THE EFFECTS OF THE GEOMETRIC PARAMETERS OF A CIRCULAR SHALLOW FOUNDATION ON ITS UPLIFT BEARING CAPACITY IN LOESS SOIL

UČINKI GEOMETRIJSKIH PARAMETROV KROŽNEGA PLITVEGA TEMELJA NA NJEGOVO NOSILNOST NA IZVLEK V RAHLIH ZEMLJINAH

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Keywords

field uplift tests; circular shallow foundation; orthogonal test method; the uplift bearing capacity

Ključne besede

terenski preizkusi na izvlek; krožni plitvi temelj; ortogonalna preizkusna metoda; nosilnost na izvlek

Abstract

In order to revel the effect of the geometric size parameter of a circular shallow foundation on its uplift capacity in loess soil, the shaft diameter d, the enlarge angle of the slab θ and the embedment ratio h_t/D of the shallow foundation were chosen to determine the field test schemes using the orthogonal test method. The field uplift tests were carried out on the tested foundations at a site located in Gangu County, Tianshui City, Gansu Province, China. The uplift load vs. the outward displacement curves of all the test foundations were recorded using automatic electronic measuring instrument. The test results revel that all the uplift load vs. outward displacement curves of the tested foundations are non-linear and take on an obvious three stages. Through the analysis on all the uplift load vs. outward displacement curves, the uplift capacities are achieved using the L_1-L_2 graphic method. By analyzing the relationship between the uplift capacities and the geometric parameters (enlarge angle of slab θ, the embedment ratio h_t/D and the shaft diameter d) of the tested foundations, it is concluded that the uplift capacities of all the tested foundations increase with the increase of θ, h_t/D and d, and the influencing degree of the three geometric factors on the uplift capacity of the circular shallow foundation is $\theta > d > h_t/D$.

Izvleček

Za ugotovitev vpliva geometrijske velikosti krožnega plitvega temelja na njegovo nosilnost na izvlek v rahlih zemljinah, so bili izbrani parametri premer temelja d, povečevalni kot plošče θ in razmerje vkopanja h_t/D plitvega temelja, s katerimi je določena shema terenskega preizkusa z uporabo ortogonalne preizkusne metode. Terenski preizkusi na izvlek so bili izvedeni na preizkušenih temeljih na gradbišču v okrožju Gangu, v mestu Tianshui, provinca Gansu, Kitajska. Krivulje odnosa med obremenitvijo na izvlek in zunanjih pomikov smo za vse preizkusne temelje zabeležili z avtomatskim elektronskim merilnim instrumentom. Rezultati preizkusa kažejo, da so vse krivulje obremenitev na izvlek - zunanji pomik na preizkušenih temeljih nelinearne, in da imajo izražene tri faze. Pri analiziranju krivulj obremenitev na izvlek - zunanji pomik so bile nosilnosti na izvlek dobljene z uporabo grafične metode L_1-L_2. Z analizo razmerja med nosilnostjo na izvlek in geometrijskimi parametri (povečevalni kot plošče θ, razmerje vkopanja h_t/D in premer temelja d) preizkušenih temeljev smo zaključili, da se nosilnost na izvlek pri vseh preizkušenih temeljih poveča s povečanjem θ, h_t/D in d, ter da je vplivna stopnja treh geometrijskih parametrov na izvlek krožnega plitvega temelja v razmerju $\theta > d > h_t/D$.

1 INTRODUCTION

Transmission towers not only transmit heavy compressive loads but also bear a considerable amount of uplift loads. The transmission towers need footings to fix them, which can anchor these towers with competent strata. Shallow foundations are widely used to bear the transmission towers. A circular shallow foundation is a very popular type of shallow foundation to support a transmission tower. Since the controlling design load for this type foundation is normally the uplift load stipulated by codes, the determination of the uplift bearing capacity of this kind of foundation is a key job for the foundation design. In deed, the factors to affect the uplift bearing capacity of a circular shallow foundation include the soil shear strength around the foundation, the geometric parameter of the foundation, the material of the foundation, etc.

Many researchers have studied how the factors influence on the uplift bearing capacity of shallow foundations. The studies were mostly conducted using indoor model experiments [1, 2, 3, 4, 5, 6, 7, 8, 9]. It is known to all that the results obtained by indoor model experiments are hard to use as a guide prototype foundation design because model experiments are always not satisfied with similarity theory. Therefore, some researchers carried out prototype pullout tests to discuss the features of the uplift load vs. outward displacement curves and the uncertainties of the parameters to fit the curves of the foundations in the Gobi field in the Northwest of China [10]. However, how multiple geometric parameters of shallow foundation influence the uplift capacity is hardly observed in the literature.

Although the effects of the geometric parameters of a shallow foundation on its uplift bearing capacity have been reported in many studies, only a limited number study the effects using prototype experiments [11,12,13]. Moreover, the prototype uplift tests reported in the literature mentioned above almost do not care for the effects of geometric parameters such as the enlarge angle of slab θ, the embedment ratio h_t/D and the shaft diameter d on the uplift bearing capacities of shallow foundations, except for some test results on the effects of normalized embedment depths (H/D) on the uplift performance of shallow foundations reported in these studies [11,12,13].

In order to understand well the effects of the geometric size parameters (enlarge angle of slab θ, embedment ratio h_t/D and shaft diameter d) of a shallow foundation on its uplift bearing capacity, in this paper, prototype uplift field tests were performed in loess soil located in northwest China, and variations of the uplift bearing capacities of the circular shallow foundations with different geometric parameters are discussed.

2 FIELD CONDITIONS

The field tests were conducted at a site located in the place of the 750-kV substation to be built in Gangu County, Tianshui City, Gansu Province, China. All the tested foundations were buried in one soil layer with relatively homogeneous loess soil. Both laboratory and in-situ tests were performed to determine the physical and mechanical parameters of the loess soil (Table 1).

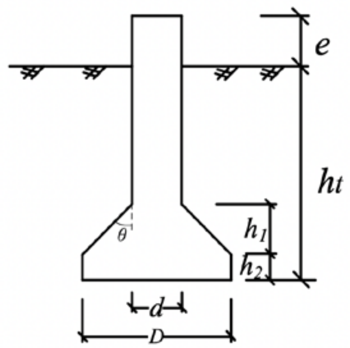
Table 1. Physical and mechanical parameters of the loess soil.

Index properties for loess	Test result
Water content / %	16.5
Nature density / kg·m^{-3}	1.89
Degree of saturation /%	43.2
Void ratio e	0.92
Liquid limit / %	30.2
Plastic limit / %	20.5
Modulus of compressibility/ kPa	15.2
Cohesion / kPa	14.8
Angle of internal friction / °	23.1

3 TEST SCHEME DESIGN

The orthogonal experimental design method is a mathematical statistical method to use an orthogonal table to study a specific indicator law determined by multiple factors. Users do fewer tests, and the regulations resulting from the tests can be found using this method [14]. The key steps of orthogonal experimental design are selecting factors for tests and determining the levels of each factor.

For the purpose of studying the effects of geometric parameters on the uplift bearing capacity of the circular shallow foundation, the orthogonal experimental design method was adopted to design the test schemes. The uplift bearing capacities of the tested foundations, which consists of a cylindrical shaft and a circular slab (Figure 1), are affected by geometric parameters such as the foundation shaft diameter d, the enlarge angle of slab θ and the embedment ratio h_t/D. Different geometric parameters have different effect degrees on the uplift bearing capacity of the foundation. In order to comprehensively analyze the effects of the three parameters on the uplift bearing capacity, the geometric parameters d, θ, and h_t/D were chosen for study. Each of the three factors (the three geometric parameters) were divided into three levels (Table 2). The parameters h_t/D, θ and d are indicated by A, B and C, respectively, in Table 2, and other geometric parameters are shown in Table 3.



$D = d + 2h_1 \tan \theta$

Figure 1. Schematic diagram of the tested foundations.

The standard orthogonal test table for the geometric parameters was used to develop the test schemes [15]. The test indicators are the uplift bearing capacity values of the tested foundations, whose geometric parameters are shown in Table 2 and Table 3. The test schemes are shown in Table 4, where *E* indicates a blank column, and the orthogonal table of factors and levels is shown in Table 4.

Table 2. Factors and levels of geometric parameters.

index	Factors (geometric parameters)		
	A h_t/D	B θ (°)	C d(mm)
1	1.5	15	900
2	2	30	1200
3	2.5	45	1500

Table 3. Other geometric parameters of the tested foundations.

parameter	value/mm
h_1	600
h_2	200
e	200

Table 4. Test schemes obtained by orthogonal experiment for L9 (3^4).

Number	1	2	3	4	*D* value in figure 1
	A	*B*	*C*	*E*	
No.1	1(1.5)	1(15)	1(900)	1	1221
No.2	1(1.5)	2(30)	2(1200)	2	1892
No.3	1(1.5)	3(45)	3(1500)	3	2699
No.4	2(2.0)	1(15)	2(1200)	3	1521
No.5	2(2.0)	2(30)	3(1500)	1	2192
No.6	2(2.0)	3(45)	1(900)	2	2099
No.7	3(2.5)	1(15)	3(1500)	2	1821
No.8	3(2.5)	2(30)	1(900)	3	1592
No.9	3(2.5)	3(45)	2(1200)	1	2399

4 PREPARATION OF THE TESTED FOUNDATIONS

The circular shallow foundations were constructed in the field. The construction procedure is a borehole with a certain size made using the manual digging method; then the reinforcement cage was placed into the

(a) Preparation for construction (b) Excavation of borehole (c) Make of reinforcement cage

(d) Installation of reinforcement cage (e) Installation of locking nut (f) Pouring of concrete

Figure 2. Construction process for the tested foundations.

borehole; after that the concrete with the compression strength of 30 MPa was placed into the hole. Finally, the foundation construction was cured for 28 days. After the process of construction, the foundation can be used for uplift tests. The construction process of the circular shallow foundation is shown in Figure 2.

5 UPLIFT TESTS

5.1 Uplift-test setup

The test setup was designed according to the criteria recommended in the Chinese Nation Code GB50007 [16] and the China Electric Power Industry Standard DL/ T 5219 [17]. The uplift test setup is a loading device shown in Figure 3. The loading device is composed of concrete supporting blocks, reaction beams made of reinforced steel plate and stiffeners, tension connecting bolts, etc. To allow the test foundations to develop possible rupture surfaces extending to the ground, the reaction beams were placed 10 m apart, perpendicular to the concrete supporting blocks. All the reaction beams were reinforced by welded steel plates and stiffeners to increase their stiffness. Based on the anticipated ultimate uplift bearing capacity of the tested foundations, tensile loading was applied by two 5000-kN hydraulic jacks using automatic electronic control with a stroke of 250 mm through the loading reaction beams. During each test, the head displacement of the tested foundation was measured by electronic gauges with a range of 50 mm. These gauges were attached to the reference beams installed over the tested foundation. The reference beams were of sufficient stiffness to support the instrumentation so that excessive variations did not occur. The same loading, reaction, and data-acquisition systems were used for all the tests. The loading direction supplied by the device is along the axial direction of the tested foundations.

5.2 Process of the uplift test

In general, the uplift test procedures of the tested foundation were conducted in accordance with the Chinese Nation Code GB50007 [16] and the China Electric Power Industry Standard DL/T 5219 [17]. All the tests were conducted with static loading, without load cycling. The process of the uplift test can be described as involving the following steps:

(1) The slowly maintained load method [17] was adopted to load on the tested foundation, that is to say, the uplift loading was applied in increments of 10% of the anticipated ultimate load for each individual foundation, and the foundation was allowed to move under each maintained-load increment until a certain rate of displacement was achieved.

(2) Each load increment was maintained after loading until the change rate of the outward displacement was less than 0.1 mm/h.

(3) Then the next load increment was applied. The uplift test was continued up to the point of failure, at which the foundation was completely pulled out from the loess, or the uplift test was terminated after the last load was maintained for 24 h with the change rate of displacement exceeding 0.1mm/h.

6 TEST RESULTS

6.1 Uplift load vs. outward displacement curves

The measured uplift load vs. outward displacement curves for all the tested foundations are presented in Figure 4. It is clear from Figure 4 that the uplift load vs. displacement curves exhibit the same three stages, which are segment *oa*, segment *ab* and segment *bc* in the curve (Figure 5).

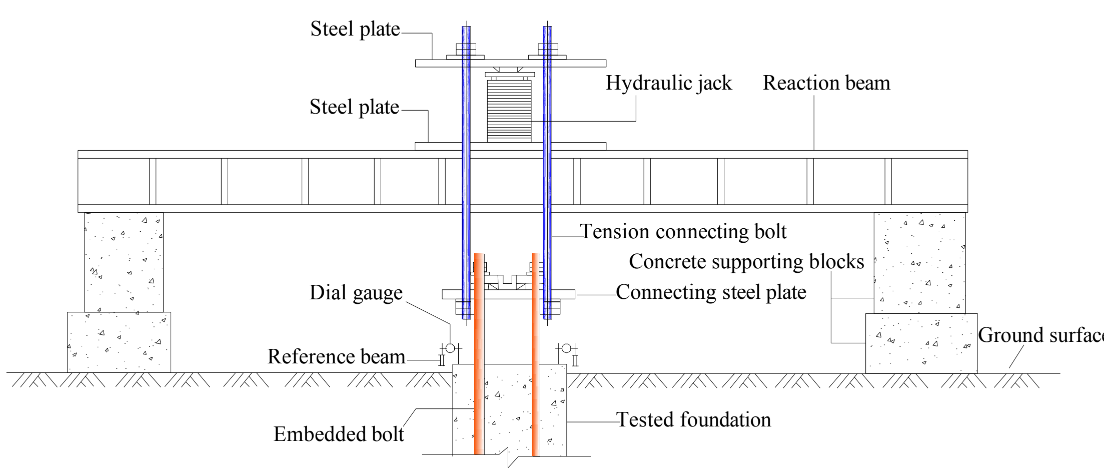


Figure 3. Loading device for uplift tests.

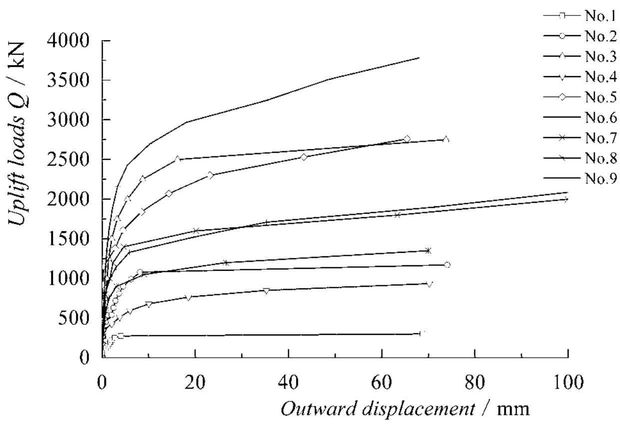


Figure 4. Uplift load vs. outward displacement curves of tested foundations.

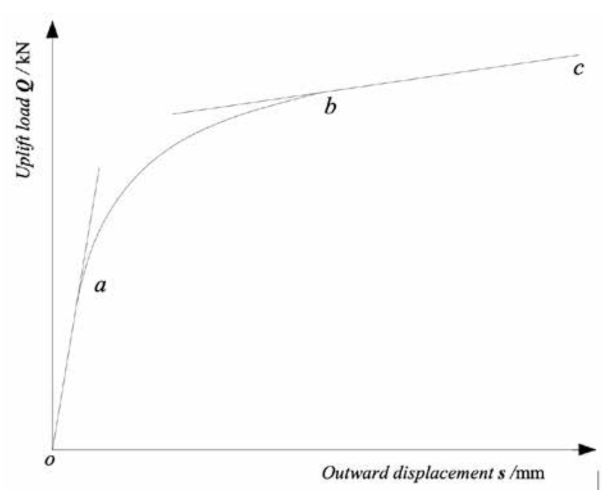


Figure 5. Three stages of uplift load vs. displacement curve.

Among these segments, segment *oa* is a straight line, where elastic deformation can be thought to occur in the loess soil around the tested foundation, and compressive deformation of the soil is dominant at this stage; the middle segment *ab* is a curve as the transition stage, indicating that plastic deformation occurs in the soil occasionally with elastic-plastic deformation, and the soil mainly takes on compressive and shear deformation; the terminal segment *bc* is a straight line with a gentle slope, and the main deformation is shear deformation in this stage.

6.2 Uplift capacity of the tested foundations

Based on the uplift load vs. outward displacement curves, the uplift bearing capacities of the tested foundations can be determined using the L_1-L_2 graphic method [18]. The method takes two steps to determine the uplift capacity of the tested foundation. Specifically, the two steps are illustrated as the following.

(1) the first step is extending the terminal segment *bc* from the last point (point *c* in Figure 5) in the uplift load vs. outward displacement curve, and then finding the intersection (point *b* in Figure 5) between the middle section *ab* and the terminal section *bc*;

(2) the second step is finding the value of the vertical coordinate in point *b*, and the value is the uplift bearing capacity (Q_{L2} in Figure 6).

Table 5. The uplift capacities of the test foundations.

Numbers	h_t/D	enlarge angle θ/°	shaft diameter d/mm	uplift bearing capacities Q_{un}/kN
No.1		15	900	269
No.2	1.5	30	1200	943
No.3		45	1500	2037
No.4		15	1200	581
No.5	2.0	30	1500	1638
No.6		45	900	1319
No.7		15	1500	1403
No.8	2.5	30	900	1108
No.9		45	1200	2422

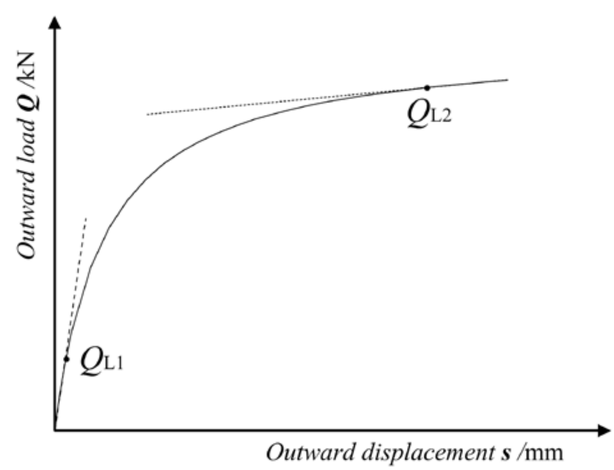


Figure 6. Graphical expression of the uplift bearing capacity of the tested foundation.

7 DISCUSSION

The uplift bearing capacities and geometric parameters of all the tested foundations are presented in Table 5. The effects of various geometric parameters on the uplift bearing capacities are discussed in terms of the test results mentioned above.

It has been shown in Table 5 that when the embedment ratio (h_t/D) equals 1.5, the uplift bearing capacities Q_{nu} increase with the increase in the enlarged angle of the slab (θ =15, 30 and 45°). Nevertheless, when the embedment ratio (h_t/D) equals 2.0 or 2.5, Q_{nu} does not increase anymore with the increase in enlarged angle of the slab θ due to the effect of the shaft diameter (d). Therefore, the uplift bearing capacities Q_{nu} of the tested foundations are influenced jointly by multiple geometric parameters of the foundation.

For analyzing the effects of multiple geometric parameters (h_t/D, θ and d) on the uplift bearing capacities Q_{nu} of the tested foundations, an orthogonal analysis was made on the test results, and the analysis results were listed in Table 6. In Table 6 the three lines K_1, K_2 and K_3 represent, respectively, the sum of the three Q_{nu} values at Level 1, 2 and 3 of each factor (A, or B, or C), and $\bar{K}_1$, $\bar{K}_2$ and $\bar{K}_3$ are the averages of the three Q_{nu} values at Level 1, 2 and 3 of each factor (A, or B, or C). It is clear from Table 6 that for the column of factor A (embedment ratio h_t/D), $\bar{K}_1<\bar{K}_2<\bar{K}_3$; for the column of factor B (enlarge angle θ), $\bar{K}_1<\bar{K}_2<\bar{K}_3$; and for the column of factor C (shaft diameter d), $\bar{K}_1<\bar{K}_2<\bar{K}_3$. So the best combination of the three factors to approach the maximum uplift bearing capacity of the foundation is $A_3B_3C_3$. The maximum uplift bearing capacity (2,422kN) in Table 6 occurs in group No.9, whose combination of the three factors is $A_3B_3C_1$, while the minimum uplift bearing capacity (269kN) can be found in group No.1 with the combination of $A_1B_1C_1$.

The difference between the maximum and the minimum of the three numbers in same column (A, or B, or C) is expressed by R in Table 6. If the value of R in each column varies differently, the level changes of the factor in the column have different effects on the uplift bearing capacity. From the variable range of R in each column in Table 6, it can be known that among the three factors (column diameter d, embedment ratio h_t/D and enlarge angle θ), the enlarged angle θ is the most sensitive to the uplift bearing capacity Q_{nu} of the foundation, the shaft diameter d is secondary, and the embedment ratio h_t/D is the least.

The trend of the uplift bearing capacities Q_{nu} for the foundations under different levels of each factor was demonstrated in Figure 7. It can be observed in Figure 7 that the enlarged angle θ has significant effects on the uplift bearing capacity Q_{nu}, to be specific, when θ increases from 15° to 45°, Q_{nu} will increase by 156%; while the embedment ratio h_t/D has the least effect on Q_{nu} among the three factors, specifically, when h_t/D increases to 2.5 from 1.5, Q_{nu} will increase by 52%; the effect degree of the shaft diameter d on Q_{nu} is between those of θ and h_t/D.

Table 6. Analysis of the uplift capacity.

No	factors			Q_{nu}/kN
	A embedment ratio h_t/D	B enlarge angle θ	C shaft diameter d	
1	1	1	1	269
2	1	2	2	943
3	1	3	3	2037
4	2	1	3	581
5	2	2	1	1638
6	2	3	2	1319
7	3	1	2	1403
8	3	2	3	1108
9	3	3	1	2422
K_1	3249	2253	2696	
K_2	3538	3689	3946	
K_3	4933	5778	5078	
$\bar{K}_1$	1083	751	899	
$\bar{K}_2$	1179	1230	1315	
$\bar{K}_3$	1644	1926	1693	
R	561	1175	794	

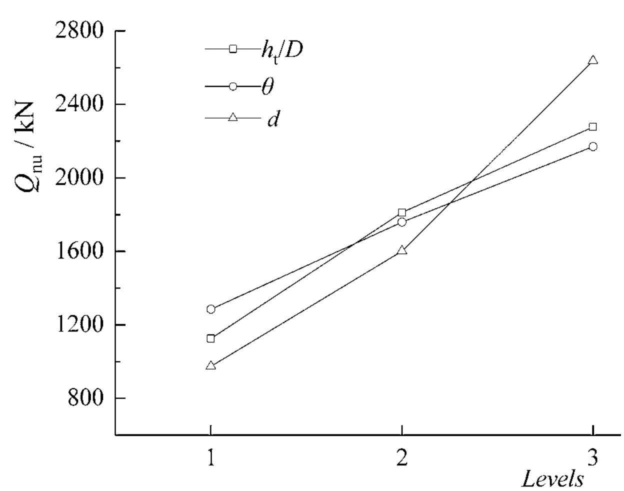


Figure 7. The trend of the uplift capacity under different factors and levels.

8 CONCLUSIONS

Based on the test results and discussions mentioned above, the conclusions can be drawn as follows:

(1) The uplift load vs. outward displacement curves of the circular shallow foundations in loess soil are

non-linear in general, and they take on three stages, of which, one stage is a curve, and the other two are straight. From the angle of engineering, the three stages represent the stage (*oa*) of elastic deformation, the stage (*ab*) of appearance and the extension of the plastic zone, and the stage (*bc*) of shear failure in loess soils around the tested foundations;

(2) The uplift bearing capacities of the circular shallow foundations in loess is related to the shaft diameter d, the embedment ratio h_t/D and the enlarge angle θ. With the increases in the three geometric parameters (d, h_t/D and θ) not only at the same time but also respectively, the uplift bearing capacities of the circular shallow foundations will increase;

(3) The discussions relating to the test results show that the sensitivity of each geometric parameter to the uplift bearing capacity of the foundation circular shallow foundation in loess soil from large to small is $\theta > d > h_t/D$.

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