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SAFETY OF ROAD EMBANKMENT STRUCTURES REINFORCED WITH GEOSYNTHETICS IN CRISIS SITUATIONS CAUSED BY LANDSLIDES

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Abstract:

The paper describes the occurrence of crisis situations on public roads caused by landslides and the issue of ensuring traffic safety in crisis situations. Particular attention has been paid to structural errors, which often represent the root cause of road structure failures, and the possibilities of eliminating such errors at the design stage. The article analyses the methods of calculating the stability of road embankments and presents example calculations of the factor of safety for a road embankment without and with reinforcement with geosynthetics. It has been demonstrated that the application of geosynthetics makes it possible to design road structures with the factor of safety of the embankment slope for which the probability of a sliding failure is very low.

Key words:

security, road embankments, landslides, geosynthetics

INTRODUCTION

The security of the state and its citizens is often disturbed by different types of crisis situations, including natural disasters. Pursuant to the Act of 26 April 2007 on Crisis Management [5], one of the significant elements during crisis situations is to ensure the protection of road infrastructure (roads and bridges). A crisis situation exerts an adverse impact on the level of safety of people and their property and on the condition of the environment, causing significant restrictions in the operation of relevant public administration bodies due to the insufficiency of available resources and means. In Poland crisis situations affecting road infrastructure occur most often during natural disasters, i.e. during floods and inundations affecting large areas. Any damage to road structures (motorways, national roads (public trunk roads), voivodship (provincial) roads, powiat (district) roads and gmina (local/communal) roads), leading to a direct disruption of transport for a longer period or to a complete closure of a road section, results in a deterioration in road traffic safety and even provokes construction collapses. The slide of a road embankment may stem from a natural disaster (e.g. as a result of a flood, washout of the slope, waterlogging caused by heavy precipitation or damage to the soil structure due to its loosening), the operation of external factors (e.g. vibrations caused by road traffic or soil displacement after excessive loading of the area) or the incorrect design of excavation or embankment slopes [9]. Figure 1a shows the landslide of the road embankment on the A1 motorway, most probably caused by the operation of numerous destructive factors, including the incorrect surface stabilisation of the embankment or its lack or the premature loading of the embankment, before it was completed, by heavy road traffic generating vibrations.

a) b)

Fig. 1. Damage to the road prism caused by the landslide of the road embankment slope: a) as a result of defects in the construction process and faulty workmanship of the A1 motorway near Wieniec in the Kujawsko-Pomorskie Province;b) as a result of the flood in Jodłówka Tuchowska in 2010

Source: a) Galczak A., Nasyp przy A1 osuwa się! Autostrada jest zagrożona? [online]. Available on the Internet: http://www.pomorska.pl/wiadomosci/wloclawek/art/6406372,nasyp-przy-a1-osuwa-sie-autostrada-jest-zagrozona,id,t.html [access: 10.2015]

b) Ochotnicza Straż Pożarna w Jodłówce Tuchowskiej, Skutki powodzi w Jodłówce Tuch. 2010, [online]. Available on the Internet: http://osp-jodlowka-tuchowska.cba.pl/ galeria_powodz.html [access: 10.2015]

Other consequences of the incorrect design or improper execution of road embankments may include the ripping of the road prism, sinkhole formation and road surface chipping and ravelling. All these consequences lead to a partial or complete paralysis of road traffic. At present, older sections of public roads, mainly in the southern part of

Poland, which were set out along the river-beds, pose a huge problem. Most often the road embankments constructed there were not reinforced at all or were reinforced to an insufficient extent. During the construction phase the embankment structure was often shifted, for economic or social reasons, towards the river-bed, resulting in a reduction in size and slope angle of the embankment and in a decreased river flow capacity. Design and workmanship defects of the Polish roads were specifically uncovered during the flood in 2010, which affected the southern part of Poland (Fig. 1b) [3]. The Provinces which suffered to the greatest extent include Małopolskie, Śląskie, Podkarpackie, Świętokrzyskie and Lubelskie. The report drawn up by the General Directorate for National Roads and Motorways, Branch in Kraków, shows that the natural disaster which occurred in 2010 led to a crisis situation on almost all national roads. Such damage as landslides and ruptures of slopes, washouts of shoulders and road surface ravelling and cracking were observed most often. Remedying the effects of this disaster was estimated at PLN 77 million at a minimum [7]. Most often the repair of a damaged road section was impossible or uneconomical, which necessitated the comprehensive reconstruction of infrastructure. The reconstruction of road infrastructure is usually more expensive than the elimination of reasons causing the occurrence of a disaster, which comprises improving skills that ensure the proper geotechnical assessment of subsoil, enhancing designers' knowledge and competences, making use of new software and designing methods, and applying modern materials.

1. METHODS OF RECONSTRUCTING AND SECURING ROADS IN CRISIS SITUATIONS

Any damage to or destruction of a road which prevents mobility and transport provokes the feeling of lack of security in the society. It usually takes several weeks or even months to reconstruct a damaged road section and, therefore, quick solutions are searched for, making it possible to reconstruct the damaged road section efficiently and to restore the flow of traffic [3]. From among numerous ways to restore and secure the roads in crisis situations the solutions making use of geosynthetics are worth consideration. The application of geosynthetics for the reconstruction of the damaged road embankment makes it possible to carry out the task in a short time, minimise the use of specialist equipment and complete a reliable road structure. Geosynthetics currently available on the market are made of polymers containing additives, which perform various functions in road engineering (e.g. reinforcement of the structure, enhancement of the embankment strength, isolation of two different media or collection and transport of precipitation water). The reinforcement with geonets used for steep slopes and road embankments provides the subsoil with a long-term tensile stress transfer capability. Geofabrics and geonets characterised by a high mechanical strength serve as the reinforcement for embankment slopes and are designed to absorb the loads applied to the structure placed above them. The strengthening and reinforcement of embankment slope slides is the most important issue, however their surface stabilisation may not be ignored. The purpose of external stabilisation is to protect the structure of the slopes from superficial erosion occurring as the consequence of atmospheric factors. Geomats and cellular geogrids are used as anti-erosion barriers to protect slopes and embankments against the destructive impact exerted by precipitation water and wind. Additional stabilisation at the surface is ensured by traditional grass seeding and planting specifically selected vegetation [1, 2, 9].

In crisis situations a relative condition making the reconstruction of a damaged road section possible at all and preventing the future occurrence of crisis situations, resulting from disasters that pose a threat to human life, is to safeguard the area and to stop any further damage. It is necessary to properly mark the slope failure, close the road section for traffic and establish a detour or limit the traffic and vehicle speed. Temporary protection in the form of buttresses and gabions should be carried out. Temporary protection is justified only in the case of a shallow slide shear plane and a slope failure limited in extent [9, 13].

2. METHODS OF CALCULATING THE STABILITY OF SLOPES AND ROAD EMBANKMENTS

The landslide phenomenon is caused by the embankment slope stability failure, when the shear strength of the soil is exceeded along any of the shear planes, and it creates a threat to transport routes. Forces that cause embankment and slope failures include mainly gravitational forces from the dead weight of the soil and road furniture and facilities or hydrodynamic forces induced by a rapid flow of water through the soil, the raising of the groundwater table or excessive moisture content in the slope. Landslides represent the most dangerous mass movements, having a destructive impact on the structure of the road prism. Taking into account the behaviour of earth masses forming embankments and slopes the following types of landslides can be distinguished: continuous active landslides (characterised by a high number of soil displacements recorded over a period of the last five years at a minimum), low activity landslides (movements of a mass of earth occur irregularly over a period of 50 years) and inactive landslides (a stabilised slope failure where no movement of a mass of earth has been observed over the last 50 years). The most dangerous landslides are the large ones, with the area of displaced material exceeding 3,000 m². Significant hazards are also created by medium-sized landslides, having an area of 1,000 to 3,000 m², and small slope failures with an area of less than 1,000 m². A natural landslide occurs as a result of a natural disaster, e.g. a flood or changes in the local subsurface and hydrological conditions. Increasingly often slope failures result from design, technological and workmanship errors, such as embankment slopes being too steep, excessive undercuts in the slopes, inappropriate soil chosen for the construction of an embankment, selection of incorrect technology for embankment compaction and incorrectly selected drainage system. Movements of earth masses within the road embankments are caused mainly by errors made during their construction, i.e. minimisation of earthworks, compaction of too thick layers of soil, making it impossible to obtain the proper degree of compaction, use of the inappropriate soil for the construction of an embankment and the lack of surface stabilisation. The majority of design and workmanship errors result most often from financial savings at both stages of works. The minimisation of funds turns out, however, to be an apparent saving, as should a disaster occur the costs of remedying its effects and reconstructing the structure are significantly higher [3, 8, 11].

Taking into account the safety of the structure, the key parameter in the dimensioning of the structure of a road embankment, without or with reinforcement, is the degree of its stability, *F*, called the factor of safety (FS). The value of this factor determines whether the structure is stable or whether there is a risk of its failure. The ranges of allowable values of the stability parameter of a road embankment slope are presented in Table 1 [8, 13].

Table 1. Allowable values of the factor of safety of road embankment slopes

Value of the factor of safety of road embankment slopes	Probability of the occurrence of a slope failure
$F_{dop} < 1.0$	highly probable
$1.0 < F_{dop} \leq 1.3$	probable
$1.3 < F_{dop} \leq 1.5$	unlikely
$F_{dop} > 1.5$	highly unlikely

Source: Jermołowicz P., Awarie i uszkodzenia konstrukcji z wbudowanymi geosyntetykami w aspekcie błędów projektowych i wykonawczych. Cz. 1. Warunki trwałości nasypów drogowych, skarp i wykopów oraz zboczy naturalnych z zastosowaniem geosyntetyków, Izolacje, nos. 7-8, 201, p. 48-53.

The determination of the value of the *F* parameter is highly complex and usually burdened with numerous errors, as this parameter depends on the type of subsoil and its physical and mechanical properties, the identification and measurement of which are complicated and costly. The determination of the *F* parameter is based on the use of reduction and material factors that increase the error of the result. At present, several methods are employed to determine the *F* parameter (e.g. methods of Fellenius, Bishop, Nonveiller, Morgenstern-Price, Janbu, Lorimer, Kezdi, Sarma), depending on the forces taken into account, verified equilibrium conditions and available software [10, 11, 14]. The Fellenius' method, also called the Swedish or ordinary method, is most frequently used at present. It relies on the condition of the equilibrium of forces and moments and on the assumption that soil shear planes are cylindrical surfaces. The Fellenius' method is characterised by a high correctness of obtained results in comparison with the other methods listed hereinabove, in which calculations have to be verified by applying another method (thus, calculations should be at least doubled), to eliminate the growing number of errors and to check the consistency of the obtained results.

3. STABILITY ANALYSIS FOR A ROAD EMBANKMENT WITHOUT AND WITH REINFORCEMENT

On the basis of the Fellenius' method the stability of a road embankment slope without and with reinforcement with geosynthetics was calculated. The embankment was designed as the base course for a motorway of traffic category 6 (KR6), in order to assess the probability of the occurrence of a slide of earth masses forming the embankment in both cases. The embankment was made of fill material, selected on the basis of a comparative analysis. The comparative analysis covered four aggregate fill materials and four criteria were adopted to determine the selection of aggregate of the appropriate type (Tab. 2). On the basis of the results of the conducted analysis a sand and gravel mix was selected as the fill material.

Table 2. Results obtained from a comparative analysis, consistent with the adopted criteria

			Criteria adopted for the comparative analysis			
			Vertical stresses in soil under the embankment, [kN/m^2]	Structure settlement, [cm]	Angle of internal friction in soil, [°]	Net market price of soil, [PLN/Mg]
Scheme type	I	Aggregate 0-16 mm	171.55	0.234	40.7	53.00
	II	Fill sand	168.63	0.230	35.4	20.00
	III	Sand and gravel mix	165.71	0.226	41.2	21.00
	IV	Gravel 2-8 mm	174.47	0.237	41.5	57.00

Source: own work

For calculation purposes a soil profile (Fig. 3) appropriate for the location of the structure, i.e. the town of Czestochowa, and geological and subsurface and hydrological conditions were adopted. In the analysed geotechnical site investigation the groundwater table was not encountered. For further calculations general data concerning the location of the structure were adopted as well as the basic data for each of the four soil horizons, i.e.:

- liquidity index for cohesive soils or degree of consolidation for non-cohesive soils;
- bulk density and unit weight of the soil;
- natural moisture content;
- angle of internal friction and its design value;
- oedometric modulus of primary and secondary compression;
- modulus of elasticity.

On the basis of the above data bearing capacity coefficients N_D, N_C, N_B were determined. In compliance with the guidelines contained in PN-S-02205 standard [16] the following embankment geometry was adopted:

- embankment height: $H_n = 5.00$ m;
- embankment toe width: $B_{pn} = 41.20$ m;
- embankment crest width: $B_{kn} = 32.00$ m;
- embankment slope: 1:1.

In accordance with the Regulation of the Minister of Transport and Maritime Economy [4], on the road embankment an A class road was designed – two-way motorway with two lanes. Due to heavy traffic loading for this road class it was categorised, pursuant to the Regulation [4], to Traffic Category 6. Then, in accordance with the Regulation [4], the road dimensions and geometry as well as its structure were determined. Permanent loads from the surface structure (q_k) were determined as the value of 13.395 kN/m^2 and on the basis of PN-EN 1991-2:2007 standard [15] variable vehicular loads for the A class road and for traffic category KR6 (q_n) were established as the value of 49.514 kN/m^2. Calculations were also performed using the GAMMA-KT program, to determine the ultimate limit state (ULS) of the subsoil for two independent geotechnical boreholes. As shown by the calculations, the allowable bearing capacity was not exceeded in any of the subsequent subsoil layers and, therefore, no additional subsoil reinforcement was required at the toe of the analysed road embankment.

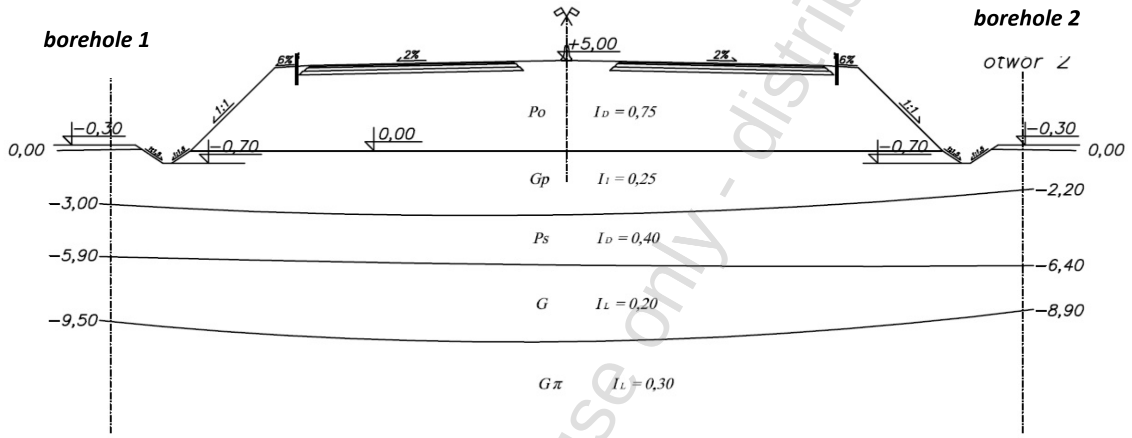

Fig. 3. Soil profile

Source: own work

The computational verification of the slope stability using the Fellenius' method consists in the determination, on the basis of mathematical calculations, of the factor of safety *F* for the slope for the potential shear plane, according to the following formula:

$$F = \frac{1.1 \cdot M_u}{1.35 \cdot M_o} \tag{1}$$

where:

M_u - moment of the forces retaining the embankment slope in equilibrium, i.e. the moment of forces retaining the soil mass in relation to the point O (Fig. 4), [kN·m];

M_o - moment of the forces shearing the slope, i.e. the moment of the forces turning the soil mass in relation to the point O (Fig. 4), [kN·m].

The embankment slope is considered stable if the following condition is met:

$$F > F_{dop} \tag{2}$$

Therefore, in accordance with the data presented in Table 1, the structure will be stable if the value of the factor of safety *F* falls within the range 1.3-1.5 or is higher. For the determination of the factor of safety *F* data from Figure 4 were used. The soil mass delimited by the radius *R* of 8.53 m, forming the sliding surface, was divided into smaller soil segments with a thickness of s_n = 1 m along the embankment slope and with a width of 0.1 *R* across the embankment slope. Thus, six slices 0.853 m wide and one slice 0.4131 m wide were obtained for consideration. The coordinates of the centre of a slip-circle and the radius of a circle were determined by employing the Sokolovski's method [12]. The coordinates of the centre and the length of the radius of the slip-circle of the soil mass were marked in Figure 4. The area of soil slices and angles of inclination for a normal component of the force exerted by the weight of soil slices were determined using the AutoCAD program and the results are presented in Table 3.

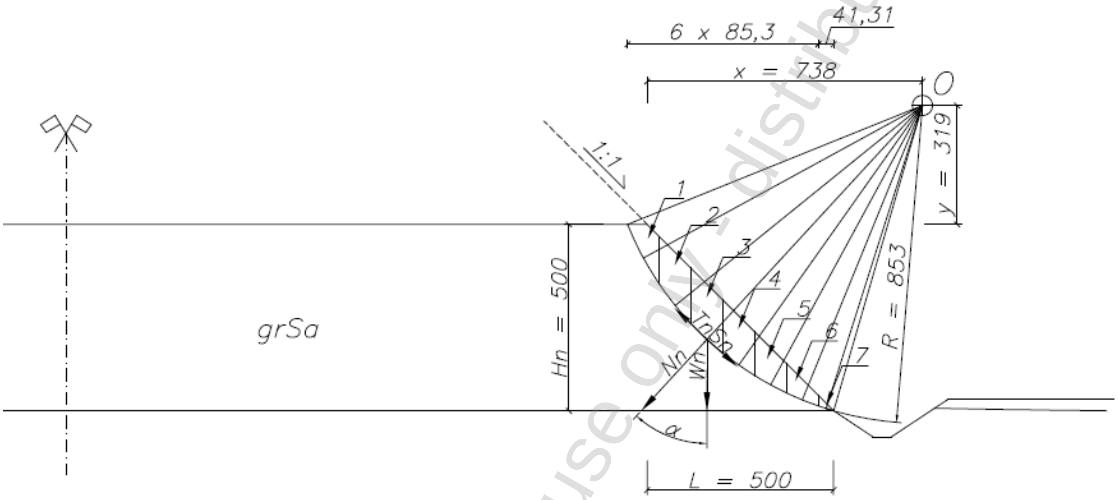

Fig. 4. Plotting of a slip-circle for the designed road embankment and division into soil slices with the indication of forces acting on them

Source: own work

Table 3. Geometric parameters of seven distinguished soil slices

n	Area of soil slice P_n, [m^2]	Volume of soil slice V_n, [m^3]	Angle of inclination of normal force α_n, [°]
1	0.674	0.674	61
2	1.299	1.299	51
3	1.220	1.220	43
4	1.039	1.039	35
5	0.810	0.810	29
6	0.534	0.534	22
7	0.191	0.191	18

Source: own work

For further calculations it was necessary to determine the weight of distinguished soil slices, which was accomplished by using the following formula:

$$W_n = V_n \cdot \gamma_{grSa} \quad [\text{kN}] \tag{3}$$

where:

V_n – volume of soil mass elements, [m^3] (assumed lateral dimension of 1.0 m),

γ_{grSa} – unit weight of the fill layer (sand and gravel mix), [kN/ m^3].

The weight W_n was split into two components (Fig. 4.):

S_n – component of the W_n force tangent to the sliding surface:

$$S_n = W_n \cdot \sin(\alpha_n) \quad [\text{kN}] \tag{4}$$

N_n – normal component of the W_n force:

$$N_n = W_n \cdot \cos(\alpha_n) \quad [\text{kN}] \tag{5}$$

where:

α_n – angle between the normal force N_n and the weight W_n, [°].

Table 4 presents the unit weight γ_{grSa} and two components: tangent component S_n and normal component N_n for each of the seven soil slices.

Table 4. Normal component and component tangent to a slip-circle and weight of a soil slice

n	Unit weight of sand and gravel mix γ_{grSa}, [kN/m^3]	Weight of a distinguished soil slice W_n, [kN]	sin(α_n)	Component tangent to a slip-circle S_n, [kN]	cos(α_n)	Normal component to a slip-circle N_n, [kN]
1	18,5	12.469	0.875	10.905	0.485	6.045
2		24.033	0.777	18.677	0.629	15.124
3		22.568	0.682	15.391	0.731	16.505
4		19.214	0.574	11.021	0.819	15.739
5		14.988	0.485	7.266	0.875	13.109
6		9.879	0.375	3.701	0.927	9.160
7		3.534	0.309	1.092	0.951	3.361

Source: own work

To calculate the moment retaining the soil mass of the road embankment (M_u) it is necessary to determine the frictional resistance force and cohesion of the soil (T_n), opposite to the tangent component of weight (S_n). The frictional resistance force was determined for each soil slice using the following formula:

$$T_n = N_n \cdot \text{tg}\,(\phi_{grSa}) \quad [\text{kN}] \tag{6}$$

where:

ϕ_{grSa} – characteristic value of the angle of internal friction of the fill soil, [°].

The moment of the forces retaining the road embankment is determined using the following formula:

$$M_u = R \cdot \Sigma\, T_n \quad [\text{kN} \cdot \text{m}] \tag{7}$$

The moment of the forces rotating the soil of the road embankment is calculated using the following formula:

$$M_o = R \cdot \Sigma\, S_n \quad [\text{kN} \cdot \text{m}] \tag{8}$$

Table 5 shows the final values of the moment of the forces retaining the soil mass of the embankment and of the moment of the forces rotating the soil mass of the road embankment. On the basis of these values the factor of safety *F* of the road embankment can be directly determined and it can be established whether or not the embankment will be damaged as a result of a landslide.

Table 5. Values of the moments of the forces retaining and rotating the soil mass of the road embankment

n	Angle of internal friction of sand and gravel mix ϕ_{grSa}, [kN]	tg(ϕ_{grSa})	Resistance force generated by internal friction T_n, [kN]	Radius of a slip-circle *R*, [m]	Moment of the forces retaining the soil mass M_u, [kN·m]	Moment of the forces rotating the soil mass M_o, [kN·m]
1	41.2	0.875	5.292	8.53	590.253	580.497
2			13.240			
3			14.449			
4			13.779			
5			11.476			
6			8.019			
7			2.942			

Source: own work

Ultimately, the factor of safety *F* of the road embankment without reinforcement is equal to 0.83, as a result of which the condition necessary to ensure the stability of the road embankment slope is not satisfied. The low value of the factor of safety *F* suggests that the occurrence of a slope failure in the road embankment is highly probable in this case. In such situation it is necessary to design the reinforcement for the embankment slope. It is proposed to reinforce the slope with layers of the geonet having the following parameters:

– basic raw material – PET;

- weight 300 g/m^2;
- characteristic short-term tensile strength (along) $F_{o.k}$ of 45 kN/m;
- strain at the rated tensile strength ≤ 10%;
- mesh aperture size 35 x 35 mm.

For the analysed case it is necessary to determine the design value of the long-term tensile strength of the geosynthetic material used as reinforcement F_d, on the basis of the allowable stress method, adopting indispensable reduction factors. The value of the parameter F_d in the analysed case is equal to 16.356 kN/m. In the next step it is necessary to determine the characteristic value of the long-term tensile strength of the geosynthetic material used as reinforcement F_k, also on the basis of the allowable stress method. The determined value of F_k is 22.898 kN/m. It is proposed to reinforce the road embankment with six layers of the geonet; the number of layers of the geosynthetic material is represented by the parameter n_z. In the next step the influence exerted by the geosynthetic reinforcement on the moment of the forces retaining the road embankment M_{uz} is investigated, in accordance with formula (9). The thickness of blocks of the soil mass along the embankment slope was adopted for calculation purposes as the value s_n = 1 m.

$$M_{uz} = F_d \cdot n_z \cdot R \cdot \mathrm{s_n} \ \ [\mathrm{kN \cdot m}] \tag{9}$$

In the analysed case the value of the moment of the forces retaining the embankment, including the reinforcement (M_{uz}), totals 837.084 kN·m. In the next step it is necessary to determine the design value of the retaining and turning effect of the moment of the forces acting on the soil mass forming the road embankment, in accordance with the following formulas:

$$M_{ud} = 1.0 \cdot M_u + M_{uz} \ \ [\mathrm{kN \cdot m}] \tag{11}$$

$$M_{od} = 1.35 \cdot M_d \ \ [\mathrm{kN \cdot m}] \tag{12}$$

In accordance with formula (11) the moment of the forces retaining the structure of the road embankment reinforced with the geonet (M_{ud}) totals 1427.3369 kN·m, whereas the moment of the forces turning the structure of the road embankment reinforced with the geonet (M_{od}) adopts, according to formula (12), the value of 783.671 kN·m. In the final calculations the factor of safety should be determined again, for the reinforced slope of the road embankment, in accordance with formula (1). The design value of F is 1.484. As this value falls within the range 1.3-1.5, the structure of the embankment slope reinforced with the proposed geonet is stable and the condition for its stability is satisfied.

Taking into consideration the results of the analysis for both cases the safety factor of the road embankment slopes F has different values. In the case of the embankment without any reinforcement the factor of safety F adopts the value of 0.83, which is below the allowable limit. In this case the road embankment slope may pose a hazard to road traffic, due to the high probability of the occurrence of a disaster in the form of a landslide affecting the road embankment. In the case where the structure of the road embankment is reinforced with six layers of the geonet the condition for the stability of the road embankment slope is satisfied, and the value of the factor of safety is equal to 1.484, which suggests that the occurrence of the road embankment failure is unlikely. In the analysed case the proposed reinforcement of the embankment is not sufficient to achieve the situation where the occurrence of a landslide is highly unlikely (as F should be higher than 1.5). In the analysed case it is suggested to increase the number of layers of the geonet by one or two or to use the geonet with a higher characteristic value of short-term tensile strength (along). The proposed solutions will lead directly to an increase in the value of the moment of the forces retaining the road embankment slope and, thus, to an increase in the factor of safety of the road embankment slope F above the value of 1.5.

CONCLUSIONS

The safety of road traffic represents an important issue, particularly in crisis situations during natural disasters. Any damage to the road infrastructure causes a temporary interruption of traffic or a permanent closure of a section of the damaged road, thus creating a crisis situation regarding traffic and communications. The reconstruction of the road infrastructure and the restoration of the traffic flow pose a huge problem and require substantial expenditure. Therefore, already at the design stage, all factors affecting the safety of the road structure should be taken into account, in particular unforeseeable accidents (floods, inundations) occurring increasingly often in Poland, and any design errors should be eliminated. It is very important to investigate and prepare in advance the technological solutions capable of restoring efficiently the flow of road traffic. At present, an optimum solution is offered by geosynthetic materials, characterised by good tensile strength and puncture resistance parameters and ensuring the high durability of the structure. As shown by the analysed example, the use of geosynthetics for the construction of road structures represents an ideal solution for the road engineering, to protect slopes and road embankments. The application of the latest computational methods, the proper identification of potential threats and the use of the state-of-the-art geosynthetic materials will make it possible to build highly durable structures of the road infrastructure.

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