Experimental investigation of connected foundation for transmission tower structure using field model load tests in soft clayey soils

Etude expérimentale de la fondation connectée pour la tour de transmission en utilisant tests de charge modèles de terrain sur un sols argileux mou

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ABSTRACT: The transmission tower structure consists of overhead power lines, steel-tower structure and lower foundation parts at each corner of the tower. Various types of foundations are used to support the upper tower structure depending on local soil condition. Pile foundation is usually adopted in soft clayey soils, as there are issues of instability problems such as insufficient load carrying capacity and large differential settlements. For such cases, connected foundation is an effective option, which can improve overall mechanical performance of transmission tower structure. In the present study, results obtained from a series of model load tests are presented to analyze the improved performance of connected foundation for transmission tower structures. Focus was given to changes in the load carrying capacity and differential settlement. The effects of load direction and connection-beam property were addressed in the analyses. The load carrying capacity and differential settlement noticeably changed with the use of connected foundation. Based on the test results, a methodology for the design application of connected foundation is presented. The validity of the method was checked with field test results.

RÉSUMÉ : Les structures de la tour de transmission sont constituées de lignes électriques aériennes, de structures de la tour en acier et de fondations qui sont placées à chaque coin de la tour. Différents types de fondations sont utilisées pour supporter la partie supérieure des structures en fonction des conditions du sol. La fondation sur pieux est habituellement adoptée dans des sols argileux mous car la fondation pourrait être soumise à divers problèmes d'instabilité tels que la capacité de charge insuffisante et d'importants tassements différentiels. Pour de tels cas, la fondation connectée est un type de fondation efficace, qui peut améliorer la performance mécanique globale de la structure de la tour de transmission dans les conditions de sol mou. Dans la présente étude, une série de tests de modèle a été menée pour étudier l'amélioration de la performance de la fondation connectée. L'accent a été mis sur les changements dans la capacité de charge et le tassement différentiel. Les effets de la direction de la charge et des propriétés du faisceau de connexion ont été pris en compte dans cette analyse. La capacité de charge et le décalage différentiel ont sensiblement changé avec l'utilisation des fondations connectées. Sur la base du résultat du test, une méthodologie pour l'application de la conception de la fondation connexe a été présentée. La validité de la méthode proposée a été confirmée en comparant les résultats d'essai à l'aide d'un modèle à grande échelle.

KEYWORDS: Connected foundation, Transmission tower, Field model load tests, Load carrying capacity, Soft clayey soils.

1 INTRODUCTION

The transmission tower structure is an important infrastructure for the electric power supply system. To guarntee stability and sustainable functionality of the electric power transmisson system, tower foundation should be installed with certain saftey margin satifying relevant sercieability criteria. Soft clayey soils widely exist in most coastal areas. Foundations consturcted in soft clayey soils can be subjected to various structural and geotechnical instability due to insufficient foundaton resistance and large differential settlements.

Connected foundation is a reinforced foundation type using additional structural components that are placed between individual main foundation parts. It is an effective option to improve structural and geotechnical performance in unfavorable soil conditions (TEPCO 1988, IEEE 2001). Wang et al. (2014) reported the use of connected foundation with H-shaped girders to prevent the instability problem of tower structure.

In the present study, the reinforcing effect of connected foundation for the transmission tower structure is presented based on the results from the model load tests of Kyung and Lee (2015) and Kyung et al. (2016). The model load tests of connected foundation were conducted considering changes in load direction. The model-transmission tower structure and foundation for the tests were prepared with different tower heights and properties of connection beam. Based on the test results, the design equations applicable in practice to estimate the load carrying capacity of connected foundation are presented and compared with measured test results obtained from large-scale field model-load tests.

2 FOUNDATION FOR TRANSMISSION TOWER

1 .1 *Design of tower foundation*

Various types of founations are used to support the tranmission tower structures (KEPCO 2011). The foundations for tower structures can be classified as axial-load (i.e. invert-T, pile and pier) and moment-load foundations (i.e. mat and single pole). Among these, piles are often adopted in soft clayey soils. The stability of tower foundations is then checked based on the following design criteria (TEPCO 1988, KEPCO 2011):

$$Q_{vc} \le R_{vc,m} = R_{vc} / FS \text{ and } Q_{vt} \le R_{vt,m} = R_{vt} / FS \text{ in vertical direction} \quad (1)$$

$$Q_{hc} \le R_{hc,m} = R_{hc} / FS \text{ and } Q_{ht} \le R_{ht,m} = R_{ht} / FS \text{ in lateral direction} \quad (2)$$

where Q_{vc} and Q_{vt} = transferred compressive and uplift tensile loads on front and rear sides; Q_{hc} and Q_{ht} = transferred horizontal loads on front and rear sides; $R_{vc,m}$ and $R_{vt,m}$ = allowable compressive and uplift resistances; $R_{hc,m}$ and $R_{ht,m}$ = allowable horizontal resistances; R_{vc}, R_{vt}, R_{hc} and R_{ht} = ultimate compressive, uplift and horizontal resistances; and FS = factor of safety.

1 .2 *Connected foundation*

Connected foundation consists of main foundation part and connection beams that are placed between individual adjacent foundations. For tower foundations, the uplift loads (Q_{vt}) usually govern overall stability and thus design, as the uplift resistance is usually smaller than the vertical compressive resistance. For the vertical-load (Q_v) dominant case, the connection beams provide additional shear resistance against vertical displacement of the foundations resulting in some increases in the load capacity and reduced differential settlement. This is described and shown in Figure 1. The application of connection beams would be therefore positively effective for the transmission tower structures in soft soils.

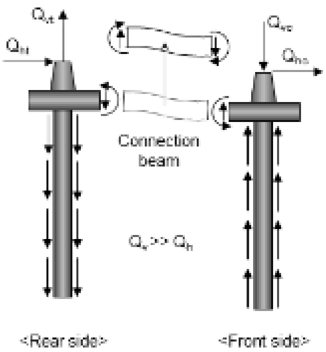

Figure 1. Load carrying mechanism of connected foundation

3 TESTING PROGRAM

3 .1 *Small scale model load tests*

Model transmission-tower structures with different types of connection beam and tower heights were manufactured and adopted in the tests, as shown in Figure 2. Three tower heights (z_h) of 0.5, 1.0 and 1.5 m and connection beam stiffness (EI) of 0.133, 6.135 and 1571 N-m^2, as designated as T1, T2 and T3, respectively, were adopted in the tests. Piles were adopted as main foundation. Model piles were made of closed-ended steel pipes with diameter (B) of 0.05 m and length (L) of 0.8 m. Lateral loads were applied on the top of tower structure with different lateral load directions (θ) of 0° and 45°. Applied lateral loads (H) on the top of the tower and transferred loads on the lower foundations at corners were measured using load cells. Thirteen LVDTs were installed at the top of the tower and each of foundations to measure vertical and lateral displacements of model structure.

Test site was located near Iksan city in Korea where soils were mostly soft clayey soils. The soils were classified into clay with low plasticity (CL) according to the unified soil classification system (USCS). The liquid limit (LL) and plasticity index (PI) were 45.0% and 22.9%, respectively. The total unit weight (γ_t), specific gravity (G_s), water content (w), and coefficient of compressibility (C_c) were 16.59 kN/m^3, 2.69, 45.8%, and 0.43, respectively. The undrained shear strength (s_u) through depths of pile embedment was around 11.28 kPa.

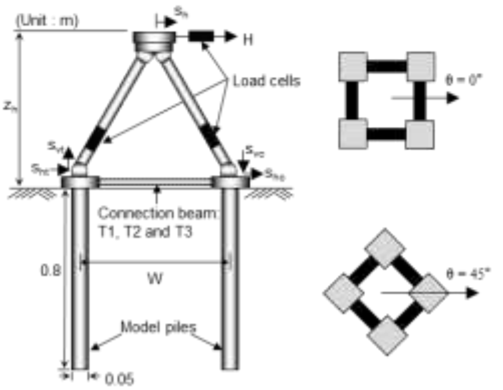

Figure 2. Detailed descriptions of small-scale model load tests

3 .2 *Test results*

3 . 2. 1 *Load carrying behavior*

Lateral load-displacement (H-s_h) curves measured at the top of tower structure are shown in Figure 3(a). Improved performance of connected foundation was observed with increases in the load carrying capacity in comparison to that of unconnected foundation. For the connected-foundation case, once yielding was reached, the load capacity continuously increased without showing clear indication to failure. The increase in load capacity after yielding was more pronounced for connection beams with higher stiffness showing additional safety margin and ductility. The values of ultimate load capacity (H_u) for connected foundations, corresponding to uplift displacement (s_{vt}) equal to 0.1B (JGS 2002, Xu et al. 2009), were obtained and indicated as dashed lines in Figure 3(a).

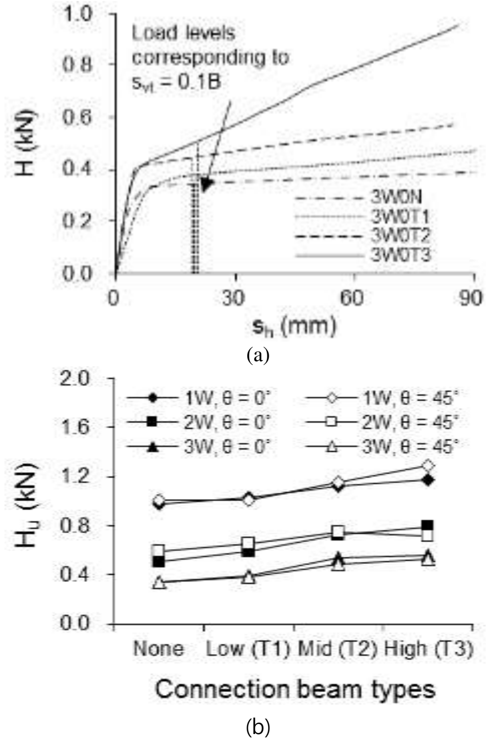

Figure 3. Load test results for model foundations: (a) lateral load-displacement curves and (b) lateral load carrying capacity.

The lateral load capacities (H_u) of unconnected and connected foundation are shown and compared in Figure 3(b). It is seen that H_u increases with increasing connection-beam stiffness similarly for all load heights. However, it was observed that the use of connection beam is more effective for higher load heights, which was confirmed from the ratio of H_u between unconnected and connected foundations. For most cases, the lateral load carrying capacities were approximately similar for different lateral load directions. This suggests that the design method for θ = 0˚ may also be applicable for θ = 45˚ and likely for other load directions.

3 . 2. 2 *Differential settlements*

Figures 4(a) and (b) show the vertical downward and uplift displacement (s_{vc} and s_{vt}) profiles at H = 0.343 kN and 0.334 kN that correspond to the load levels of the ultimate load capacities of unconnected foundations for θ = 0˚ and 45˚, respectively. For both cases of θ = 0˚ and 45˚, downward settlements and uplift displacements decreased with the application of connected foundations, which was more noticeable for higher beam stiffness cases. The differential settlement (Δs_v) between s_{vc} and s_{vt} for θ = 45˚ was much larger than for θ = 0˚ due to smaller number of resisting foundation at compression sides.

Figure 4(c) shows the ratios of differential settlements between connected and unconnected foundations ($\Delta s_v/\Delta s_{v,un}$). For all cases, differential settlements of connected foundation were smaller than unconnected foundation. Differential settlements decreased with increasing stiffness of connection beams and increasing tower heights. It means that the connected foundation is more effective for taller structures such as transmission tower structures.

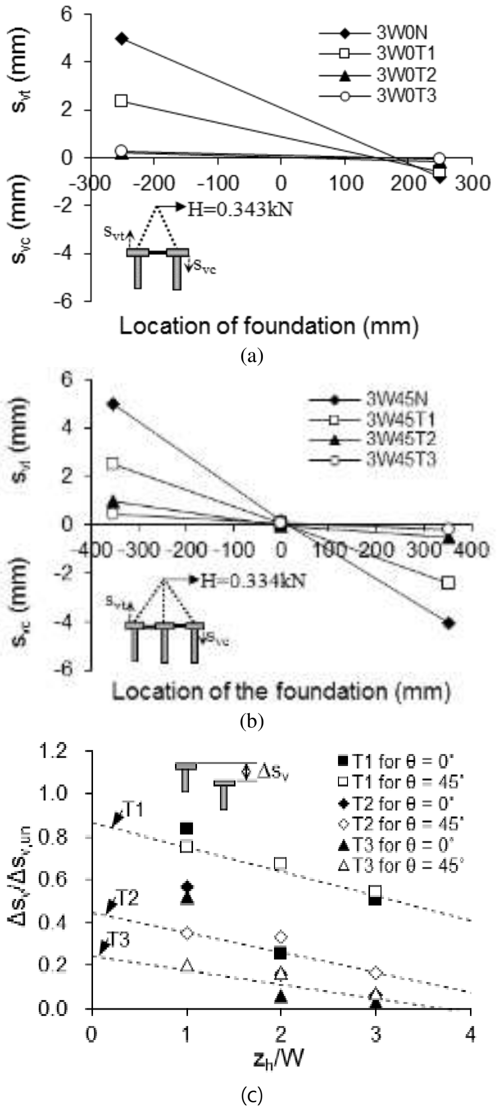

Figure 4. Vertical displacements for (a) θ = 0° and (b) θ = 45°; and (c) relatively differential settlement of connected foundation ($\Delta s_v/\Delta s_{v,un}$).

3 .3 *Design application for connected foundation*

The ultimate lateral load capacity of transmission tower (H_u) can be expressed as a function of vertical and horizontal resistances (R_v and R_h) of the individual foundation components. Considering the equilibrium condition of entire structural system, H_u can be estimated given as follows:

$$H_u = (2\,R_{ht} + 2\,R_{hc})/FS = 4\,R_h/FS \tag{3}$$

$$H_u = 2\,R_{vt}\,W/(z_h\,FS) \tag{4}$$

$$H_u = 2\,R_{vc}\,W/(z_h\,FS) \tag{5}$$

where R_{vc} and R_{vt} = compressive and uplift resistances, respectively; R_{hc} and R_{ht} = horizontal resistances; W = contiguous distance between foundations. The smallest H_u is determined from Equations (3)–(5), which would then control the design. For most cases of transmission tower structures, R_{vt} is the smallest and Equation (4) tends to control the design.

The uplift resistance (R_{vt}) of connected foundations can be defined in terms of that of unconnected foundation as follows:

$$R_{vt,c} = C_R\,R_{vt} \tag{6}$$

where $R_{vt,c}$ and R_{vt} = uplift resistances of connected and unconnected foundations, respectively and C_R = resistance increase factor. Introducing C_R, the ultimate lateral load of Equation (4) can be rewritten as:

$$H_{u,c} = 2\,C_R\,R_{vt}\,W/(z_h\,FS) \tag{7}$$

where $H_{u,c}$ = ultimate lateral load capacity of connected foundations.

From the correlation analysis of the test results for different tower heights, stiffness of connection beams and soil conditions shown in Figure 5, the C_R was obtained as follows:

$$C_R = 1 + \alpha\,(z_h/W)/(3.36 + 1.05\,(z_h/W)) \tag{8}$$

where α = stiffness-related model parameter. The values of α were found to be 0.4, 1.2, and 1.4 for low (T1), medium (T2), and high (T3) stiffness cases, respectively, indicating some variability with connection beam stiffness. The value of C_R would change with soil condition as the load capacity of foundation depends on soil condition. The values of α in Equation (8) were therefore evaluated considering the connection beam stiffness (EI) normalized with the uplift pile load capacity given by pile skin friction (q_s), pile shaft area (A_s) and pile base area (A_b), obtained as follow:

$$\alpha = 0.1015\,\ln\,(EI/(q_s\sum A_s\sum A_b)) + 0.784 \tag{9}$$

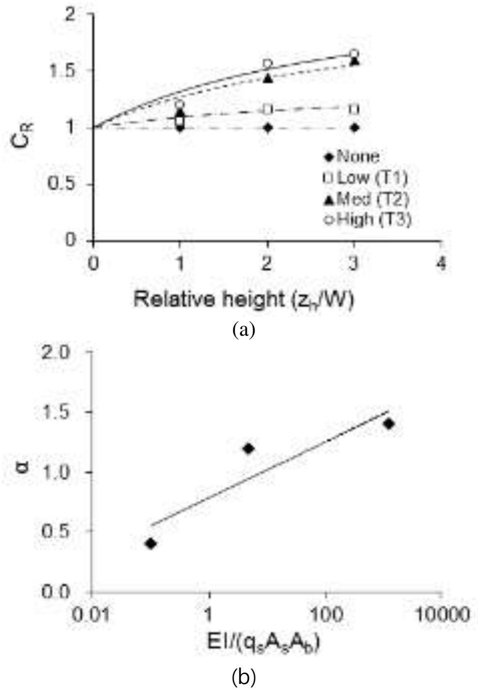

Figure 5. Correlation for resistance increase factor: (a) resistance increase factor (C_R) and (b) correlation parameter (α).

4 COMPARISON

4 .1 *Large scale model load tests*

To check the improved load carrying behavior of connected foundation, large-scale field-model load tests were conducted in soft clayey soils. The soil at the test site was clay with low plasticity (CL) with SPT N values smaller than 2, indicating very compressible and soft soil condition. The total unit weight (γ_t), water content (w), liquid limit (LL), plastic index (PL), and compressive index (C_c) for the upper sandy clay layer were 15.5 kN/m^3, 69.6%, 55.9%, 29.2%, and 0.58, respectively.

The height of the model transmission structure (z_h) was 2.856 m and the contiguous distance (W) was 1.28 m. For foundations at each corner, a square mat and four closed-ended piles were installed. The width and height of the mat were 0.5 m and 0.085 m and the diameter and length of piles were 0.102 and 4.5 m, respectively. Two types of connection beams were used with the beam widths of 0.125 and 0.250 m that represent the connection-beam stiffness (EI) equal to 25% and 50% of mat stiffness. Lateral loads (H) were applied at the top of model transmission tower using a hydraulic cylinder.

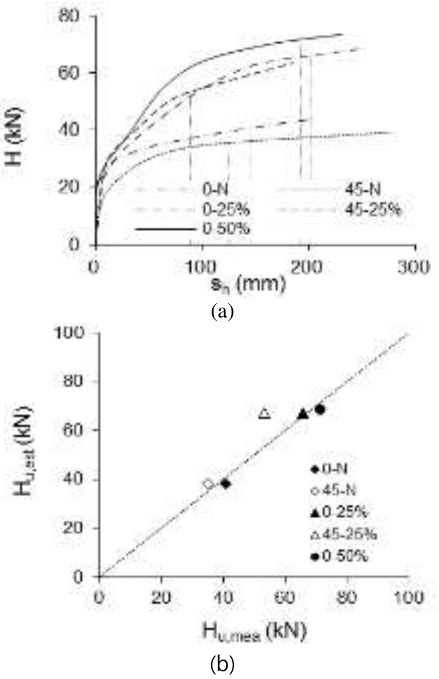

Figure 6. Field model load-test results: (a) lateral load-displacement curves and (b) comparison between measured and estimated H_u.

4 .2 *Measured and estimated results*

Figure 6(a) shows lateral load-displacement (H-s_h) curves measured at the top of the model tower structures. As for the small-scale model load tests, connected foundations showed higher load carrying capacity than unconnected foundation. The load carrying capacity increased as the connection beam stiffness increased while similar shapes of the load-displacement curves were observed for both connected and unconnected foundations. The ultimate load capacity (H_u), defined at 0.1B uplift displacement, was indicated as dashed lines in Figure 6(a). It is confirmed that the ultimate load capacities for θ = 0˚ and 45˚ are similar.

To check the design method presented herein, the values of H_u were estimated and compared with the measured results. Figure 6(b) shows the estimated ($H_{u,est}$) and measured ($H_{u,mea}$) results. The values of C_R were 1.76 and 1.79 for the 25%- and 50%-connection beam stiffness, respectively. As compared in Figure 6(b), the estimated values of $H_{u,est}$ were in good agreement with measured values of $H_{u,mea}$.

5 CONCLUSION

In this study, the improved load carrying behavior of connected foundation for transmission tower structures was analyzed based on the results obtained from a series of model load tests. Variety of test conditions, including different connection-beam stiffness, load heights and lateal load directions, were considered and addressed in the tests and analyses.

Connected foundation showed improved load carrying capacities and reduced displacements for both load directions of θ = 0˚ and 45˚. The load carrying capacities for θ = 0 ˚ and 45˚ were not significantly different for both unconnected and connected foundations. Changes in the load capacity and differential settlement were more pronounced as connection-beam stiffness increases. Design equations to estimate the load capacity of connected foundation were presented.

Field load tests using large-sclae model structure were conducted to confirm the performance of connected foundations. Two connection-beam stiffness of 25% and 50% mat stiffness were considered for the model structures. The estimated load carrying capacity using the design equations showed good agreement with measured results.

6 ACKNOWLEDGEMENTS

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