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Mitigation of Flourd (Pol e safid) landslide, Northern Iran, using non-woven geotextiles

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Укрепване на свлачището Флоурд (гр. Пол е сафид), Северен Иран, чрез използването на нетъкан геотекстил

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Abstract. Hazardous landslides are ordinary phenomena in north of Iran. In this paper, mitigation of Flourd landslide in Savadkouh by using non-woven geosynthetic was investigated.

Reinforced slope was designed using limit equilibrium analysis and numerical method such as those based on the Federal Highway Administration of the USA (FHWA) guidelines and finite element method and with in-situ residual soil parameters. The main goal of this paper in designing a reinforced slope instead of failed slope is finding number of reinforcement layers and vertical distance of reinforcement layers.

Using the non-woven fabric to repair failed slope is a good option to prevent respective failures. When the non-woven fabric is used, it not only generates the tension forces to enhance the overall stability of slopes, but also prevents the development of pore water trapped in clayey soils by providing horizontal drainage through the fabric. Results of analysis showed that positive effects of reinforcement are clear and lead to decrease of horizontal displacement.

Key words: landslide, mitigation, geosynthetic, FHWA, finite element method.

Абстракт. Рисковите свлачища са обичайно явление в Северен Иран. Настоящата статия представя резултатите от укрепването на свлачището Флоурд, до гр. Савадкоух, чрез използването на нетъкан геосинтетичен материал.

Укрепеният откос е проектиран, чрез използването на равновесния метод и числени методи, базирани на препоръките на Федералната пътна администрация на Съединените щати (FHWA), метода на крайните елементи и параметрите на остатъчната якост на почвата (in-situ). Основна цел на статията е при проектирането на укрепения склон на мястото на свлечения склон, да се определи броя на укрепителните слоеве и вертикалното разстояние между тях.

Използването на нетъкан геотекстил за укрепването на свлачищни склонове е един добър подход за предотвратяване на свличания. Употребата на нетъкан материал не само генерира опънови сили, които водят до цялостно подобряване на стабилността на склона, но и предпазва от образуването на капсуловани порови води в глинестите почви, чрез осъществяването на хоризонтално дрениране през материала. Резултатите показват ясен позитивен ефект от укрепването, който води до намаляване на хоризонталното преместване.

Ключови думи: Иран, свлачище, укрепване, геотекстил, метод на крайните елементи.

Introduction

Landslides are frequently responsible for considerable losses of both money and lives, and the severity of the landslide problem worsen with increased urban development and change in land use. Given this understanding it is not surprising that landslides are rapidly becoming the focus of major scientific research, engineering study and practices, and land-use policy throughout the world.

In every slope there are forces which tend to promote down slope movement and opposing forces which tend to resist movement. A general definition of the factor of safety, F, of a slope results from comparing the down slope shear stress with the shear strength of the soil, along an assumed or known rupture surface. Starting from this general definition, Terzaghi (1950) divided landslide causes into external causes which result in an increase of the shearing stress (e.g. geometrical changes, unloading the slope toe, loading the slope crest, shocks and vibrations, drawdown, changes in water regime) and internal causes which result in a decrease of the shearing resistance (e.g. progressive failure, weathering, seepage erosion). However, Varnes (1978) pointed out there are a number of external or internal causes which may be operating either to reduce the shearing resistance or to increase the shearing stress. There are also causes affecting simultaneously both terms of the factor of safety ratio.

The methods used to design reinforced slopes are mainly based on the limit equilibrium concept. Methods such as: Reugger (1986); Schmertmann et al. (1987); Leshchinsky and Boedcker (1989); Jewell (1980, 1989) and Michalowski (1997) all utilize limit equilibrium analysis or limit analysis in the design of reinforced slopes (Table 1).

Extensive experimental studies have been devoted to the evaluation of effect of reinforcement on stability of soil slopes. One of the most important studies in this field were conducted by Zornberg et al. (1998a, 1998b); Zornberg (2003); Zornberg and Arriaga (2003) who observed the behavior of reinforced slopes in the centrifuge. The effect of reinforcement on stability of soil slopes, and the associated failure mechanisms were assessed in their study. These authors showed that, if a prototype of actual dimensions is modeled with a reduced scale of 1/N and subjected to an acceleration field N times that of gravitational acceleration, a stress field similar to the prototype structure would be reproduced within the reinforced slope model in the centrifuge. Other parameters such as density and internal angle of friction are unchanged while tensile strength of geotextile layers in the model is reduced by a factor of N. Some important findings of Zornberg et al. (1998a, 1998b); Zornberg, (2003); Zornberg and Arriaga (2003) from centrifuge tests performed on reinforced soil slopes may be summarized as follows:

– failure in the reinforced slope model was observed to pass through the slope toe, which is in good agreement with the assumption of limit equilibrium methods;

– failure initiated from mid height of the reinforced model which contradicts the assumption made in limit equilibrium method that failure develops through the toe of the slope;

– location of maximum reinforcement load and the associated maximum strain along the potential failure surface depend on slope angle and overburden pressure;

– stability of the reinforced slope is governed by peak strength of the soil.

Site description

Geographical location

The Flourd site is located in the north of Iran at 5 km from Pol e sefid city, at Savadkouh Azad University grounds in the rural surroundings of Savadkouh, (Figs. 1, 2, 5).

The elevation of the site is 350 m above sea level and like the surrounding lands, a forest vegetation cover and a mountainous morphology is dominant. The extent of the landslide is shown by a scarp along with tilted trees (Fig. 3).

The area investigated consists of an old slide mass which had several slides during the Quaternary, associated with saturated conditions and dynamic loading caused by severe earthquakes. Peat, lignite remains and coal remains from Alder trees which were revealed from boreholes at the site indicate that the site had several previous slides and that generally similar paleoclimatic conditions existed in the past.

Table 1
Specifications of limit equilibrium methods for design of reinforced slopes

Таблица 1
Методи на граничното равновесие при проектиране на укрепени склонове

Michalowski 1997	Jewell 1989	Reugger 1989	Leshchinsky, Boedcker 1989	Schmertman, 1987	Method
Kinematics limit analysis	Two-part wedge	slices	Internal stability: Variational Limit equilibrium	Two-part wedge	Model
($c = 0, \phi$)	($c = 0, \phi$)	($c = 0, \phi$)	($c = 0, \phi$)	($c = 0, \phi$)	Soil
0, 0.25, 0.5	0, 0.25, 0.5	0	0	0	(r_0)
30°–90°	30°–90°	40°–90°	45°–90°	30°–80°	Slope Angle
Parallel to slope face	Not parallel to slope face	Parallel to slope face	General case	Not parallel to slope face	Reinforcement Arrangement
20°–50°	20°–50°	40°–90°	15°–40°	15°–35°	ϕ
0.5–0.8	0.8	0.6–1	0.6–1	0.9	μ
Triangular or Rectangular	Triangular	Rectangular	Triangular	Triangular	Distribution of reinforcement force with height

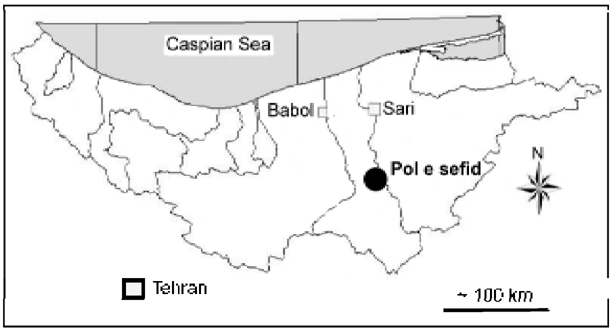

Fig. 1. Geographical location of Flourd landslide

Фиг. 1. Географско местоположение на района на свлачището Флоурд

Geological characterization

One of the important factors affecting the instability potential of a landslide hazard area is the engineering geological parameters and characteristics of that site. In this context, the parameters considered usually consist of site geometry, failure mechanisms observed, effect of slide on existing structures, assessment of the causes and the risks for future occurrence of slides, and classification of the landslide and the existing soil characteristics. All these have been studied in Flourd landslide and have revealed the high landslide hazard of the site. The geological units occurring in the locality consist of sediments of Mezosoic and Cenozoic age (Fig. 2). Some lithological varieties (marls, shales and siltstones) are susceptible to landslide occurrence.

Hydrogeological conditions

Underground site investigations indicate that no stable underground water table exists. However, underground seepage flow seems to exist within the direction of silt and gravel lenses which exist in the stratification. Bore pits dug in the area show that seepage water exists at the depth of three to five meters below ground level. Water level was observed in several observation wells at depths ranging from 10 to 15 m, at the interface between the slide mass and the underlying bedrocks.

A part of the run-off flow outside the active slide area leaks into the slide area which is in addition to the rainfall induced seepage from surface water absorption. The slide mass is therefore considered to be saturated at the time of flow.

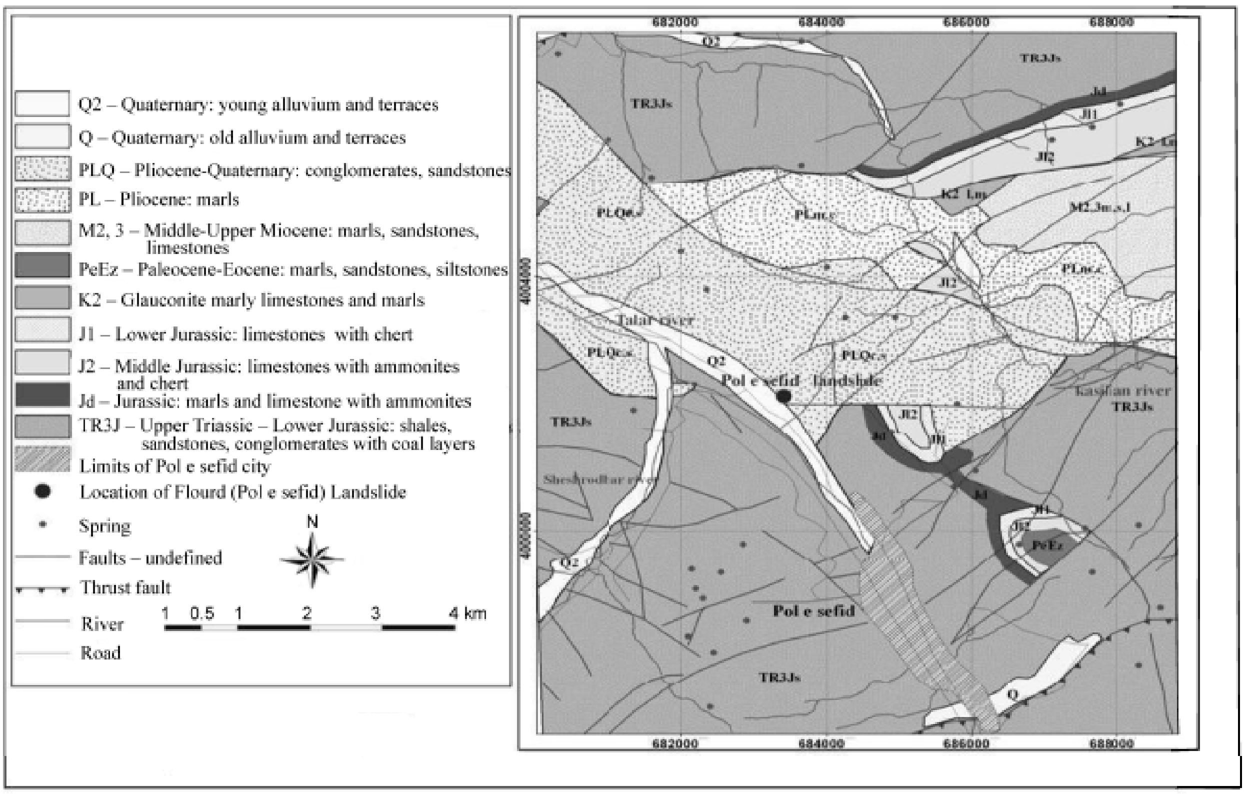

Fig. 2. Geological map of Pol e sefid area with location of Flourd landslide (After Pazoki et al., 2003).
Small letters beside age indexes on the map indicate dominating lithology (c – conglomerates, s – sandstones, l – limestones, m – marls)

Фиг. 2. Геоложка карта на района на свлачището

Site geometry

The slide mass is part of a sliding slope facing the south eastern direction. It extends to the calcareous sediments on the south west side, and to the river at the foot (Fig. 3). Steady state seepage passages through the medium and above the level of the rock basement. A volume of 15 to 20 liters per second were predicted for these seepage flows. The slide mass does not have any visible surface flow paths and the existing paths are rather scattered in the whole region.

From the lateral scarps, silty clay along with boulders is visible. The slide initiated at the point where little vegetative growth existed. Surface water from rainfalls directly penetrated the underlying soils at theses surfaces and was lead through the shear zone of the sliding mass. Some springs visible at the foot of the sliding mass are an indication of this process.

The upper surface of the slide has a concave form which gathers rainfall water into the sliding mass. Therefore, each period of heavy rainfall caused a reactivation of the slides.

Tilting of the existing trees indicates that a creep type of active slide is dominant in the area (Fig. 4).

The effect of landslide on existing geotechnical structures in the area was generally in the form of slides in the slopes, creep, tilt and structural cracks in the geotechnical structures. These defects were mainly attributed to poor engineering characteristics of the structures, both in design and construction.

Fig. 3. Scarp of Flourd landslide with tilted trees

Фиг. 3. Свлачищен откос с наклонени дървета („пияна гора“)

Fig. 4. A view of the active slide at the site – tilting trees and visible roots indicate an active sliding

Фиг. 4. Активната хлъзгателна повърхнина на свлачището – наклонените дървета и изровени корени показват свлачищна активност

Modeling Flourd Landslide

In order to better understand and assess Flourd landslide and the potential applicability of using geotextile reinforced in-situ cohesive soil for mitigation of this landslide, initially, limit equilibrium method was utilized in this study. The method suggested by Federal Highway Administration (FHWA) was followed in the analyses. Limit equilibrium analysis code Reinforced Soil Slopes (RSS) was effectively utilized to run limit equilibrium analyses in order to evaluate the effect of reinforcement on the factor of safety against landslide. RSS calculates the factor of safety for an existing non-reinforced slope and is able to calculate the required amount of reinforcement in order to reach a desired factor of safety associated with equilibrium or stable conditions. RSS is able to design a reinforced slope by one of the three following procedures:

– calculating reinforcement spacing for a given slope configuration in order to reach a desired factor of safety;

– determination of the required reinforcement strength in order to reach a desired factor of safety;

– calculation of the factor of safety of a reinforced slope with a given configuration of reinforcements.

It is noteworthy that RSS follows all the design procedures suggested by Federal Highway Administration of the (FHWA).

In order to mitigate Flourd landslide using in-situ cohesive soils reinforced with horizontal geotextile layers, an initial reinforcement configuration was first designed, and through limit equilibrium analysis using RSS, the factor of safety of the reinforced slope was determined. Next, the resulting factor of safety was checked by design suggestions from the literature in order to verify the adequacy of the design (Cornforth, 2004). After verifying the given initial reinforcement configuration, the design procedure suggested by FHWA was followed in order to obtain the necessary reinforcement spacing and strength in RSS code.

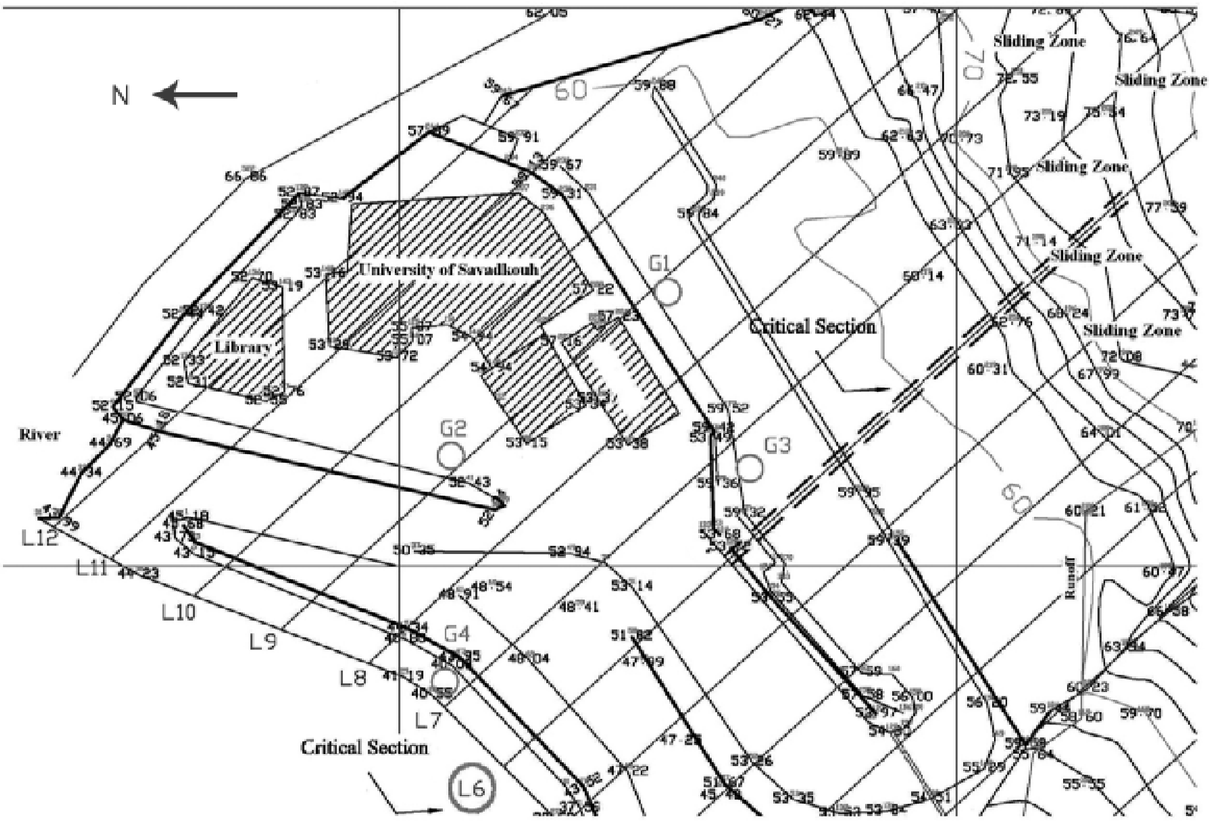

Fig. 5. Topography of the landslide area

Фиг. 5. План на района на свлачището

Prior to numerical analysis of a landslide, it is necessary to select a critical section of the landslide geometry, so that plane strain calculations can be performed. In this context, Flourd landslide was observed by the topography maps available, and a critical section (Fig. 5, line L6) was chosen for analysis. This section is believed to be representative of the behavior of the landslide since a relatively wide area is covered by the slide and therefore the assumption of plane strain conditions is not irrelevant for this section. Moreover, the majority of site investigation was conducted in the vicinity of this section and therefore, more thorough information is available in this vicinity.

The final design was obtained by following the above mentioned design procedure for three different slopes of one, 1.5 and two horizontal to one vertical. The reinforced slope area is actually the slope which is responsible for mitigation of the sliding backfill.

Each analysis involves careful determination of the initial unstable slope, and the evaluation of the necessary reinforcement configuration for obtaining stable conditions. The initial design configuration involves a reinforcement vertical spacing of 0.5 m and a reinforcement length of 15 m. Reinforcement length is automatically checked for necessary factor of safety against pullout failure, by the program. The results of the initial analysis showed that the slope geometry with a face slope of two horizontal to one vertical was stable under natural conditions and no reinforcement design was required for this design. Therefore, only the slope angles of one and 1.5 horizontal to one vertical were considered in the consecutive analyses. A reinforced soil slope factor of safety of 1.4 was considered adequate for conditions of equilibrium and chosen for design, following the suggestions of Cornforth (2004) for a medium size landslide with limited site characterization information.

Results and discussion

Limit equilibrium analysis was first performed on the section chosen (Fig. 5, line L6), in order to observe the possible failure mechanisms of the slide, as well as to suggest a design for the reinforced soil slope intended to mitigate the landslide. An initial analysis was performed in each case in order to evaluate the factor of safety of the slide section. Then, the design section of RSS (Elias et al., 2001) was used to give a suitable design for a reinforced soil slope in order to mitigate the landslide. The reinforced slope was extended into the bedrock in order to prevent failure surface from developing through the interface between the reinforced mass

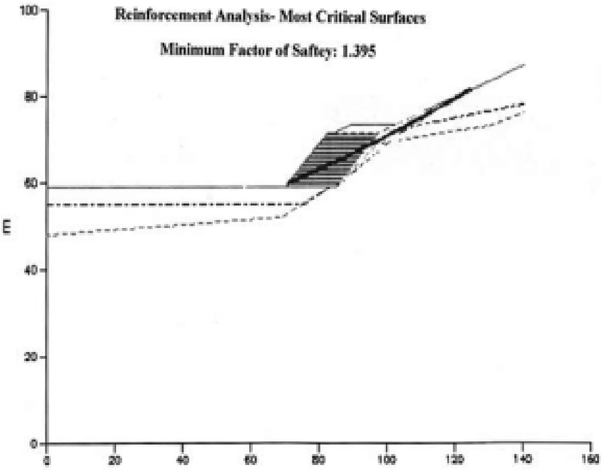

Fig. 6. Initial design of reinforced slope for 1.5:1 slope

Фиг. 6. Начално проектиране на укрепения склон при отношение 1,5: 1

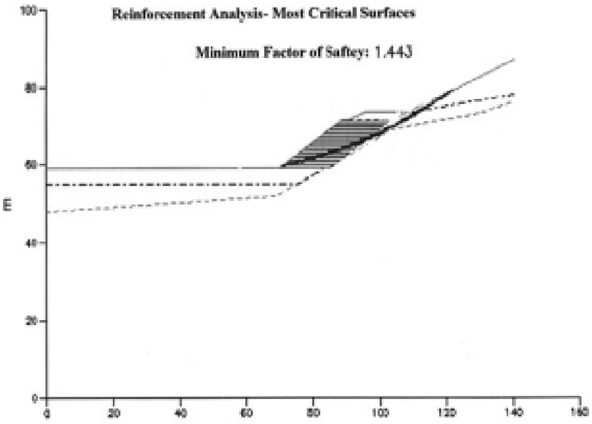

Fig. 8. Initial design for 1:1 slope

Фиг. 8. Начално проектиране при наклон на склона 1:1

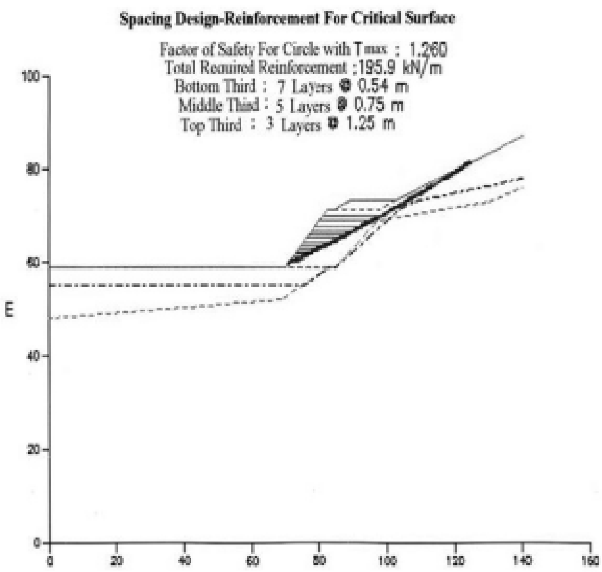

Fig. 7. Reinforced Soil Slopes (RSS) design for 1.5: 1 slope

Фиг. 7. Резултат за проектиран укрепен почвен склон при отношение 1,5: 1

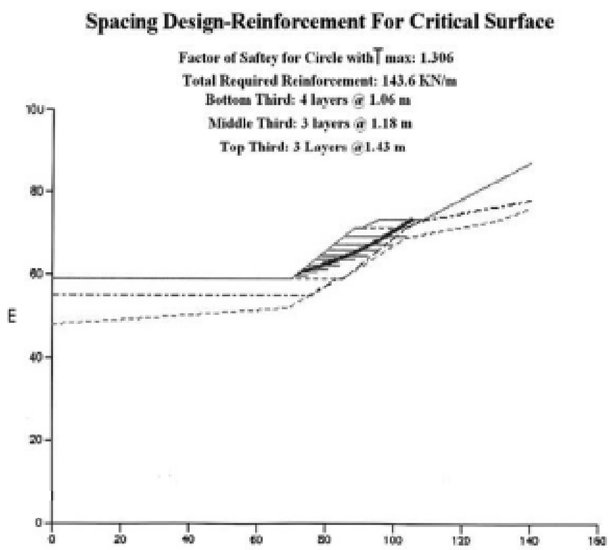

Fig. 9. RSS design for 1:1 slope

Фиг. 9. Резултат за проектиран укрепен почвен склон при отношение 1:1

and bedrock. Several RSS model analysis results were produced (Figs. 6–9), which show design outputs for the reinforcement based on FHWA guidelines. From the results of mechanical tests, the parameters used for the RSS calculations, finite element model (Tables 2–3) and also the results of the limit equilibrium analyses (Table 4) becomes clear that a reinforced slope is adequately capable of mitigating the landslide.

Furthermore, ultimate geotextiles strength and geotextiles stiffness were considered 90 KN/m and 45 KN/m, respectively, for using in limit equilibrium and finite element analysis.

Limit equilibrium analysis gives a good initial design for the reinforced slope area in the landslide. However, no information is provided by the method regarding the deformations. In order to verify the suitability of the given design for mitigation of Flourd landslide, Finite Element analysis was performed on one of the models in order to assess the deformation characteristics of the model. PLAXIS (Vermeer, Brinkgreve, 1998) Finite Element code was used for the analysis. The constitutive model used in the simulations is the standard Mohr Coulomb material within PLAXIS; 15 node elements were used to create a mesh for the problem. Moreover, the residual strength

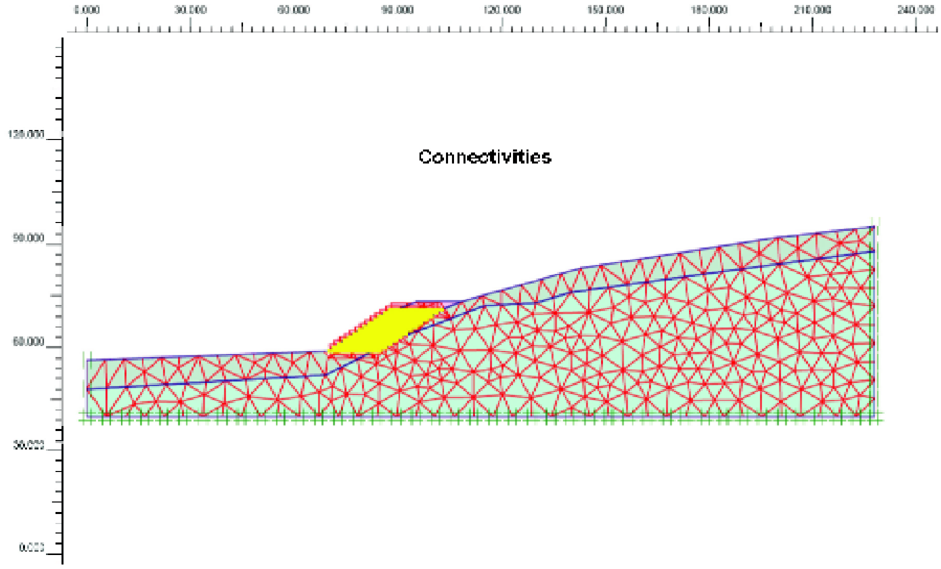

Fig. 10. Finite element mesh for the reinforced slope

Фиг. 10. Мрежа на крайните елементи за укрепения склон

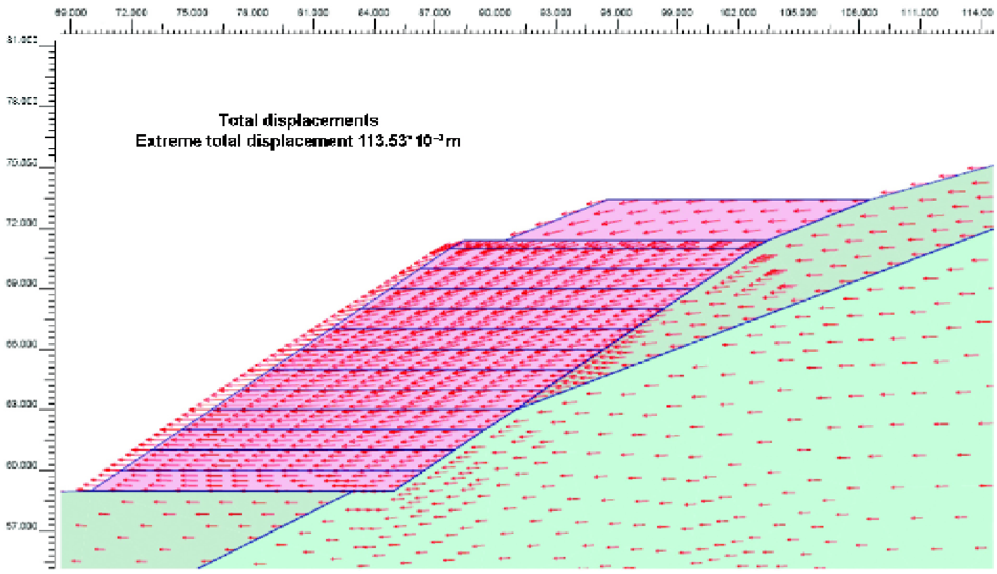

Fig. 11. Extreme total displacement vectors in the reinforced slope mass

Фиг. 11. Вектори на пълното преместване в укрепения масив

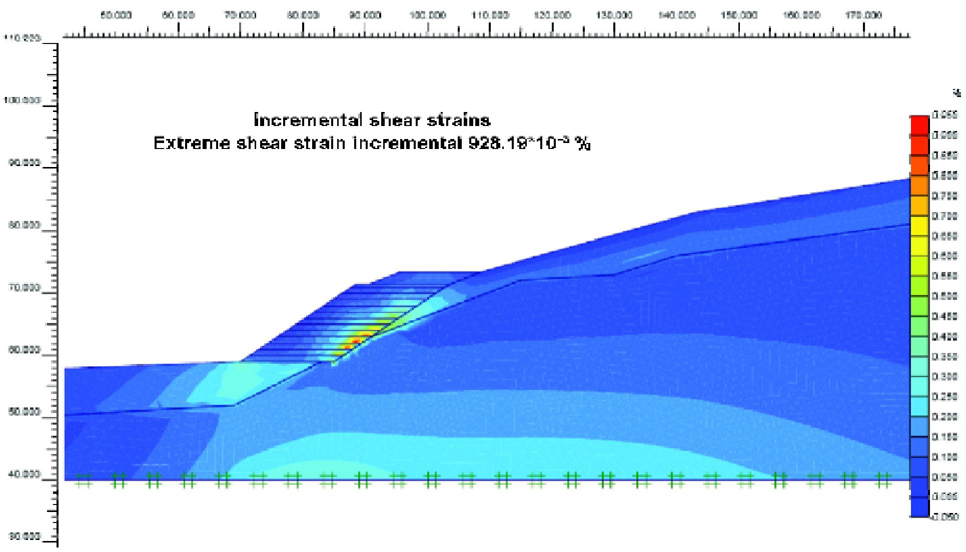

Fig. 12. Incremental shear strains within the reinforced mass

Фиг. 12. Нарастване на срязващите напрежения в укрепения масив

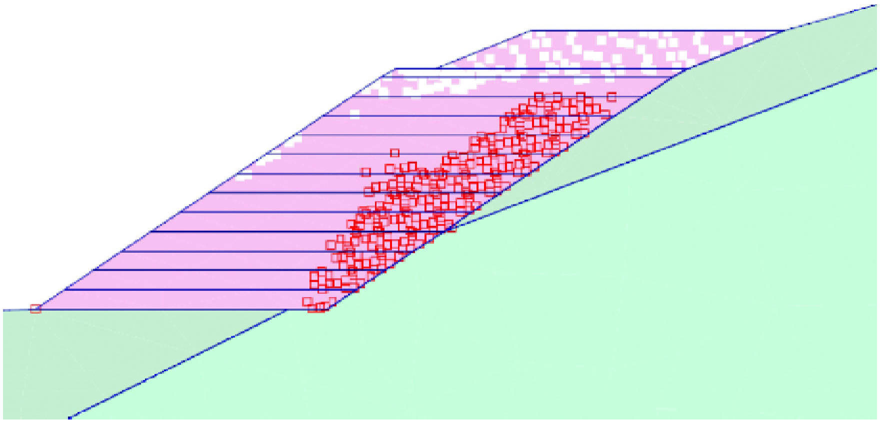

Fig. 13. Plastic points from the finite element analysis

Фиг. 13. Пластични точки от метода на крайните елементи

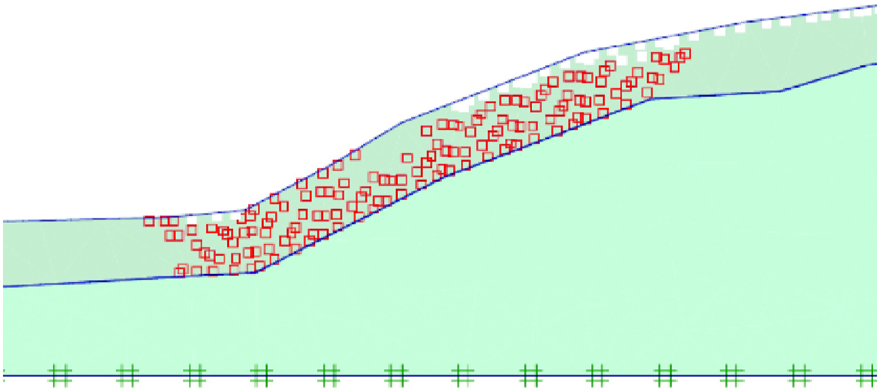

Fig. 14. Plastic points within the unreinforced embankment

Фиг. 14. Пластични точки в неукрепения откос

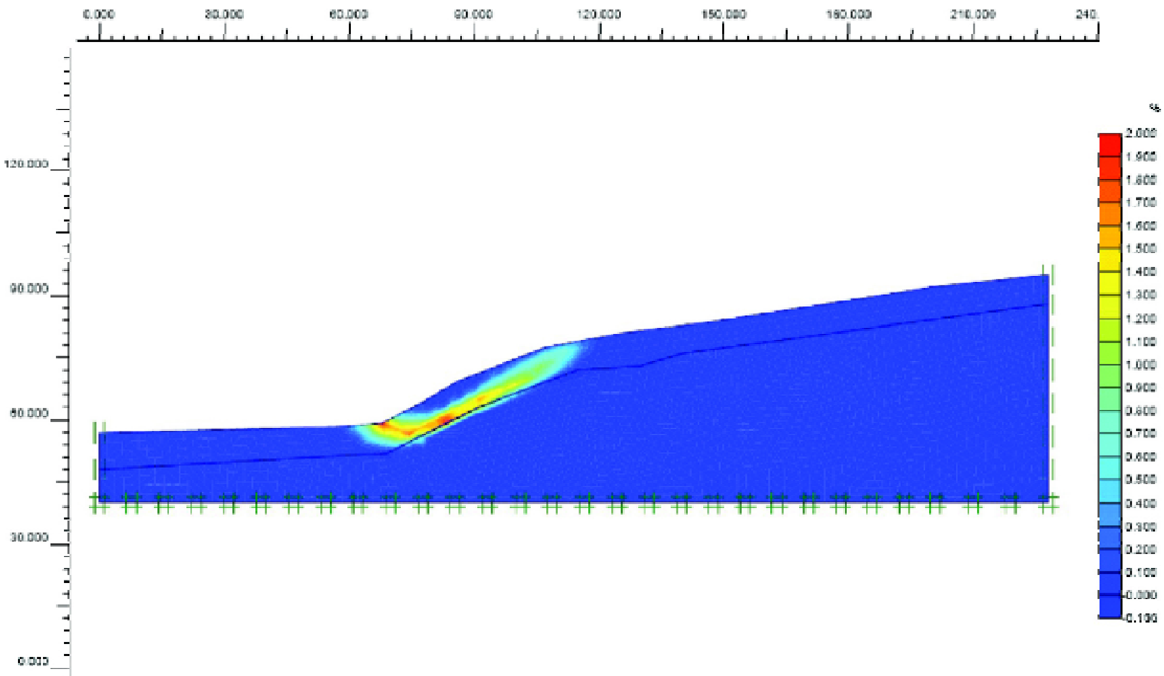

Fig. 15. Shear strains within the unreinforced embankment revealing circular failure surface

Фиг. 15. Срязващи напрежения в неукрепения откос показващи кръгово-цилиндрична хлъзгателна повърхнина

Table 2
Results from mechanical tests

Таблица 2
Резултати от механичните тестове

Number of Models	Lithological Varieties	Depth (m)	Triaxial Tests		Direct Shear	
			c_y (kPa)	ϕ_y (degree)	c_y (kPa)	ϕ_y (degree)
G_1	Silty clay with gravels and boulders, sand	0.5	–	–	8	28
G_2	Clay with siltstone, marl, silty clay	1.5	0.39	24	–	–
G_3	Silty clay with gravels and boulders, sand, sandy clay	3	–	–	8	28
H	Heavy clay, sand	3.5	–	–	0	34
I	Clay with gray to green slime	4.5	0	22	–	–

Table 3
Properties of soils used in limit equilibrium and finite element analysis

Таблица 3
Показатели на почви използвани в изчисленията по методите на граничното равновесие и на крайните елементи

Soil Type	Moist Unit Weight γ_{wet} (kN/m^3)	Saturated Unit Weight γ_{sat} (kN/m^3)	Internal Friction Angle (degree)	Cohesion (kPa)	Modulus of Elasticity calculated by SPT experiments (MPa)	Poisson's Ratio
Bed Rock	20	20.5	45	100	100	0.25
Unreinforced Soil	17.4	18.5	28	5	7	0.35
Reinforced Soil	18	19.2	15	10	15	0.30

Table 4
Reinforced Soil Slopes (RSS) results for different slope angles

Табица 4
Резултати за укрепените почвени склонове при различен наклон

Reinforced Slope				Unreinforced slope	Slope Angle
RSS Design		Initial Design			
Reinforcement layout	Required Reinforcement	Simplified Bishop Factor of Safety	Sliding Block Factor of Safety	Factor of Safety	-------
*7@ 0.54 m 5@0.75 m 3@1.25 m	180/62 m/m	1.395	1.423	1.260	1:1
4@1.06 m 3@1.18 m 3@ 1.43 m	153.1 m/m	1.443	1.812	1.306	1.5:1
---	---	1.549	2.329	1.485	2:1

* 7@ 0.54 m = 7 geotextile layers with 0.54 m length

of soil was utilized due to shear failure of mass, resulting in a finite element mesh (Fig. 10). A reinforcement vertical spacing of 0.5 m was chosen for the model, since only the deformation characteristics were intended from this analysis and no design output was to be arrived at this stage. Lateral boundaries were fixed in the horizontal direction while the bottom horizontal boundary was fixed in both directions. Geotextile elements available in PLAXIS code were used to model geotextile layers. An interaction index of 0.85 was chosen for the interface elements (Athanasopoulos, 1996).

Maximum displacements in the reinforced slope were obtained as 11.4 cm, which is equivalent to 0.9% of the slope height. Total displacement vectors (Fig. 11) show a maximum displacement of 0.3 cm.

Incremental shear strains as depicted (Fig. 12) reveals that strain localization occurs mainly in the interface area between soil-geotextile layers. It can be seen that maximum shear strain increment is measured as 0.93%. These low values prove that geotextile layers adequately mitigate the strains within the slide mass. The plastic points of the slope (Fig. 13), once again show that maximum displacements occur in the soil-geotextile interface, and that no clear failure mechanism is forming in the slope. Moreover, comparison between plastic points and incremental strains show that plastic points are attributed not to the base soil of the embankment, but to the interface area of soil-geotextile layers. This is due to low interface properties of non-woven-geotextile layers. Although woven geotextiles have higher interface properties, however, drainage characteristics of non-woven geotextiles result in an increase of shear strength in the interface area, thus increasing interface properties compared to woven geotextiles. Therefore, the observed behavior in the reinforced soil is inevitable and shear strength properties may only be increased through other methods such as the sandwich technique.

Stress-strain analysis was also performed by PLAXIS on non-reinforced model of the natural state of the slide area in order to observe actual displacement characteristics of the landslide prior to mitigation. Natural state prior to the slide was predicted from the slide geometry. Displacement vectors revealed that maximum displacement of 52.7 cm occurs in the slope which is equivalent to 4.25% of the slope height. These high displacement values reveal the circular failure mechanism that is forming within the slope. Plastic points and shear strains within the model (Figs. 14, 15), better reveal the circular failure mechanism.

Conclusions

Based on limit equilibrium analysis and stress-strain analysis performed both on unreinforced and reinforced models of Flourd landslide, general conclusions are drawn as follows:

– finite element analysis on the slide mass revealed that circular failure surface developed in the landslide, therefore approving the circular failure mechanism assumed in the LE analysis;

– the analyses showed that using in-situ cohesive soil reinforced with geotextile layers is adequately able to mitigate shallow to medium landslides;

– in order to make full use of beneficial effects of reinforcement, the reinforced area should extend into the harder medium;

– reinforcing the slope reduces both horizontal and vertical displacements substantially.

– non-woven geotextile layers are more suitable for reinforcing cohesive soils than woven geotextiles, due to proper drainage properties.

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