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Sliding resistance mechanism and whole stability analysis for reinforced soft foundation of embankment with geofabric

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ABSTRACT: The safety coefficients are improved little with circular failure analysis method stated in the criterion for preventing deep sliding of reinforced underlying layer of embankment with geofabric, which doesn't agree with the actual effect of reinforced geofabric. By comprising the full scale test of embankment without reinforced underlying layer with the other two sections being provided with one or two reinforced underlying layers, the sliding resistance and reinforcement effect are revealed. Making use of the data of the full scale test, a new circular sliding surface passing the point of maximal vertical settlement, which is the center point of interface between embankment and geofabric, is put forward. The computed safety coefficients of the embankment without or with one or two reinforced underlying layers are improved obviously with the new sliding surface and closer to actual situation than the old one.

1 INTRODUCTION

Circular failure analysis method, which is used to calculate the safety coefficient of embankment in deep sliding, has been thought of trustiness and efficiency, so it is adopted in many technical standards. This is the case of preventing deep sliding of reinforced underlying layer of embankment with geofabric. But in engineering practice, some problems appear, which can be concluded as follows (stated in Technical standard for applications of geosynthetics, GB50290-98) "At present, the safety coefficients are improved little with circular failure analysis method stated in the criterion for preventing deep sliding of reinforced underlying layer of embankment with geofabric, which doesn't agree with the actual effect. It shows that the circular arc analysis method doesn't reflect the whole effect of reinforced geofabric. We think that the distinct role of reinforced underlying layer is related with the following facts: for example, the latent sliding surface tends to develop deeply, the horizontal displacement of foundation soil is partly restricted and the stress distribution in foundation has been changed, but these factors are not reckoned in for circular failure analysis method. So the analysis methods in existence are to be improved." Recently, some theory researches and analysis for engineering in practice have appeared (e.g., Chen et al. 1990, Xu Shaoman 1991, Zhao Jiuzhai et al. 1991, Xu and Hong 2000, Lin et al. 2000, Liu et al. 2003). The contribution of the present work is to analyze interactional mechanism between soil and geofabric detailedly with a full scale test and put forward a new circular sliding surface passing the point of maximal vertical settlement, which is the center point of interface between embankment and geofabric. The safety coefficients of the embankment without or with one or two reinforced underlying layers are improved obviously with the new sliding surface and closer to actual situation than the old one.

2 ANALYSIS OF MECHANISM BETWEEN SOIL AND GEOFABRIC

In the case of whole failure of reinforced embankment, the sliding resistance effect of reinforced geofabric can be known by calculating the minimum safety coefficient of embankment with circular failure analysis method at the state of limit equilibrium. Based on the sliding resistance mechanism and the sliding resistance effect, it can be deduced that three typical sliding resistance mechanism and three typical sliding resistance forces may occur between soil and the geofabric.

Type I: If the anchoring forces acting on two ends of geofabric are almost the same, the sliding body will slide along the geofabric near the failure surface when the sliding body along the failure surface slides downwards and is just going to traverse the geofabric, and the geofabric will exhibit shearing resistance against the soil. As the shearing displacement of sliding body is large enough to reach the state of failure, the shearing resistance force is the sliding resistance force of geofabric. If the shearing resistance force is the limit value, the sliding resistance force of geofabric achieves the max. Subsequently, it will be the residual shear strength. It is noticeable that the shear strength is related to the angle between the direction of shearing force and the sliding surface.

Type II: If the anchoring forces acting on two ends of geofabric are a great way different, the geofabric in the sliding body has the tendency of pulling-out the geofabric in the stable body as the sliding body slides outside along the failure surface. Whereas, the geofabric in the stable body has the tendency of pulling-out the geofabric in the sliding body. Which one being the main tendency lies on the value of tensile strain and the value of anchoring force acting on them. They two have the effects of holding back the sliding body. It is noticeable that, when the tensile strain of geofabric in the direction of pulling-out is so large that the sliding failure occurs, the pulling-out resistance force is the sliding resistance force of geofabric. If the pulling-out resistance force is the limit value, the sliding resistance force of geofabric achieves the max. Subsequently, it will be the residual pulling-out strength.

Type III: If the anchoring forces acting on two ends of geofabric are almost the same, the geofabric which the failure surface passes by is in the tensile state mainly. If the tensile deformation is larger than the stretching deformation of pulling out from one side or two sides of soil body possibly and does not lean to any side obviously, then the tension resistance force is the sliding resistance force of geofabric when the tensile deformation is large enough to make the soil body reach the state of failure. If the tension resistance force is the limit value, the sliding resistance force of geofabric achieves the max. Subsequently, if the geofabric is mangled into pieces, it will be the residual tearing strength.

3 ANALYSIS FOR REINFORCED SOFT FOUNDATION OF EMBANKMENT WITH GEOFABRIC

3.1 *Full scale tests of section A and section B*

In the 1980's, a great deal of embankment against the seawater had been built in the seaport of Shengli Oil Field. But later, the project had to be shut down because some sections of embankment can not achieve the height of obstructing out the seawater due to their instability and collapse. The reason is that but the surface layer(sandy loam with thickness of 1.0~2.0 m) of embankment foundation has some bearing capacity, the lower part is soft layer of mucky loam with thickness of 2.6~9.3 m. The instability and failure of embankment is mainly related to the insufficient bearing capacity of soft layer. To get the essential data to examine the effect of some building plan, and to approve the experimental and numerical results, the field full scale failure tests are put up. The testing embankment with the foundation of 2.6~9.3 m thick soft layer of mucky loam is divided into four sections. The typical section is depicted in Fig. 4. Here only three main sections (namely section *A*, *B* and *C*) are to be introduced. Section *A* is the natural embankment without reinforced geofabric; Section *B* is the embankment with one reinforced underlying layer of geofabric spreading on the surface of its foundation, and the thickness of soft layer of mucky loam is 0.5 m greater than that of A's; Section *C* is the embankment with two reinforced layers of geofabric, one spreading on the surface of its foundation and the other spreading at the height of 0.3 m above the surface of its foundation. The filling material is sandy loam, with 0.3 m thick one layer. After rolling the dry density should be 1.55 g/cm^3. At the same time, the observation instruments such as border piles, surface settlement plates, displacement gauges of geofabric, magnetic probe extensometers, pore water pressure cells and so on are buried in the embankments and its foundations. In addition, the geological prospecting and vane shear test in field, and tensile tests of the strips with width of 5 cm selected in the longitude and latitude directions from the geofabric are carried out in laboratory. Figure 1 illustrates the relationship between tensile force and tensile strain. The shear strength parameters between soil and geofabric are: cohesion c = 6 kPa, friction angle φ = 29.5°; The strength parameters of geofabiric pulling-out from soil are: cohesion c = 3 kPa, friction angle φ = 28.5°.

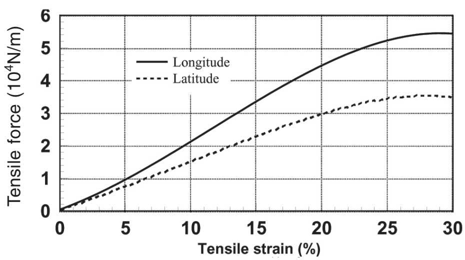

Figure 1. The relationship between tensile force and tensile strain of geofabric.

When the height of filling soil of section *A*, *B* and *C* achieve 3.86 m, the horizontal displacement observed by border piles and the vertical settlement observed by surface settlement plates on the surface of foundation, and the tensile strain observed by displacement gauges of geofabric start to increase. When the height of filling soil of section *A* and section

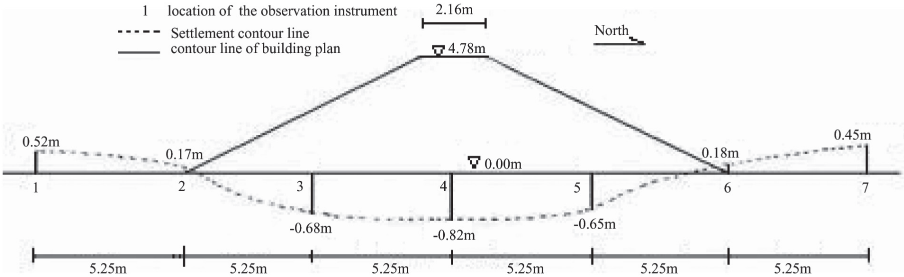

Figure 2. The settlement contour line of section B.

B achieve 4.0 m, the observed numerical value increases rapidly. When horizontal displacement and vertical settlement increased from several decades to one hundred millimetres everyday, section *A* and section *B* can be considered to enter the state of limit equilibrium. When the heights of section *A* and section *B* achieve 4.78 m, a majority of embankment together with part of foundation slide towards one side and the whole instability of section *A* and section *B* occurs. At the same time the tensile strain of geofabric, the horizontal displacement and the vertical settlement on the surface of foundation increase to the maximum rapidly, then cease or start to decrease. The settlement contour line of section *B* is depicted in Fig. 2. Section *C* is only built to the height of 4.0 m on schedule, which is the height of blocking the tide out.

Figure 3 illustrates the development of tensile strain of geofabric with the time as the height of section *B* increases continuously. Observation point of Curve B_3 locates at the surface center of foundation. Observation points of Curves B_2, B_4, B_1, and B_5 are 5 m left, 5 m right, 10 m left, 10 m right away from the centre of foundation separately.

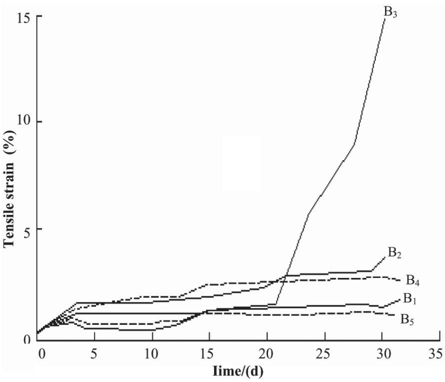

Figure 3. Development of tensile strain of geofabric of reinforced embankment B.

3.2 *Effect analysis for reinforced soft foundation of embankment with geofabric*

Table 1, Table 2 and Table 3 illustrate the results by analyzing and cleaning up correlative observation data obtained from the full scale tests. It can be found that for the magnitude of whether the vertical settlement, or the horizontal displacement, or the vertical settlement difference per day, section *A*'s exceed section *B*'s and section *B*'s exceed section *C*'s. All of these reflect the geofabric's role of dispersing, balancing and minifying the stress in the foundation.

Table 1. Vertical settlement of the bottom of embankment at the height of 4.0 m.

Sections	Vertical settlement of settlement plates (mm)						
	1	2	3	4	5	6	7
A	–76	–50	219	337	234	–42	–61
B	–67	–31	170	292	208	26	–52
C	–42	–14	178	266	179	–14	–39

Table 2. Horizontal displacement of the basement of embankment at the height of 4.0 m.

Sections	A			B			C		
	Border pile number								
	1	2	3	4	5	6	7	8	9
North (mm)	81	93	91	89	81	62	63	70	56
South (mm)	90	100	106	82	81	70	41	40	43

Table 3. Difference of vertical settlement between the center and the slope of embankment at various elevations everyday.

Sections	Heights of embankment (m)					
	3.0	3.2	3.4	3.6	3.8	4.0
A(mm/d)	7.2	8.0	9.0	10.0	11.0	12.0
B(mm/d)	6.8	7.3	8.1	8.8	9.7	10.9
C(mm/d)	6.6	6.9	7.4	8.1	8.8	9.8

3.3 *Analysis for sliding resistance role of geofabric*

3.3.1 *Comparison of three typical sliding resistance mechanism for section B*

According to observation data of section *B* in the state of limit equilibrium and instability, and referring to Fig. 4, the sliding resistance force of type 1 can

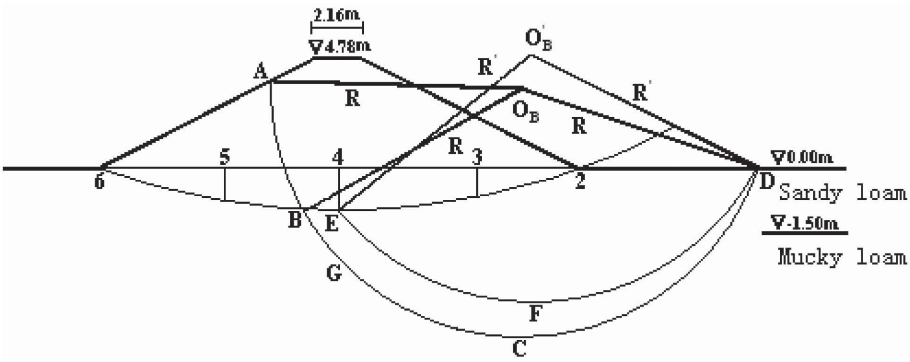

Figure 4. New and old limit slip surfaces of embankment B.

adopt the limit shearing resistance strength of the width (0.72 m) of two strips of geofabric near the failure surface, with the angle of 60° between the failure surface and the strips and the force arm of 10.9 m, which is the radius of sliding arc; the sliding resistance force of type 2 can adopt the pulling-out resistance strength supplied by geofabric (8.4 m long) in the stable body, which corresponds to average pulling strain (1.7%) measured. The force arm is 3.5 m, which is the perpendicular distance from the centre of the circle to the pulling-out resistance force; the sliding resistance force of type 3 can adopt the tension resistance strength supplied by geofabric near the failure surface and corresponds to the maximum of tensile strain (15.58% of curve B_3). The force arm is 3.5 m, which is the same as type 2.

Corresponding to the field failure test of section *B* and using circular failure analysis method, the most dangerous arc of section *B* got is the arc ABGCD, with the centre O_B and the radius O_BE (10.9 m long) of the circle, and the minimum coefficient of stability (K) are: $K_{BI} = 0.960$ for type I, $K_{B2} = 0.938$ for type II, $K_{B3} = 0.876$ for type III.

If the reinforcement effect of geofabric is not reckoned in, then the minimum safety coefficient K_B is 0.848. It is obvious that the contributions of geofabric to increasing the minimum safety coefficients are: 0.112 for type I, 0.09 for type II, 0.028 for type III.

3.3.2 *Comparison of section A and section B*

Though the foundation properties (mainly the thickness of soft soil layer) of section *A* and section *B* vary in some degree, the limit instability heights are the same (4.78 m). The minimum safety coefficient K_A of section *A* worked out with circular failure analysis method is 0.935, which is 0.087 greater than K_B (0.848) of section *B* worked out without the reinforcement effect of geofabric taken into account. The difference also reflects the reinforcement effect of geofabric.

Otherwise, the mechanism of pulling-out resistance of type II accords to the actual failure status mostly as K_{B2} is nearest to K_A (the difference being 0.003 only).

If the minimum safety coefficient of section *B* without reinforcement of geofabric was the same as section *A*'s (0.935), then the limit height of section *A* can but decreased to 3.91 m. The difference is 0.87 m, which can also reflect the reinforcement effect of geofabric.

It's noticeable that after the occurrence of failure the height of section *A* decreases 0.55 m, but the height of section *B* only decreases 0.23 m in succession. The difference is 0.32 m, which reflects that the reinforcement effect of geofabric is still to continue and can lighten bad sequence. This can be explained most suitably by the mechanism of pulling-out resistance of type II because relative to the measured pulling strain of geofabric there is still a lot to be exerted.

4 THE RESULTS WITH THE NEW CIRCULAR SLIDING SURFACE

4.1 *Problems of the old circular sliding surface*

According to Technical standard for applications of geosynthetics, the safety coefficients are improved little with circular failure analysis method for preventing deep sliding of reinforced underlying layer of embankment with geofabric, which doesn't agree with the actual effect. This situation exists in circular failure analysis methods used above, though concerned parameters are chose from field and laboratory tests and not reduced by a series of influence factors according to Technical standard.

For example, according to Technical standard for applications of geosynthetics, the minimum safety coefficient should not be less than 1.3, then five reinforced layers of geofabric are to be used by pulling-out resistance force related to the measured pulling strain of geofabric. Even if use the unreduced limit strength of pulling-out resistance, four reinforced layers of geofabric are to be used.

4.2 *New circular sliding surface suggested*

According to relative deformation observation data of full scale tests in the field, the vertical settlement, settlement difference, horizontal displacement and stress level of soft foundation reinforced by geofabric are less than those of soft foundation not being reinforced. In addition, the minimum safety coefficients (1.05 and 1.01) are almost the same in both cases of 2.5 m thick loading berms being located on both sides of embankment and of 1.0 m thick loading berms being located on both sides of embankment with two layers of geofabric, but the former radius is 1.75 m larger than the latter's. It can be deduced that the circular will ascend after the soft foundation is reinforced with geofabric. Otherwise, the maximum of tensile strain should be at the place where geofabric intersects circular because of the maximum of relative displacement, and the measured maximum (15.58%) of tensile strain of geofabric occurs in the position locating at the center of foundation surface. Besides, when we do triaxial shear test with one horizontal layer of geofabric in the middle of the soil sample in laboratory, we can find that the failure surface doesn't run through the geofabric but be separated into the upper part and the lower part. So it can be concluded that the failure surface does not run through the geofabric continuously, and the below part of failure surface should originate from the center of foundation surface.

So the potential new circular of section *B* is suggested as Fig. 3: keep the magnitude of radius ($R = O_B B = O'_B E$) and arc *AB* unchanged, the old arc *BGCD* in the foundation is changed to arc *EFD*, which starts from the center point *E* and runs through the foundation to the point *D*, where the upheaval of foundation surface is observed. I.e. the old arc *ABGCD* has been replaced with arc *AB* + *BE* + *EFD*. Arc 4*E* is the observed settlement of the center point 4, and O'_B is the center of the arc *EFD*.

4.3 *Aanalysis results with the new circular sliding surface*

Referring to Fig. 3, the stability analysis of arc *AB* and arc *EFD* are carried out with old circular adopting the mechanism of pulling-out resistance, but the contribution of arc *BE* is reckoned in with shearing resistance force according to the testing results in laboratory considering the mechanism of shearing resistance. This is the case of intercross sliding resistance mechanism of type I (shearing resistance) and type II (pulling-out resistance) in reinforced earth structures with geofabric possessing middle tensile strength and modulus. The sliding resistance moment of the new arc *EFD* is 2.60 times that of the old arc *GCD*, but the sliding moment of the new one is 3.66 times that of the old one. After counteraction, the sliding moment of arc *EFD* is 40.65 T · m larger than the sliding resistance moment. It can be seen that the raised new arc *EFD* is more dangerous than old arc *GCD* indeed. But then the sliding resistance moment of the new arc *AB* + *BE* is 2.19 times that of the old arc *ABG*, the sliding moment of the old one is 5.16 times that of the new arc *ABG*. Synthesizing these two factors, for the new arc *AB* + *BE* + *EFD* the sliding resistance moment is 70.826 T· m larger than the sliding moment and the safety coefficient K'_{B2} is 1.055, which is greater than K_{B1}, K_{B2}, K_{B3} and K_A and is more closer to 1.0 than K_A and K_{B2}. All of these indicate that the new arc *AB* + *BE* + *EFD* reflects more important effects of reinforcement geofabric, so it is more closer to the actual situation.

4.4 *Sliding resistance effects of two layers of reinforcement geofabric*

Section *C* is filled to the height of 4.0 m and does not reach the state of failure. In this process, the strain curve observed is basically identical with that of section *B* possessing only one layer of reinforcement geofabric before the limit equilibrium state reached. So it can be figured out that if section *B* possessed two layers of reinforcement geofabric as section *A*, their tensile strain curves observed would be identical when failure occurs, especially their tensile strain observed at the center of embankment would get to the value of 15.58% corresponding to the state of failure. The safety coefficient got according to old sliding arc K''_{B2} is 1.009, which is 0.071 larger than K_{B2} (0.938) only. If the new sliding arc is used, then K''_{B2} will be 1.18, which is not only 0.242 larger than K_{B2} (0.938) and 0.125 larger than K'_{B2} (1.055), but also 0.332 larger than K_B (0.848). So the sliding resistance effects of geofabric will be more obvious when the new arc is used.

5 CONCLUSIONS

The above three sliding resistance mechanism of shearing resistance, of pulling-out resistance and of tension resistance may play some role of strengthening the embankment and its foundation. In actual engineering they may intercross each other, but it should be pointed out that there is a leading sliding resistance mechanism. It can be seen that the safety coefficients are different based on different mechanism.

When the tensile strain of geofabric at the place of failure occurrence can suffice the instability of soil body, the reinforcement effect brought into play is the sliding resistance force supplied by geofabric. Generally, even if the minimum safety coefficient gained by reduction of some limit strength suffices technical standard, there exists concealed danger in fact. At the same time, it should be pointed out that there is a long way to go to apply the mechanical parameters of geofabric tested in laboratory to actual reinforcement engineering, which is hardly rescued by reduction of several influencing coefficients.

The sliding circular used in analyzing the limit equilibrium of slope will be changed in preventing deep sliding of reinforced underlying layer of embankment with geofabric. Making use of the data of the full scale test, a new circular sliding surface passing the point of maximal vertical settlement, which is the center point of interface between embankment and geofabric, is put forward. The computed safety coefficients of the embankment without or with one or two reinforced underlying layers are improved obviously with the new sliding surface and closer to actual situation than the old one.

REFERENCES

Chen, H., Deng, W. and Zheng, Y. (1990). "Non-linear FEM analysis of the stability of geotextile reinforced embankment". Selected Thesis of the 2nd Chinese Conference of Geosynthetics. Tianjin: The Press of Tianjin University, pp. 296-303.

Construction Engineering Headquarters of Shengli Oil Field, Civil Engineering Dalian University of Technology (1989). "Study report of foreshore soft foundation transaction", Dalian: Dalian University of Technology.

Chinese GB50290-98. (1998). "Technical standard for applications of geosynthetics".

Lin, X., Zhou, L. and Wu, J. (2000). "The application of geotextile-reinforced sand cushion in ground treatment of buildings", Rock and Soil Mechanics, Vol. 21, No. 3, pp 252-255.

Liu, H., Wu, W. and Gao, Y. (2003). "Nonlinear finite element analysis of reinforced dike with geotextile", Rock and Soil Mechanics, Vol. 24, No. 4, pp 79-82, 87.

Xu, S. (1991). "Analysis for geotextile reinforcement on soft groud under embankment". Journal of Fuzhou University-Natural Science Edition, 13(2): 73-81.

Xu, S. and Hong, C. (2000). "A stability analysis method for soft subgrade under embankment considering strengthened cushion", China Civil Engineering Journal, Vol. 33, No. 4, pp 88-92.

Zhao, J., Long, G., Xu, X. and Yang, C. (1991). "Analysis for the symmetrical failures of subgrade reinforced with geotextile and natural "subgrade". Chinese Journal of Geotechnical Engineering, 13(2): 73-81.