ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

UDC 621.131.543:517.9

V. D. PETRENKO[1], O. L. TIUTKIN[2*], D. YU. IHNATENKO[3]

[1] Department «Bridges and Tunnels» of Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan Str., 2, Dnepr, Ukraine, 49010, tel. +38 (050) 708 50 69, e-mail petrenko.diit@gmail.com, ORCID 0000-0003-2201-3593
[2*] Department «Bridges and Tunnels» of Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan Str., 2, Dnepr, Ukraine, 49010, tel. +38 (066) 290 45 18, e-mail alexeytutkin@gmail.com, ORCID 0000-0003-4921-4758
[3] Department «Bridges and Tunnels» of Dnipro National University of Railway Transport named after Academician V. Lazaryan, Lazaryan Str., 2, Dnepr, Ukraine, 49010, tel. +38 (097) 442 36 63, e-mail undulula@gmail.com, ORCID 0000-0001-6805-6703

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, or 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

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

unstable earth masses of the slope. At the same time, for calculating the protection retaining structures, 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 considers 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 ($\tau = \sigma tg\varphi + C$), the stresses are replaced by forces;

5) in some methods, the force of interaction between the compartments on which the shrink block is split is not taken into account;

6) the following assumptions regarding the values and manifestations of ground water pressure and seismic force are adopted;

7) in some methods, when considering equilibrium of the slope, on equation of statics is taken;

8) In some cases, the theory of boundary equilibrium is applied to a soil slope located in an out-of-bound state (with C_{ls} <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 determined by the geological structure itself, for example, when the cover soils slide over the indigenous 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 calculations, 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, & Alkhdour, 2019; Гинзбург, 2007).

The position of the sliding surface, as well as the value of the characteristics of soil strength (C and φ) (Строкова, 2008), established on the basis of engineering geological surveys, should be verified by inverse calculations based on the value of the coefficient of stability of the slope, approximately corresponding to its value at the actual state of the slope (in the unstable position of the slope $C_{ls} \approx 1$). 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 landslide 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 (especially clay) in some conditions may be significant, which must be taken into account during design.

Results

The software complex «LIRA CAD 2016» allows us to calculate the nonlinear problem of geomechanics using special FEs that simulate the work of the soil (Albataineh, 2006; Griffits, & Lane, 1999; Petrenko, Tiutkin, Ihnatenko, & Kovalchuk, 2018).

Soil layers have been modeled by bulky elements of the type FE 271-276 with the corresponding physical and mechanical characteristics, obtained as a result of engineering geological surveys, depicted in different colors in fig. 1.

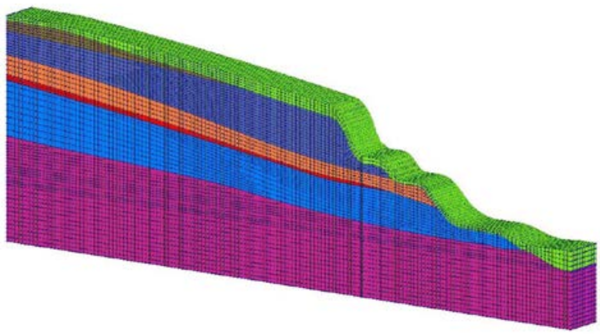

Fig. 1. Finite element model of landslide slope

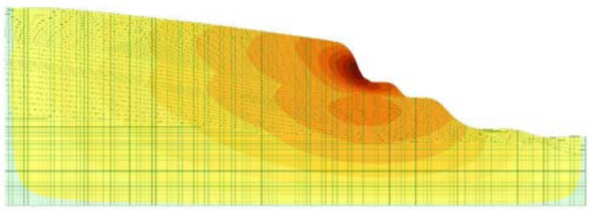

Fig. 2. The results of calculating the shear stage are horizontal displacement of the slope

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

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.

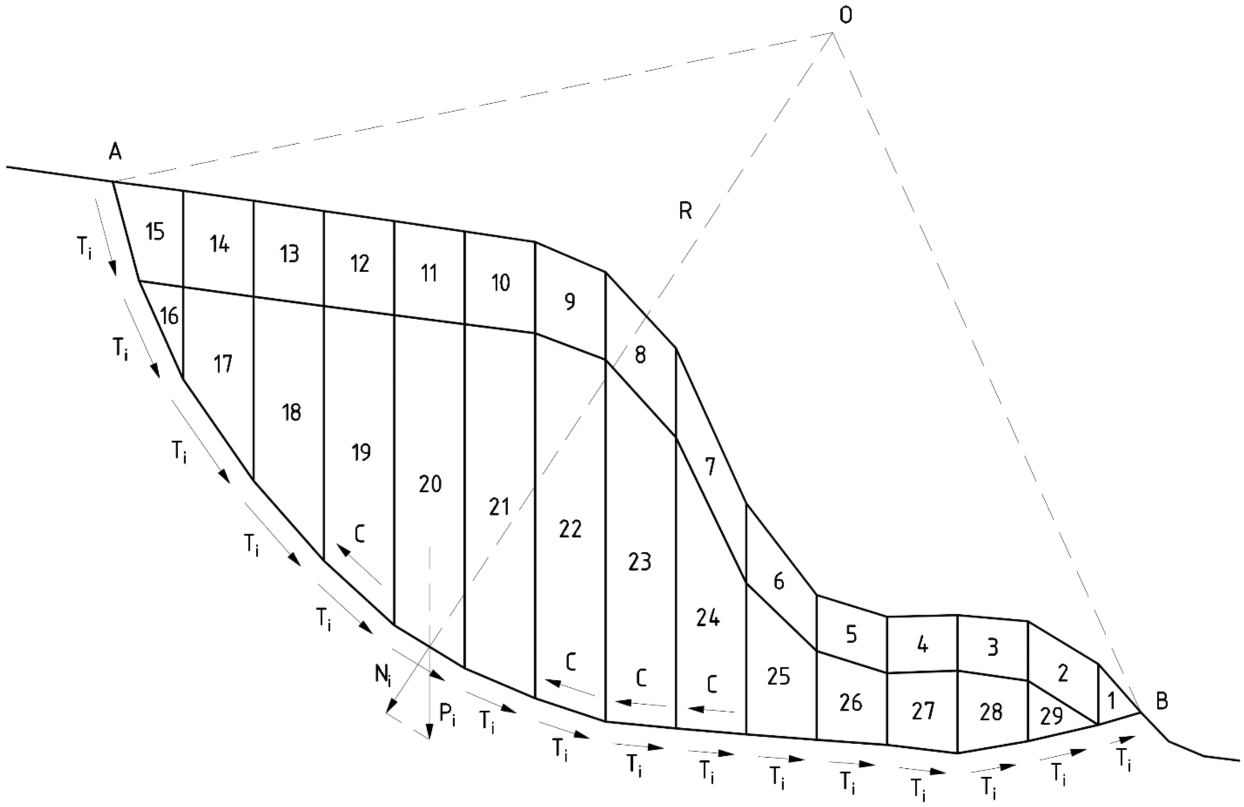

Fig. 3. Scheme for calculating the coefficient of stability of the slope by the method of a circular-cylindrical surface

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:

$$\sum M(0) = \sum T_i \cdot R - \sum P_i \cdot \text{tg}\varphi \cdot R - C \cdot L \cdot R, \qquad (1)$$

where L – length of arc sliding AB; φ – angle of internal friction of the soil; C – specific gravity of the soil.

Friction force:

$$T_i = P_i \cdot \sin\varphi. \qquad (2)$$

Hold-up weight of soil:

$$N_i = P_i \cdot \text{tg}\varphi. \qquad (3)$$

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:

$$M_i = \sum T_i \cdot R\,. \qquad (4)$$

$$M_i = \sum P_i \cdot \text{tg}\varphi \cdot R + C \cdot L \cdot R\,. \qquad (5)$$

Their ratio is the coefficient of stability of the slope:

$$C_{ls} = \frac{\sum T_i}{\sum N_i}\,, \qquad (6)$$

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:

$$f = \text{tg}\varphi. \qquad (7)$$

Table 1

Compartment number	Design layer of soil	Angle of internal friction φ, deg.	Area of the compartment, m^2	Specific gravity of soil, t/m^3	Weight of the compartment, t
1	1	25	1.05	1.87	1.96
2		26	3.42		6.40
3			3.27		6.11
4			3.18		5.95
5			3.19		5.97
6			3.86		7.22
7			4.8		8.98
8			5.02		9.39
9			5.08		9.50
10			5.23		9.78
11			5.31		9.93
12			5.37		10.04
13			5.42		10.14
14			5.46		10.21
15		25	4.43		8.28
16	3	26	1.64	1.84	3.02
17			7.85		14.44
18			12.46		22.93
19			16.04		29.51
20			18.58		34.19
21			20.14		37.06
22			20.65		38.00
23			18.54		34.11
24			12.56		23.11
25			6.81		12.53
26			4.56		8.39
27			4.39		8.08
28			4.07		7.49
29			1.72		3.16

Table 2

Combined compartments	Weight of combined compartments *P*, t	*T*, t	*N*, t
1	1.96	0.83	0.92
2+29	35.91	15.74	17.51
3+28	13.60	5.96	6.63
4+27	14.02	6.15	6.84
5+26	14.36	6.29	7.00
6+25	19.75	8.66	9.63
7+24	32.09	14.07	15.65
8+23	43.50	19.07	21.22
9+22	47.50	20.82	23.17
10+21	46.84	20.53	22.84
11+20	44.12	19.34	21.52
12+19	39.56	17.34	19.29
13+18	33.06	14.49	16.13
14+17	24.65	10.81	12.02
15+16	11.30	4.95	5.27

Coefficient of stability of the slope:

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

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, Тютькін, 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_{ls}. 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).

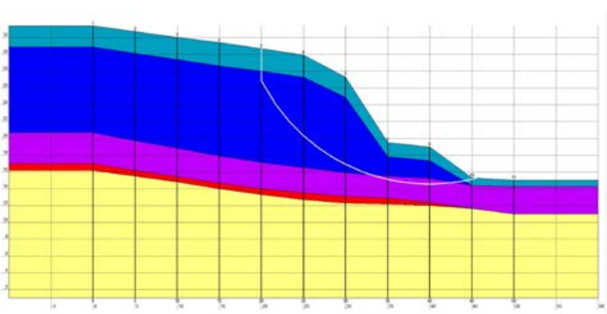

Fig. 4. Results of calculating the stability of the slope by the Bishop's method (simplified), C_{ls} = 1,363

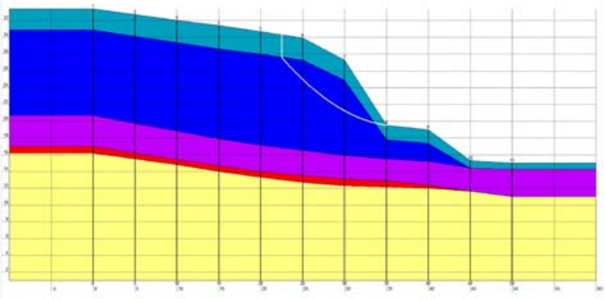

Fig. 5. Results of calculating the stability of the slope by the Corps of Engineers method #1, C_{ls} = 1,396

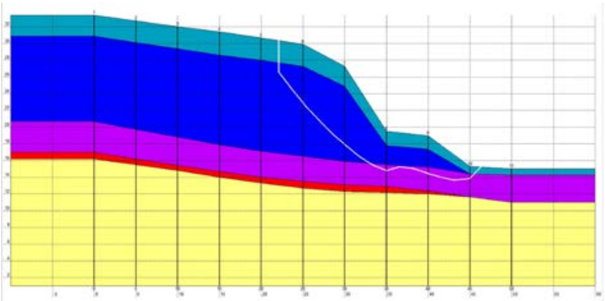

Fig. 6. The results of calculating the stability of the slope by the method Lowe-Karafiath, C_{ls} = 1,147

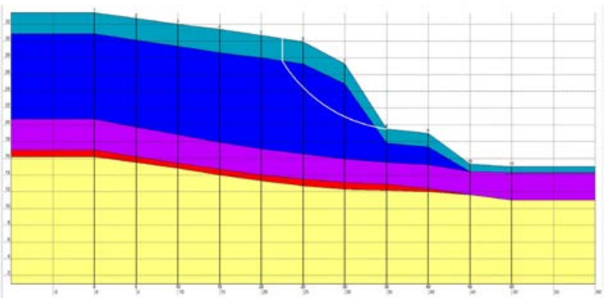

Fig. 7. Results of calculating the slope stability using the Spencer's method, C_{ls} = 1,348

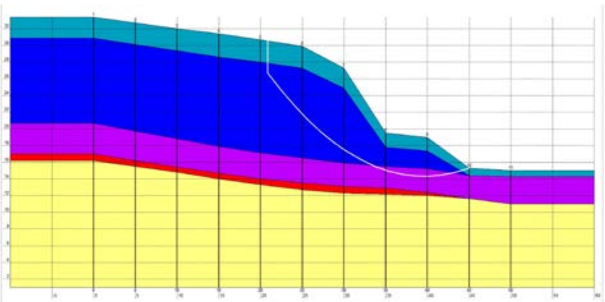

Fig. 8. Results of calculating the stability of the slope by the method of Fedorovsky-Kurilo, C_{ls} =1,272

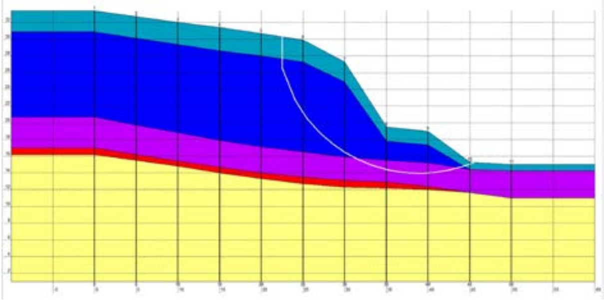

Fig. 9. Results of calculating the slope stability using the Fellenius' method, C_{ls} = 1,174

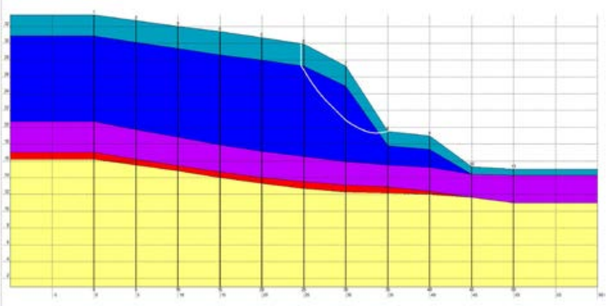

Fig. 10. Results of calculating the stability of the slope using the Yanbu's method (corrected), C_{ls} = 1,22

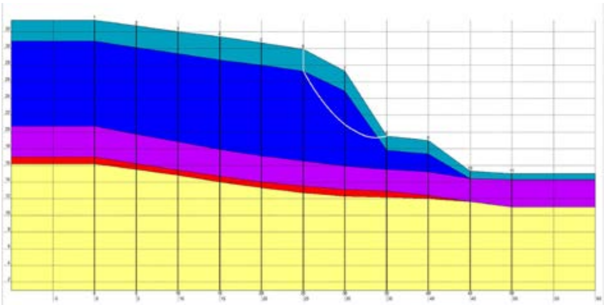

Fig. 11. Results of calculating the stability of the slope using the Yanbu's method (simplified), C_{ls} = 1,144

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

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

the case when the stability coefficient is minimal, that is, according to the Yanbu method (fig. 11).

Table 3

The name of the method	The obtained coefficient of stability C_{ls}
Bishop's method	1.363
Corps of Engineers method #1	1.396
Lowe's-Karafiath's method	1.147
Spencer's method	1.348
Method of Fedorovsky-Kurilo	1.272
Fellenius' method	1.174
Yanbu's method (corrected)	1.220
Yanbu's method (simplified)	1.144

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.

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.

Table 4

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

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.

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 Felenius' 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 Yanbu's method, but the variation is only 0.26 % in the direction of decrease.

REFERENCES

Albataineh, N. (2006). *Slope stability analysis using 2D and 3D methods*. The university of Akron, Ohio, United States.

Griffits, D. V., & Lane, P. A. (1999). Slope stability analysis by finite elements. *Geotechnique*, 49(3), 387-403.

Ignatenko D., Tiutkin, O. L., Petrenko, V. D., & Alkhdour, A. M. (2019). Application of centrifugal modeling for the study of landscape structure stability. *International Journal of Civil Engineering and Technology (IJCIET)*, 10(01), 2179-2187.

Petrenko, V. D., Tiutkin, O. L., Ihnatenko, D. Yu., & Kovalchuk, V. V. (2018). Comparative calculation of the stability of the landslide slope in the software complexes «OTKOS» and «LIRA-CAD 2017». *Mosti ta tuneli: teoriia, doslidzhennia, praktyka*, 14, 101-109.

Гинзбург, Л. К. (2007). *Противооползневые сооружения*. Днепропетровск: Лира ЛТД.

Гольдштейн, М. Н. (1971). *Механические свойства грунтов. Основные компоненты грунта и их взаимодействие*. Москва: Стройиздат.

Дорфман, А. Г., & Туровская, А. Я. (1975). Исследование устойчивости склонов. *Вопросы геотехники*, 24, 132-156.

Малышев, М. В. (1980). *Прочность грунтов и устойчивость оснований сооружений*. Москва: Стройиздат.

Маслов, Н. Н. (1977). *Механика грунтов в практике строительства*. Москва: Стройиздат.

Перельмутер, А. В. (2002). *Расчетные модели сооружений и возможности их анализа*. Киев: Сталь.

Петренко, В. Д., Тютькін, О. Л., Дубінчик, О. І., & Кільдєєв, В. Р. (2015). Оцінка стійкості природних схилів методами математичного моделювання в програмі «ОТКОС». *Мости та тунелі: теорія, дослідження, практика*, 8, 23-32.

Строкова, Л. А. (2008). Определение параметров для численного моделирования поведения грунтов. *Известия Томского политехнического университета*, 1, 69-74.

Терцаги, К. (1961). *Теория механики грунтов*. Москва: Стройиздат.

Федоровский, В. Г. (1997). Метод расчета устойчивости откосов и склонов. *Геоэкология*, 6, 95-106.

В. Д. ПЕТРЕНКО[1], О. Л. ТЮТЬКІН[2*], Д. Ю. ІГНАТЕНКО[3]

[1*] Кафедра «Мости та тунелі», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (050) 708 50 69, ел. пошта petrenko.diit@gmail.com, ORCID 0000-0003-2201-3593

[2] Кафедра «Мости та тунелі», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (066) 290 45 18, ел. пошта alexeytutkin@gmail.com, ORCID 0000-0003-4921-4758

[3] Кафедра «Мости та тунелі», Дніпровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпро, Україна, 49010, тел. +38 (097) 442 36 63, ел. пошта undulula@gmail.com, ORCID 0000-0001-6805-6703

АНАЛІЗ РОЗБІЖНОСТЕЙ РЕЗУЛЬТАТІВ РОЗРАХУНКІВ КОЕФІЦІЄНТА СТІЙКОСТІ ЗСУВОНЕБЕЗПЕЧНОГО СХИЛУ

Мета. Підвищення точності визначення стійкості зсувонебезпечного схилу в ряді випадків вимагає використання відразу декількох методів відшукання коефіцієнта стійкості. Тому слід проаналізувати розбіжності результатів розрахунків коефіцієнта стійкості зсувонебезпечного схилу. **Методика.** Вирішення задачі скінченно-елементного моделювання схилу в програмному комплексі «ЛІРА-САПР 2016» базується на

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

створенні просторової скінченно-елементної моделі. З її допомогою вирішено нелінійну задачі геомеханіки з використанням спеціальних скінченних елементів, що моделюють роботу ґрунту. В якості еталонного виконано розрахунок коефіцієнту стійкості методом круглоциліндричної поверхні ковзання. Створено та розраховано зсувонебезпечний схил в програмному комплексі «ОТКОС». **Результати.** Отримано результати розрахунку скінченно-елементної моделі зсувонебезпечного схилу в програмному комплексі «ЛІРА-САПР 2016». Отримано значення коефіцієнту стійкості зсувонебезпечної ділянки схилу в програмному комплексі «ОТКОС» за допомогою восьми методів. Результати розрахунку в програмному комплексі «ОТКОС» порівняно із коефіцієнтом стійкості, визначеним методом круглоциліндричної поверхні ковзання. **Наукова новизна.** Результати розрахунку коефіцієнтів стійкості в програмному комплексі «ОТКОС» дозволили поділити криві поверхні ковзання на дві групи – ті, що не відносяться до круглоциліндричних, та ті, що задовольняють результатам скінченно-елементного моделювання. **Практична значимість.** Провівши ряд розрахунків та проаналізувавши отримані результати, з'ясовано, що не всі методи однаково вирішують задачу стійкості зсувонебезпечного схилу. Це пов'язано з різними обмеженнями кожного з методів, тому в якості критерію адекватності отриманих результатів необхідно аналізувати величину розбіжності між отриманими значеннями коефіцієнтів стійкості.

Ключові слова: зсувонебезпечний схил; зсув; метод скінченних елементів; поверхня ковзання; коефіцієнт стійкості

В. Д. ПЕТРЕНКО[1], А. Л. ТЮТЬКИН[2*], Д. Ю. ИГНАТЕНКО[3]

[1*] Кафедра «Мосты и тоннели», Днепровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепр, Украина, 49010, тел. +38 (050) 708 50 69, эл. почта petrenko.diit@gmail.com, ORCID 0000-0003-2201-3593
[2] Кафедра «Мосты и тоннели», Днепровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепр, Украина, 49010, тел. +38 (066) 290 45 18, эл. почта alexeytutkin@gmail.com, ORCID 0000-0003-4921-4758
[3] Кафедра «Мосты и тоннели», Днепровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, Днепр, Украина 49010, тел. +38 (097) 442 36 63, эл. почта undulula@gmail.com, ORCID 0000-0001-6805-6703

АНАЛИЗ РАСХОЖДЕНИЙ РЕЗУЛЬТАТОВ РАСЧЕТОВ КОЭФФИЦИЕНТА УСТОЙЧИВОСТИ ОПОЛЗНЕОПАСНОГО СКЛОНА

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 оползнеопасный склон в программном комплексе «ОТКОС». **Результаты.** Получены результаты расчета конечно-элементной модели оползнеопасного склона в программном комплексе «ЛИРА-САПР 2016». Получено значение коэффициента устойчивости оползнеопасного участка склона в программном комплексе «ОТКОС» с помощью восьми методов. Результаты расчета в программном комплексе «ОТКОС» сравнены с коэффициентом устойчивости, определенным методом круглоцилиндрической поверхности скольжения. **Научная новизна.** Результаты расчета коэффициентов устойчивости в программном комплексе «ОТКОС» позволили 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 оползнеопасных 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: оползнеопасный склон; оползень; метод конечных элементов; поверхность скольжения; коэффициент устойчивости

ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Мости та тунелі: теорія, дослідження, практика, 2019, № 15

REFERENCES

Albataineh, N. (2006). *Slope stability analysis using 2D and 3D methods*. The university of Akron, Ohio, United States. (in English)

Griffits, D. V., & Lane, P. A. (1999). Slope stability analysis by finite elements. *Geotechnique, 49(3)*, 387-403. (in English)

Ignatenko D., Tiutkin, O. L., Petrenko, V. D., & Alkhdour, A. M. (2019). Application of centrifugal modeling for the study of landscape structure stability. *International Journal of Civil Engineering and Technology (IJCIET), 10(01)*, 2179-2187. (in English)

Petrenko, V. D., Tiutkin, O. L., Ihnatenko, D. Yu., & Kovalchuk, V. V. (2018). Comparative calculation of the stability of the landslide slope in the software complexes «OTKOS» and «LIRA-CAD 2017». *Mosty ta tuneli: teoriia, doslidzhennia, praktyka, 14*, 101-109. (in English)

Ginzburg, L. K. (2007). *Protivoopolznevye sooruzhenija*. Dnepropetrovsk: Lira LTD. (in Russian)

Gol'dshtejn, M. N. (1971). *Mehanicheskie svojstva gruntov. Osnovnye komponenty grunta i ih vzaimodej-stvie*. Moskva: Strojizdat. (in Russian)

Dorfman, A. G., & Turovskaja, A. Ja. (1975). Issledovanie ustojchivosti sklonov. *Voprosy geotehniki, 24*, 132-156. (in Russian)

Малыshev, M. V. (1980). *Prochnost' gruntov i ustojchivost' osnovanij sooruzhenij*. Moskva: Strojizdat. (in Russian)

Maslov, N. N. (1977). *Mehanika gruntov v praktike stroitel'stva*. Moskva: Strojizdat. (in Russian)

Perel'muter, A. V. (2002). *Raschetnye modeli sooruzhenij i vozmozhnosti ih analiza*. Kiev: Stal'. (in Russian)

Petrenko, V. D., Tiutkin, O. L., Dubinchyk, O. I., & Kildieiev, V. R. (2015). Otsinka stiikosti pryrodnykh skhyliv metodamy matematychnoho modeliuvannia v prohrami «OTKOS». *Mosty ta tuneli: teoriia, doslidzhennia, praktyka, 8*, 23-32. (in Ukrainian)

Strokova, L. A. (2008). Opredelenie parametrov dlja chislennogo modelirovanija povedenija gruntov. *Izvestija Tomskogo politehnicheskogo universiteta, 1*, 69-74. (in Russian)

Tercagi, K. (1961). *Teorija mehaniki gruntov*. Moskva: Strojizdat. (in Russian)

Fedorovskij, V. G. (1997). Metod rascheta ustojchivosti otkosov i sklonov. *Geojekologija, 6*, 95-106. (in Russian)

Надійшла до редколегії 06.05.2019.
Прийнята до друку 20.05.2019.