the creation of a spatial finite element model. With its help, the nonlinear problem of geomechanics was solved with the introduction of special finite elements, which simulates the work of the soil. As a reference, the coefficient of stability was calculated by the round-cylindrical sliding surface method. Landslide slope in the software package «OTKOS» was created and calculated. **Results.** The results of the calculation of the finite element model of the landslide slope in the LIRA-SAPR 2016 software package were obtained. The value of the coefficient of stability of the landslide-hazardous section of the slope in the «OTKOS» was obtained using eight methods. The calculation results in the «OTKOS» are compared with the coefficient of stability determined by the method of a circular-cylindrical sliding surface. **Originality.** The results of the calculation of the coefficients of stability in the «OTKOS» allowed us to divide the curves of the sliding surface into two groups: that which do not belong to circular-cylindrical, and that which satisfy the results of finite element modeling. **Practical value.** After a series of calculations and after analyzing the results, it turned out that not all methods equally solve the problem of the stability of landslide slopes. This is due to the different limitations of each of the methods, so as a criterion for the adequacy of the results obtained, it is necessary to analyze the magnitude of the discrepancy between the obtained values of the coefficient of stability.

**Key words:** landslide; landslide slope; finite element method; sliding surface; coefficient of stability

**Introduction**

When designing any kind of protection against landslides of slopes, during construction on unstable slopes or when placing mechanisms on the slopes, on the sides of the ravine, work should begin with an assessment of the state of stability of the inclined surface of the earth. Such an estimate has been making by calculating the stability coefficient, which is characterized by the ratio of holding forces to the forces that shift the body of the slope. To design the landslide protection, it is often necessary to determine the amount of soil pressure (shear pressure) from the displacement of the body to the protective structure. For such calculations there is a very large number of calculation methods, which, in essence, are not regulated by normative documents.

**Purpose**

To calculate the slope stability and to find the sliding surface, it is advisable to apply several methods of calculation, since when using different methods, the results are always slightly different, and increasing the accuracy of the calculation in some cases requires the using of several methods at once.

**Methodology**

Most of the existing methods for calculating the stability of the slopes have been developed to calculate the slope stability coefficient. Then these calculations are transformed to determine the shear pressure, that is the pressure, transmitted from the
unstable earth masses of the slope. At the same
time, for calculating the protection retaining struc-
tures, methods of constructing a shearing diagram
of the displacement are developed.

All calculating methods for assessing the state
of stability of slopes are based on the application
of the theory of boundary equilibrium, which con-
siders the boundary stress state of the soil massif.
In the calculation model, a number of conditional
assumptions are adopted:
1) the hypothesis of a solid body is used (the
prism of a possible displacement is considered as a
hardened wedge);
2) the narrow slope of the slope is considered
1 m wide, the conditions of its work are kept for
the whole slope;
3) a certain form of surface of a slip is allowed;
4) when using the main strength criterion
(\( \tau = \sigma \tan \varphi + C \)), the stresses are replaced by forces;
5) in some methods, the force of interaction be-
tween the compartments on which the shrink block
is split is not taken into account;
6) the following assumptions regarding the val-
ues and manifestations of ground water pressure
and seismic force are adopted;
7) in some methods, when considering equili-
rium of the slope, on equation of statics is taken;
8) In some cases, the theory of boundary equi-
librium is applied to a soil slope located in an out-
of-bound state (with \( C_\nu < 1 \)).

In calculations of shear pressure, the position of
the most dangerous surface of a landslide, as a
rule, is taken already found.

It is often, when the surface of the slide is de-
termined by the geological structure itself, for ex-
ample, when the cover soils slide over the indige-
nous rocks. However, in such cases, caution should
be applied to the analysis. If the indigenous soils
are semi-skeletal soils (argillites, aleurolytics,
limestones, etc.), then the surface of sliding can
pass both above and below the surface of such
rocks. In the final form, to simplify the calcula-
tions, the sliding surface should be taken in the
form of the simplest forms – from broken lines,
from the arcs of the circle, etc. (Ignatenko, Tiutkin,
Petrenko, & Alkhour, 2019; Гинзбург, 2007).

The position of the sliding surface, as well as
the value of the characteristics of soil strength (\( C \)
and \( \varphi \)) (Строкова, 2008), established on the basis
of engineering geological surveys, should be veri-
fied by inverse calculations based on the value of
the coefficient of stability of the slope, approxi-
mately corresponding to its value at the actual state
of the slope (in the unstable position of the slope
\( C_\nu \approx 1 \)). At the same time, according to the results
of studies of many scientists (Гольдштейн, 1971;
Дорфман, & Туровская, 1975; Малышев, 1980;
Маслов, 1977; Терцаги, 1961), the value of land-
slide characteristics of soils at the surface of the
sliding surface can be reduced due to the possible
change in their time in the light of creep. Such a
decrease in the strength of soil properties (especial-
ly clay) in some conditions may be significant,
which must be taken into account during design.

**Results**

The software complex «LIRA CAD 2016» al-
 lows us to calculate the nonlinear problem of geo-
mechanics using special FEs that simulate the
work of the soil (Albataineh, 2006; Griffits, &
Lane, 1999; Petrenko, Tiutkin, Ihnatenko, & Ko-
valchuk, 2018).

Soil layers have been modeled by bulky ele-
ments of the type FE 271-276 with the correspond-
ing physical and mechanical characteristics, ob-
tained as a result of engineering geological sur-
veys, depicted in different colors in fig. 1.

![Fig. 1. Finite element model of landslide slope](image1)

The results of calculating the shear stage are hor-
izontal displacement of the slope

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For practical calculations, we can use the method of a circular cylindrical surface of the slide (fig. 3). Let’s consider the prism of sliding. The center of rotation \( O \) and the value of radius \( R \) are given based on the results of calculating the finite-element slope model.

We split the prism of sliding through vertical sections into a number of compartments and we take the weight of each compartment \( P_i \) conditionally applied to the point of intersection of the line of action with the corresponding slice arc segment. Weigh strength forces in the direction of the radius of rotation \( (N_i) \) and it is perpendicular \( (T_i) \). Then we formulate the equilibrium equation in the form of the sum of moments of all forces relative to the center of rotation:

\[
\sum M(0) = \sum T_i \cdot R - \sum P_i \cdot \tan \phi \cdot R - C \cdot L \cdot R,
\]

(1)

where \( L \) – length of arc sliding \( AB \); \( \phi \) – angle of internal friction of the soil; \( C \) – specific gravity of the soil.

Friction force:

\[
T_i = P_i \cdot \sin \phi.
\]

(2)

Hold-up weight of soil:

\[
N_i = P_i \cdot \tan \phi.
\]

(3)

In this equation, the first term is a shear moment, and the other two are the values of the restraining moment of the opposite direction:

\[
M_i = \sum T_i \cdot R.
\]

(4)

\[
M_i = \sum P_i \cdot \tan \phi \cdot R + C \cdot L \cdot R.
\]

(5)

Their ratio is the coefficient of stability of the slope:

\[
C_s = \frac{\sum T_i}{\sum N_i},
\]

(6)

where \( \sum T_i \) – holding forces; \( \sum N_i \) – shifting forces.

In this expression the value of the radius of rotation \( R \) had gone.

Soil friction coefficient:

\[
f = \tan \phi.
\]

(7)
<table>
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<tr>
<th>Compartiment number</th>
<th>Design layer of soil</th>
<th>Angle of internal friction $\phi$, deg.</th>
<th>Area of the compartment, $m^2$</th>
<th>Specific gravity of soil, t/m$^3$</th>
<th>Weight of the compartment, t</th>
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Table 2

<table>
<thead>
<tr>
<th>Combined compartments</th>
<th>Weight of combined compartments $P$, t</th>
<th>$T$, t</th>
<th>$N$, t</th>
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<td>35.91</td>
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<td>3+28</td>
<td>13.60</td>
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<td>6.63</td>
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<td>6.15</td>
<td>6.84</td>
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<td>14.36</td>
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<td>7.00</td>
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<td>9.63</td>
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<td>15+16</td>
<td>11.30</td>
<td>4.95</td>
<td>5.27</td>
</tr>
</tbody>
</table>

Coefficient of stability of the slope:

$C_s = \frac{205.64 + 0.18 \cdot 37.3}{185.06} = 1.147$.

Thus, this slope is stable, but at the same time it has a rather small stock (about 15%) of stability, so it needs to be strengthened.

The calculation of the stability of the landslide slope in the software complex «OTKOS» (Перельмутер, 2002; Петренко, Тюткін, Дубінчик, & Кільдеєв, 2015; Федоровский, 1997) allows us to determine the coefficient of stability of slopes. As a mechanism of stability loss, a sliding mechanism of a sliding slope relative to a stationary slope is taken. The resistance to slide surface displacement is calculated as for static conditions. Along the entire surface, the criterion for soil destruction, adopted in the form of the Coulomb law, is maintained.

The real stresses of the shift obtained by calculation is compared with the marginal displacement resistance, and the result of this comparison is expressed as a coefficient of stability of the $C_s$. The coefficient of stability of the slope (slope) is the minimum of the coefficients of stability of the stability on all possible slip surfaces satisfying the given restriction, laid down in the calculation method (fig. 4-11).

Fig. 4. Results of calculating the stability of the slope by the Bishop’s method (simplified), $C_s = 1.363$
Output includes:
- the dimensions of the sloping slope area;
- the depth of burrowing (if there is an active marker for licking);
- characteristics of soils;
- states and characteristics of wells;
- load acting on specified slopes.

The calculation results can be summarized in the table.

In this case, we can conclude that the worst scenario of the development of the shift occurs in
the case when the stability coefficient is minimal, that is, according to the Yanbu method (fig. 11).

<table>
<thead>
<tr>
<th>The name of the method</th>
<th>The obtained coefficient of stability $C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishop’s method</td>
<td>1.363</td>
</tr>
<tr>
<td>Corps of Engineers method #1</td>
<td>1.396</td>
</tr>
<tr>
<td>Lowe’s-Karafiath’s method</td>
<td>1.147</td>
</tr>
<tr>
<td>Spencer’s method</td>
<td>1.348</td>
</tr>
<tr>
<td>Method of Fedorovsky-Kurilo</td>
<td>1.272</td>
</tr>
<tr>
<td>Fellenius’ method</td>
<td>1.174</td>
</tr>
<tr>
<td>Yanbu’s method (corrected)</td>
<td>1.220</td>
</tr>
<tr>
<td>Yanbu’s method (simplified)</td>
<td>1.144</td>
</tr>
</tbody>
</table>

After analyzing the nature of the curves of the sliding surfaces, we can conclude that the relatively small value of the coefficient of stability is due to a rather steep incident curve sliding surface.

Table 4

<table>
<thead>
<tr>
<th>Stability factor obtained by the method of a circular-cylindrical surface of a slide</th>
<th>The name of the method</th>
<th>Stability factors obtained in the software complex «OTKOS»</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.147</td>
<td>Corps of Engineers method #1</td>
<td>1.396</td>
<td>21.71 %</td>
</tr>
<tr>
<td></td>
<td>Bishop’s method</td>
<td>1.363</td>
<td>18.83 %</td>
</tr>
<tr>
<td></td>
<td>Spencer’s method</td>
<td>1.348</td>
<td>17.52 %</td>
</tr>
<tr>
<td></td>
<td>Method of Fedorovsky-Kurilo</td>
<td>1.272</td>
<td>10.90 %</td>
</tr>
<tr>
<td></td>
<td>Yanbu method (corrected)</td>
<td>1.220</td>
<td>6.36 %</td>
</tr>
<tr>
<td></td>
<td>Fellenius’ method</td>
<td>1.174</td>
<td>2.35 %</td>
</tr>
<tr>
<td></td>
<td>Lowe’s-Karafiath’s method</td>
<td>1.147</td>
<td>0.00 %</td>
</tr>
<tr>
<td></td>
<td>Yanbu’s method (simplified)</td>
<td>1.144</td>
<td>-0.26 %</td>
</tr>
</tbody>
</table>

At the same time, as a result of finite-element simulation, a similar surface displacement slip was obtained, which confirms the correctness and reliability of the obtained coefficients of stability for these methods.

Originality and practical value

Having carried out a number of calculations and analyzed the results obtained, we can conclude that not all methods are equally solvable for the same stability problem. First of all, this is due to the fact that different methods of calculation have different constraints and the basis on which the method is based. Therefore, as a criterion for the adequacy of the results obtained, it is necessary to take into account the magnitude of the discrepancy between the obtained values of the stability coefficients and to compare the calculated values of the surface of the slip with the result of the calculation of the finite element model.

Conclusions

It should be noted that the methods Fellenius, Bishop (simplified) and Spencer allow to find only circular cylindrical surfaces of sliding.

As a result of calculations made by the method of finite element modeling, the curve of the sliding surface can be considered circularly-cylindrical, that is, one that has an imaginary center of rotation of the displacement body. Accordingly, the coefficients of stability and the sliding surface curves...
obtained in the software complex "OTKOS" can be divided into two groups – those that do not belong to circular-cylindrical ones, and those that satisfy the results of the finite element modeling. That is, according to Table 4, the Fellenius’ method can be considered to be the most consistent with the circular-cylindrical surface method, with a rejection of only 2.35 %, while other methods of Bishop and Spencer have a significant discrepancy compared to the Fellenius’ method. As already mentioned earlier, other methods in the software complex "OTKOS" determine the sliding surface as not round-cylindrical, but nevertheless they deserve attention. The lowest coefficient of stability was obtained using the simplified Yau’s method, but the variation is only 0.26 % in the direction of decrease.

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МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

Цель. Повышение точности определения устойчивости оползнеопасных склонов в ряде случаев требует использования сразу нескольких методов отыскания коэффициента устойчивости. Поэтому следует проанализировать расхождения результатов расчетов коэффициента устойчивости оползнеопасных склонов. Методика. Решение задачи конечно-элементного моделирования склона в программном комплексе «ЛИРА-САПР 2016» базируется на создании пространственной конечно-элементной модели. С ее помощью решена нелинейная задача геомеханики с использованием специальных конечных элементов, моделирующих работу грунта. В качестве эталонного выполнен расчет коэффициента устойчивости методом круглоцилиндрической поверхности скольжения. Создан и рассчитан оползневый склон в программном комплексе «ОТКОС». Результаты. Получены результаты расчета конечно-элементной модели оползневого склона в программном комплексе «ЛИРА-САПР 2016» и оползневого участка склона в программном комплексе «ОТКОС» с помощью восьми методов. Результаты расчетов в программном комплексе «ОТКОС» сравнины с коэффициентом устойчивости, определенным методом круглоцилиндрической поверхности скольжения. Научная новизна. Результаты расчета коэффициентов устойчивости в программном комплексе «ОТКОС» позволяли разделить кривые поверхности скольжения на две группы - те, которые не относятся к круглоцилиндрической, и те, что удовлетворяют результатам конечно-элементного моделирования. Практическая значимость. Проведя ряд расчетов и проанализировав полученные результаты, выяснилось, что не все методы одинаково решают задачу устойчивости оползневопасных склонов. Это связано с различными ограничениями каждого из методов, поэтому в качестве критерия адекватности полученных результатов необходимо анализировать величину расхождения между полученными значениями коэффициентов устойчивости.

Ключевые слова: оползневый склон; оползень; метод конечных элементов; поверхность скольжения; коэффициент устойчивости
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