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Design on limit equilibrium of foundation reinforced with geosynthetics

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ABSTRACT: The effects of reinforcement on bearing capacity of foundation on reinforced earth include upward tension of vertical component and lateral restraint of horizontal component of reinforce . Based on the principle of limit equilibrium, the formula of ultimate bearing capacity is deduced. The results of calculation using the formula are coincided with that from reference given by other researchers. The length of reinforcement is given based on limit pull out analysis and puncture shear failure mode. The design tensile force of geosynthetics in the formula of ultimate bearing capacity is equal to ultimate tensile strength. A factor of safety, Fs= about 3.0, is applied to the ultimate bearing capacity and to the ultimate tensile strength of geosynthetics as well to arrive the allowable bearing capacity. The effects of numbers of reinforcements on bearing capacity and settlement of foundation are analyzed, and a conclusion is given that sand cushion reinforced with layers of geosynthetics is reasonable selection. The available design formula of foundation reinforced with geosynthetics should concern with spread of vertical stress in the cushion and surcharge modification of bearing capacity due to increase of depth of the foundation. A case history of foundation of sluice reinforced by geogrid is given.

1 INTRODUCTION

Shallow strip foundation resting on reinforced earth is made up of single layer or several layers of reinforcements horizontally placed in the soil under the foundation. A great number of model tests show it has the advantage of improving bearing capacity, and this type of foundation has been applied in many structures. Original galvanized steel ties used as reinforcements have been replaced by geosynthetics. The design methods of this type of foundation mainly include the followings: (1) Analysis of stresses in reinforcement and soil by Boussinesq's solution (Binquet and Lee, 1975), (2) Formula of Improving Terzaghi ultimate bearing capacity (Yamanouch and Gotoh, 1979), (3) Finite element method, (4) Analysis of reinforced foundations by the slip-line method. Many assumptions have been used in these methods. For example, method (1) supposes that reinforced earth and substratum are homogeneous medium, the tensile force of reinforcement is vertical and upward, and the length of reinforcement reaches the point where the increase of vertical stress equals to 0.1 times the load, q, method (2) supposes the deformation of reinforcement on both sides of the foundation forms a arc of circle, it's hard to determine the radius of arc and the direction of tensile force, method (3) and method (4) have little application because of their complication.

This paper deduced the formula of ultimate bearing capacity based on the principle of limit equilibrium and the formula of determining the length of reinforcement based on the equilibrium of anchoring segment outside shear failure (load spread) lines by analyzing two limit equilibrium modes, those are limit breaking and pullout of reinforcement. The ultimate bearing capacity calculated by the formula is very consistent with the results of model tests given by other researchers and a case of foundation of sluice reinforced with geogrid designed by the method is given.

2 LIMIT ANALYSIS ON BREAKING AND PULLOUT OF REINFORCEMENT

When the upper layer of reinforcement below the foundation is located at a depth, z_1, less than about 2/3 b, the lowest layer of reinforcement is located at a depth, z_n, less than about $2b$ (b = width of the foundation), the number of reinforcement layers, N, is greater than 3 and the ties is sufficiently long, in this case, the soil mass fails when the upper reinforcement break. The breaking points below the foundation are the intersection points of reinforcements and load spread lines, AC and BD, as shown in figure 1, and the spread angle (θ) doesn't increase no matter the adding of reinforcements (Love, 1987).

The effects of reinforcement on bearing capacity of foundation include upward tension of vertical component $2NT\sin\alpha/(b+2\ z_n\ \tan\theta)$ and lateral restraint of horizontal component of reinforce. And the latter can be calculated by limit equilibrium theory.

$$\Delta\sigma_3 = NT\cos\alpha / D_u$$

$$\Delta\sigma_1 = \Delta\sigma_3 \tan^2(45° + \phi/2) \quad (1)$$

Where T= ultimate tensile strength of reinforcement, α= angle of tensile force and horizontal surface. Let α= 45°+ϕ/2, ϕ= angle of friction, D_u= maximum depth of slip surface in soil. So the improvement of ultimate bearing capacity by reinforcement, Δq_u

$$\Delta q_u = NT(2\sin(45°+\phi/2)/(b+2\ z_n \tan\theta) + \cos(45°+\phi/2)\tan^2(45°+\phi/2)/D_u) \quad (2)$$

$$\Delta q_r = NT(2\sin(45°+\phi/2)/(b+2\ z_n \tan\theta) + \cos(45°+\phi/2)\tan^2(45°+\phi/2)/D_u)/F_s \quad (3)$$

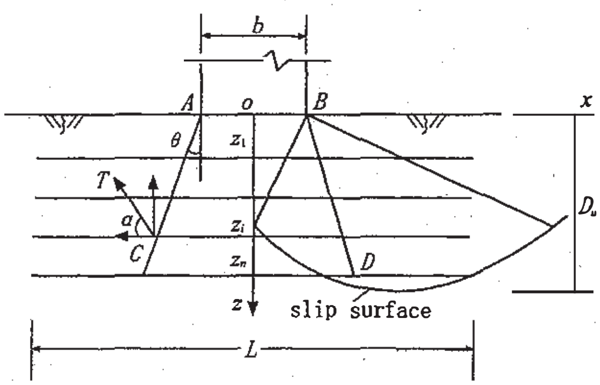

Figure 1. Cross section of reinforced foundation.

Where the factor of safety F_s is equal to about 3.0. F_s is applied to the ultimate bearing capacity and to the ultimate tensile strength of geosynthetics as well to arrive the improvement of allowable bearing capacity, Δq_r.

The total improvement of allowable bearing capacity of foundation reinforced with geosynthetics, Δq,

$$\Delta q = \Delta q_r + \gamma z_n N_q / F_s + 2q z_n \tan\theta/(b+2\ z_n \tan\theta) \quad (4)$$

Where N_q= bearing capacity factor, q= load of foundation, kPa. The third term in the formula (4) is reduction of q at level z_n, because spread of load.

The improvement of the ultimate bearing capacity has generally been expressed in a non-dimensional form called the bearing capacity ratio (BCR),

$$BCR = \frac{q_{ur}}{q_u} \quad (5)$$

Where q_{ur} and q_u = ultimate bearing capacity of the foundation supported on reinforced and unreinforced earth, respectively.

The BCR increases with the increase of the length, L, and N of reinforcements until the mass of reinforced earth covers the whole zone of failure surface. We deduced the length L_u of the whole zone of general shear failure on both sides of the foundation,

$$L_u = b(1+2\tan(\pi/4+\phi/2)\ e^{\pi/2\ \tan\phi}) \quad (6)$$

In the transitional zone the failure surfaces are curves being arcs of a logarithmic spiral, the maximum depth, D_u, can be gotten by derivation of the depth,

$$D_u = \frac{b\cos\phi}{2\cos(\pi/4+\phi/2)}\ e^{(\pi/4+\phi/2)\tan\phi} \quad (7)$$

Refer to formulas (6) and (7), L_u and D_u are given in the table, 1 available from different values of ϕ.

Table 1. Length and depth of slip Surface.

ϕ(o)	0	5	10	15	20	25	30	35
L_u (×b)	3.00	3.50	4.14	4.97	6.06	7.53	9.58	12.53
D_u (×b)	0.71	0.79	0.89	1.01	1.16	1.35	1.59	1.90

From Table 1, the D_u is less than $2b$, that can be reached by properly arrangement of reinforcements ($2/3b<z<2b$). However, if we determine the length of reinforcement by the L_u, this will use too many reinforcements and cause the excessive width of excavation. So in order to get relatively short length of reinforcement , it may be proper to lose some bearing capacity. Moreover, based on many researches, the failure surface in reinforced foundation will not be a complete slip line extended to ground surface, but extend vertically and downward by edge of the foundation, or form a spread angle from vertical direction. So in this paper, we suggest that the load spread lines at the case of have no reinforcement are taken as the failure surfaces and the lengths of reinforcement are calculated by the stability against pullout of the reinforcement outside two failure surfaces. We just take normal stress caused by self-weight stress of superimposed soil into account in calculating friction on the surface of reinforcement and do not consider the increased stress caused by load of foundation. The length of the ith layer of reinforcement, L_i

$$L_i = b+2\ z_i \tan\theta + \frac{T_a F_{sp}}{f_p\ \gamma\ (d+z_i)} \quad (8)$$

Where. T_a= allowable tensile force of reinforcement , kN/m, F_{sp}= safety factor against pullout of reinforcement, F_{SP}=3, f_p= coefficient of friction between reinforcement and soil, determined by test and without test data the (Chinese Standard for application of geosynthetics in hydraulic and hydro-power engineering) SL/T225-98 takes f_p= 2/3tanϕ for geotextile, f_p= 0.8tanϕ for geogrid.

Considering in formula (8) $T_a F_{sp}= T$, then,

$$L_i = b+2\, z_i \tan\theta + \frac{T}{f_p\, \gamma (d+z_i)} \qquad (9)$$

Where d= embedment of foundation, in fig. 1, d=0.

In order to examine the limit analysis method, the ultimate bearing capacity calculated by formula (2) has been compared with the results based on model tests by Ju et al(1996). In the model test. the uniform and dense sand has relatively density D_r = 75%, unit weight γ= 15.5kN/m^3. Width of model foundation b= 0.1.m, the ultimate bearing capacity of sand foundation was q_u = 161.9kPa. And the friction angle ϕ=45°are determined by back analysis based on classical bearing capacity theory by Ju et al. Geonet used as reinforcement has a ultimate tensile strength T= 2 kN/m , Other parameters of the tests are length L=6b, the number of reinforcement layers is from 1 to 6, distance $\Delta z = z_1 = 0.25b$ = 0.025m. Figure 2 gives the curves for load versus settlement.

The load-settlement behavior of unreinforced sand (N=0) shows a peak in Figure 2. The ultimate bearing capacity and settlement at peak are 161.9 kPa and 8.05 mm, respectively. Table 2 gives the variation of the ultimate bearing capacity (q_{ur}) and BCR at the same settlement (8.05 mm) according to the increase of N. In order to compare the test results with that from limit analysis, the improvement of ultimate bearing capacity (Δq_u) calculated by formula

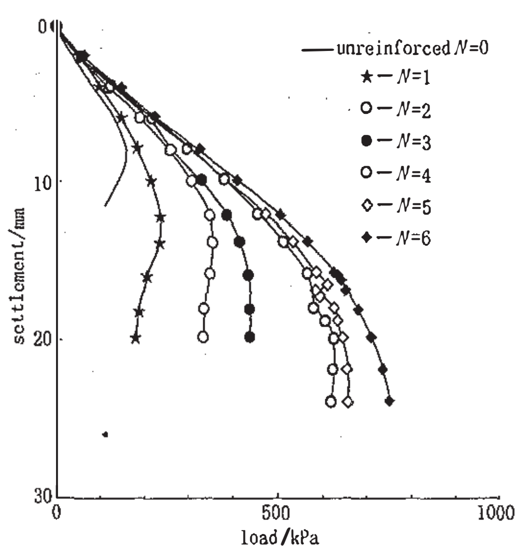

Figure 2. Curves for load versus settlement in sand (after Ju J.W, Son S.J, Kim J.Y and Jung L.G, 1996).

Table 2. A comparison of ultimate bearing capacity of sand foundation reinforced with geonet.

N	Calculated			Tests	
	Δq_u kPa	q_{ur} kPa	BCR	q_{ur} kPa	BCR
0		161.9		161.9	
1	43.9	205.8	1.27	196.0	1.21
2	77.3	239.2	1.48	271.6	1.68
3	105.1	267.0	1.65	274.8	1.70
4	134.8	296.7	1.83	317.4	1.96
5	151.8	313.7	1.94	319.5	1.97
6	172.6	334.5	2.07	340.8	2.11

* θ = 30°, D_u=0.284 m

(2), ultimate bearing capacity (q_{ur}, q_{ur}= q_u(161.9 kPa)+Δq_u) and BCR are also given in table 2.The results from tests and formula(2) are very consistent with each other in the Table 2.

3 A CASE HISTORY

Huangshi Hexing Sluice lies in Hubei Province of China, which was first established in 1876 and reestablished in 1956. The foundation of the sluice rest on mucky soil, the thickness of the mucky soil is 10 to 18m, below it lies thick silt layer. Crack and deformation of the sluice caused by different settlement of untreated ground and aging of the sluice structure made it a serious hidden danger to Yangtze River dyke. So it had to be pushed over and reestablished after flood in 1998. The new foundation supported on 93 piles according to original design, then the plan of reinforced earth with geogrid have been accepted and designed by this method.

Width of the sluice foundation b=5m, load of foundation q = 280 kPa, embedment d = 1.20m, allow bearing capacity of mucky soil, q_{all}=100kPa, γ= 18.4kN/m^3 c=40kPa, ϕ=16°. The number of geogrid layers is 3, z_1 = 0.6m, z_3 = 1.6m , distance between each layer is 0.5m, angle of friction in sand liner ϕ=33°. The structure of sand cushion reinforced with 3 layers of geogrids is shown in Figure 3.

The result of Δq calculated by this method is 180kPa, which include modified surcharge offers 74.25kPa, and load spread offers 74.5kPa(θ = 30°) and reinforcement only offers Δq_r=20.25kPa. Other results are D_u=5.2m, T=46.61kN/m. The length of each layer of reinforcement are 6.79m, 7.12m and 7.47m. Finally, an uniform length of 7.5m was adopted. The geogrid has ultimate tensile strength of 50kN/m.

When Δq_u was calculated with formula (2) the ϕ=16° (mucky soil) was taken, because the thickness

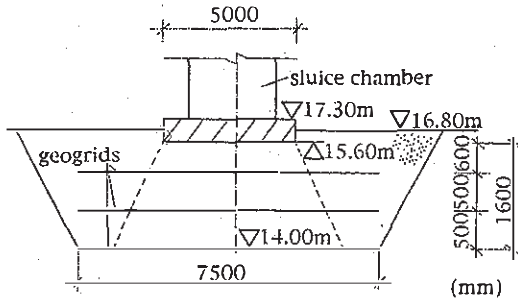

Figure 3. Sand cushion reinforced with 3 layers of geogrids in Huangshi Hexing Sluice.

of sand cushion was only 1.6m more less than D_u=5.2m.

The foundation of reinforced earth was accomplished in Jan. of 1999. It only took one month. The sluice has played an important role in control flood in 1999 and 2000.

4 CONCLUSIONS

1. The effects of reinforcement on ultimate bearing capacity include horizontal restraint and upward tension of the reinforce.

2. The horizontal restraint stress of reinforcement is equal to horizontal component of tensile force divided by the maximum depth of slip surface, then the improvement of ultimate bearing capacity can be deduced based on limit equilibrium theory.

3. Because of safety factor of both geosynthetics and allow bearing capacity are about 3, the ultimate tensile strength should be used as tensile force at limit equilibrium analysis.

4. The best type of reinforced earth is the sand cushion reinforced with geosynthetics. In spite of considering the effects of reinforcements, the load spread and increase of surcharge must be accounted.

5 For sand cushion reinforced with multiple of geosynthetics the design methods (1) and (2) are not adopted.

6. The layout of reinforcements, z_1, less than about 2/3 b, and z_n, less than about 2b can be applied in design of foundation reinforced with geosynthetics.

7. The length of reinforcement is given based on limit pull out analysis and puncture shear failure mode.

8. The method of limit analysis has been verified by test result and a case history.

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