

Reliability Analysis on Ultimate Uplift Capacity of Digged Foundation in Transmission Line

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Abstract. Reliability analysis of uplift stability based on the first order second order method for digged foundation in gravel soil has been made by non-dimensionalization for ultimate state equation and combining with the test results. The ratio of test value to calculated uplift capacity K_p that reflects the uncertainty of calculation model obeys normal distribution via single sample K-S test. When the ratio ρ of variable and permanent loads is certain, reliability index β increases linearly with safety factor K . For given value of K , reliability index β change slightly with ρ . For digged foundations in gravel soils, the reliability index β ranges from 2.74 to 3.22 when $K=2.5-4.0$.

Introduction

Gobi desert is widely distributed in the northwest of China, which is the terrain with coarse sand and gravel overlying the hard soil layer. With the development of power grid construction, more and more transmission lines need to go through the Gobi desert area. The cost, time and labor for transmission tower foundation construction account for a large proportion in the whole project [1]. The uplift resistance of the foundations under normal circumstances is the design control conditions. It is effective to reduce the project cost and improve the level of environmental protection when suitable foundation type is selected. Foundation hole is digged by manual work in mountain area and it is actually rigid enlarged pile. This kind of foundation can provide good uplift capacity because soil structure and strength cannot be disturbed. The estimation of its uplift capacity is based on limited equilibrium method, consisting of vertical component of shear strength along failure surface, self-weight of soil within failure surface and self-weight of foundation. Technical code for design of foundation of overhead transmission lines (DL/T 5219-2014) [2] presented formula of uplift capacity. Luxian Long et al. [3, 4] performed reliability analysis using formula of uplift capacity in last version of design code (DL/T 5219-2005). And the reliability analysis of digged foundation should be performed based on updated formula. It is necessary to carry out reliability-based design for foundation in transmission line to coincide with superstructure design theory [5, 6].

Therefore, this paper established uplift ultimate limit state equation of digged foundation using shear method's formula provided in new design code. The distributions and statistical parameters of variables in state equation were determined by combining with uplift test results of digged foundations. Reliability index is calculated by using "the first order second order method (JC)". The relationship of reliability level and frequently-used safety factor is established, which can provide reference reliability-based design.

The Formula of Uplift Capacity

Shear method is proposed in design code [2], and the calculation model is shown in Fig. 1. Calculation formula of uplift capacity T_{uk} for digged foundation is expressed as

For $h_t \leq h_c$

$$T_{uk} = \frac{A_1 c h_t^2 + A_2 \gamma_s h_t^3 + \gamma_s (A_3 h_t^3 - V_0)}{2.0} + G_f \quad (1.a)$$

For $h_t \geq h_c$

$$T_{uk} = \frac{A_1 c h_c^2 + A_2 \gamma_s h_t^3 + \gamma_s (A_3 h_c^3 + \Delta V - V_0)}{2.0} + G_f \quad (1.b)$$

where c is soil cohesion; h_t is embedment depth; h_c is critical embedment depth; A_1, A_2, A_3 are non-dimensional coefficients determined by friction angle φ and λ ($\lambda = h_t/D$); D is diameter of foundation base; ΔV is the volume of cylinder of depth $(h_t - h_c)$. V_0 is the volume of foundation; G_f is self-weight of foundation.

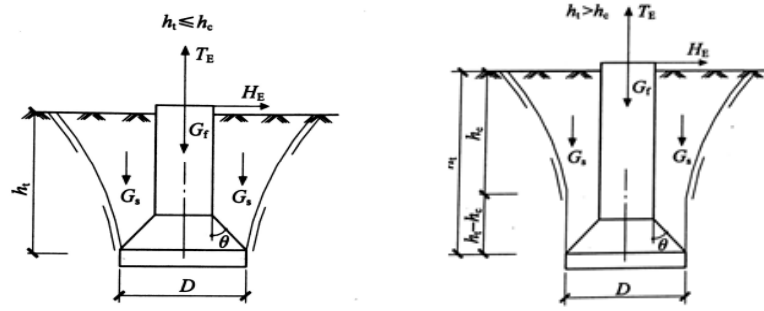


Fig. 1 Calculation model of uplift capacity.

Limit State Equation

Working state equation of uplift stability of digged foundation can be expressed as Eq. (2), where S and R represent action effects and resistance respectively.

$$Z = R - S \quad (2)$$

With the changes in R and S , the performance function Z has three states: When $Z < 0$, the structure is in a failure state; if $Z > 0$, it means that the structure is in the reliable state; when $Z = 0$, it means that the structure is in the limit state.

The load acting on the transmission line tower structure can be divided into dead load, live load and special load. Special load such as earthquake and conductor break is not considered here. Thus state equation comprises three basic random variables: uplift resistance, dead load effects and live load effects. Then Eq. (2) can be rewritten as Eq. (3).

$$g(T, G, Q) = T - G - Q = 0 \quad (3)$$

where T , G and Q represent the uplift capacity of foundation, the design dead load effects and the design live load effects respectively.

If the probability distributions for three basic random variables can be obtained, the reliability analysis can be made by JC method.

According to the deterministic method [7], standard values of three basic random variables T_{uk} , G_k and Q_k yield the following relationship.

$$T_{uk} = K(G_k + Q_k) = K(1 + \rho) G_k \quad (4)$$

where T_{uk} is calculated value of uplift capacity; G_k , Q_k is the standard value of the dead load and live load effects respectively, determined according to the load code; K is safety factor, in foundation engineering, K is generally taken as 2.5-4.0; ρ = the values of the live load effect to dead load effect ratio (Q_k/G_k).

Substituting Eq. (4) into (3) and both sides of equation divided by T_{uk} and, we can get

$$\frac{T}{T_{uk}} - \frac{1}{K(1 + \rho)} \frac{G}{G_k} - \frac{\rho}{K(1 + \rho)} \frac{Q}{Q_k} = 0 \quad (5)$$

T/T_{uk} , G/G_k and Q/Q_k are defined as K_p , K_G and K_Q respectively, then Eq. (5) is written as,

$$K_p - \frac{1}{K(1+\rho)} K_G - \frac{\rho}{K(1+\rho)} K_Q = 0 \quad (6)$$

Actually, Eq. (6) with non-dimensional variables is equivalent to limit state Eq. (3). This will make the calculation of reliability index β greatly simplified. β only relates to the statistical characteristics of random variables K_p , K_G , K_Q , the values of the live load effects to dead load effect ratio ρ and safety factor K .

Statistical Analysis of the Basic Variables

The Statistical Analysis of Load. Load types applied on tower foundation and their statistical parameters accord to transmission tower. For simplicity, statistical characteristics of $K_G = G/G_k$ in “load code for design of building structures” is adopted [7]. K_G obeys normal distribution with mean $\mu_{K_G} = 1.06$, variance $\sigma_{K_G} = 0.074$. By χ^2 or K-S inspection, when significance level is 0.05.

Based on load code [7], the probability distribution of the maximum wind pressure value is regarded as GUMBEL I by statistical analysis at the confidence level of 5% for a group of representative wind data from meteorological station throughout the country. The statistical parameters of random variable K_Q are that $\mu_{K_Q} = 0.998$ and $\sigma_{K_Q} = 0.193$ in terms of a great deal of research data of wind load for transmission towers in the world.

The Load Effects Ratio ρ

Wind load is the main control factor in many live loads, hence this analysis consider wind load merely. A large amount of statistical results show that the ratio of wind load effect and dead load effect ρ is between 0 ~ 9. ρ is taken as 0.5, 1, 2, 2.5, 1.5, 3, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5, 8.0, 8.5 and 9 in this analysis.

Statistical Analysis of Non-Dimensional Uplift Capacity K_p

Table 1 shows the calculated value T_{uk} and measured values T of uplift capacity. K_p is also calculated, which reflect the uncertainty of calculation model and parameter. Probability distribution of K_p satisfies normal distribution by K-S hypothesis test under the condition of 5% confidence level, shown in Fig. 2. The mean and variance of K_p are 1.309 and 0.251 respectively.

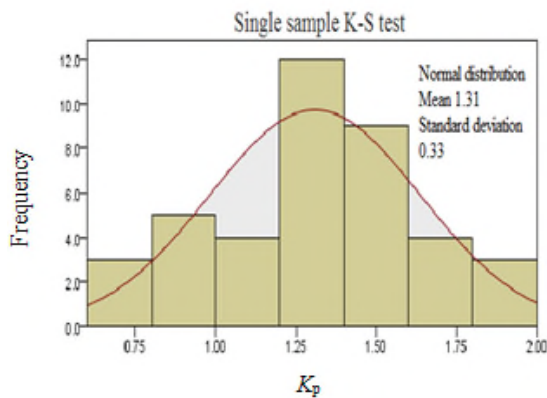


Fig. 2 Distribution of K_p .

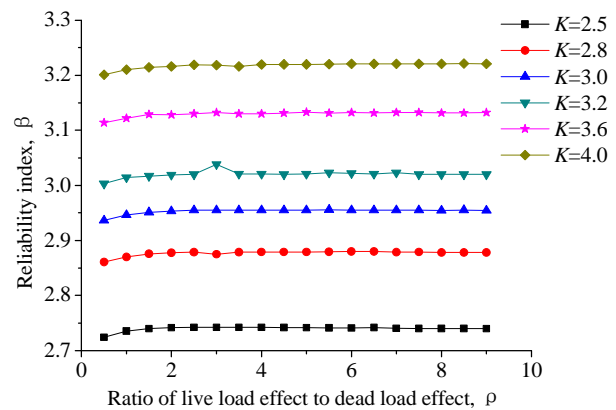


Fig. 3 Reliability index β for foundation.

The Reliability Index

Table. 1 The theoretical and test results of uplift capacity of foundation in Gobi gravel soil and value of K_p .

No.	h_t/m	D/m	c/kPa	$\varphi(^{\circ})$	$\gamma_s^s/kN.m^3$	A_1	A_2	A_3	Test T/kN	Cal T_{uk}/kN	K_p
1	1.52	1.01	10.5	41.4	20.1	3.290	0.965	1.322	442.9	246.5	1.797
2	2.46	1.64	10.5	41.4	20.1	3.290	0.965	1.322	1287.9	912.6	1.411
3	3.44	2.29	10.5	41.4	20.1	3.290	0.965	1.322	2787.9	2277.8	1.224
4	3.53	1.41	10.5	41.4	20.1	2.220	0.590	0.686	2235.4	1446.3	1.546
5	5.09	2.04	10.5	41.4	20.1	2.220	0.590	0.686	5377.8	4056.6	1.326
6	3.73	1.49	10.5	41.4	20.1	2.220	0.590	0.686	2021.3	1667.7	1.212
7	6.34	1.81	10.5	41.4	20.1	1.851	0.458	0.496	6233.4	5755.8	1.083
8	4.33	1.24	10.5	41.4	20.1	1.851	0.458	0.496	3425.1	1936.2	1.769
9	6.62	1.89	10.5	41.4	20.1	1.851	0.458	0.496	5103.4	6539.3	0.780
10	1.52	1.01	23.0	43.3	21.0	3.196	0.987	1.343	345.8	346.2	0.999
11	2.46	1.64	23.0	43.3	21.0	3.196	0.987	1.343	1042.6	1137.6	0.916
12	3.44	2.29	23.0	43.3	21.0	3.196	0.987	1.343	3591.4	2853.1	1.259
13	3.53	1.41	23.0	43.3	21.0	2.157	0.601	0.697	2254.9	1831.2	1.231
14	3.73	1.49	23.0	43.3	21.0	2.157	0.601	0.697	2678.2	2149.7	1.246
15	6.34	1.81	23.0	43.3	21.0	2.157	0.601	0.697	7132.0	6884.0	1.036
16	4.33	1.24	23.0	43.3	21.0	1.799	0.467	0.505	3109.6	2446.0	1.271
17	1.52	1.01	14.7	44.2	21.4	3.320	0.998	1.353	555.0	293.7	1.890
18	2.46	1.64	14.7	44.2	21.4	3.320	0.998	1.353	1650.0	1059.8	1.557
19	3.44	2.29	14.7	44.2	21.4	3.320	0.998	1.353	4471.2	2664.3	1.678
20	3.53	1.41	14.7	44.2	21.4	2.130	0.607	0.703	3103.9	1645.6	1.886
21	5.09	2.04	14.7	44.2	21.4	2.130	0.607	0.703	5882.5	4565.4	1.288
22	3.73	1.49	14.7	44.2	21.4	2.130	0.607	0.703	3135.7	1900.9	1.650
23	1.85	1.20	19.0	40.0	20.0	3.300	0.929	1.272	598.5	499.8	1.197
24	2.40	1.23	19.0	40.0	20.0	2.714	0.731	0.923	1131.7	763.6	1.482
25	3.35	1.20	19.0	40.0	20.0	2.133	0.535	0.608	1930.9	1326.0	1.456
26	3.00	1.40	19.0	40.0	20.0	2.538	0.672	0.823	1829.8	1259.5	1.453
27	4.55	1.60	19.0	40.0	20.0	2.115	0.529	0.599	4377.8	2984.6	1.467
28	3.88	1.80	19.0	40.0	20.0	2.523	0.667	0.815	3278.2	2486.4	1.318
29	4.60	1.85	19.0	40.0	20.0	2.270	0.581	0.677	4233.7	3404.4	1.244
30	2.30	1.64	15.6	42.1	20.9	3.630	1.108	1.580	669.6	993.9	0.674
31	4.73	1.36	15.6	42.1	20.9	1.838	0.461	0.499	1705.5	2779.1	0.614
32	1.66	1.10	16.5	43.6	21.3	3.180	0.990	1.346	753.5	377.1	1.998
33	2.30	1.53	16.5	43.6	21.3	3.180	0.990	1.346	868.6	893.4	0.972
34	3.27	2.30	16.5	43.6	21.3	3.480	1.102	1.550	2377.3	2610.3	0.911
35	3.26	1.34	16.5	43.6	21.3	2.200	0.620	0.728	1848.2	1395.1	1.325
36	4.12	1.65	16.5	43.6	21.3	2.147	0.603	0.699	3037.8	2567.3	1.183
37	4.54	1.20	16.5	43.6	21.3	1.730	0.447	0.478	3050.1	2445.1	1.247
38	5.32	1.50	16.5	43.6	21.3	1.790	0.468	0.506	5922.3	3994.0	1.483
39	4.77	1.35	16.5	43.6	21.3	1.790	0.468	0.506	4167.4	2937.4	1.419
40	3.48	1.74	20.1	40.6	21.1	2.618	0.712	0.885	1797.5	2080.6	0.864

The reliability index can be calculated by JC method for various load ratio ρ and safety factor K . The results of reliability index are plotted in Fig. 3. When load ratio ρ is certain, reliability index β increases with safety factor K . For given value of K , reliability index β change slightly with ρ .

The load ratio ρ ranges from 3.3 to 8.3 commonly. Therefore, the values of reliability index are averaged in the range of ρ for various safety factors, listed in Table 2, which can provide reference for reliability-based design.

Table 2. Reliability index for various safety factors.

Safety factor	2.5	2.8	3.0	3.2	3.6	4.0
Reliability index(mean value)	2.741	2.879	2.955	3.023	3.132	3.220

Conclusion

Reliability analysis of uplift stability based on JC method for digged foundation in Gobi gravel soil has been made by non-dimensionalization for ultimate state equation and combining with the test results. The main conclusions are as follows: (1) The ratio of test value to calculated uplift capacity K_p that reflects the uncertainty of calculation model obey normal distribution with mean value of 1.309 and variance of 0.251. This indicates that formula of the ultimate uplift capacity of digged foundation in design code will underestimate the uplift capacity. It is safe for project. (2) When the ratio ρ of the variable load effect and permanent load effect is certain, reliability index β increases with safety factor K . And reliability index β changes slightly with the ratio ρ for a given safety factor. For gobi gravel soils, when $K = 2.5 - 4.0$, the reliability index β ranges from 2.741 to 3.220. (3) Sufficient test data and accuracy of theoretical calculation are beneficial to improve the results of reliability analysis. This study can provide a reference to the reliability calibration analysis of uplift stability.

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