Load-carrying behavior of transmission-tower connected foundations subjected to different load directions

Doohyun Kyung, Junhwan Lee*

School of Civil and Environmental Engineering, Yonsei University, Yonseiro 50, Seodaemun-gu, Seoul, Republic of Korea

Received 31 March 2014; received in revised form 2 January 2015; accepted 2 February 2015
Available online 8 May 2015

Abstract

Connected foundations comprise an effective option for improving the mechanical performance of transmission tower foundations. In this study, the load-carrying behavior of connected foundations for transmission tower structures was investigated focusing on the effect of the load direction based on the field experimental testing program. Improved performances of connected foundations were observed for load directions of both $\theta = 0^\circ$ and $45^\circ$ considered in this study. The downward settlements at the compressive side for $\theta = 45^\circ$ were larger than those for $\theta = 0^\circ$, while the upward displacements were similar. For both vertical and lateral displacements, the use of connected foundations was more effective for $\theta = 45^\circ$, and the effectiveness became more pronounced as the connection-beam stiffness increased. However, the lateral load-carrying capacities for $\theta = 0^\circ$ and $45^\circ$ were not significantly different for all connection-beam conditions. From the prototype-scaled model load tests, it was confirmed that the use of connected foundations for transmission tower structures is similarly effective for different load directions. Based on the test results, it was suggested that a unified design methodology is applicable for the stability analysis of transmission tower structures subjected to different load directions.

& 2015 The Japanese Geotechnical Society. Production and hosting by Elsevier B.V. All rights reserved.

Keywords: Transmission tower structures; Connected foundations; Field load tests; Load capacity; Differential settlement; Soft soils; Model structures; IGC:E04

1. Introduction

Transmission tower structures comprise an important infrastructure used to support overhead power lines and electric transmission systems. To maintain the stability and suitable functionality of transmission tower structures, the foundations of the structures should be installed with a certain margin of safety which satisfies the relevant serviceability criteria. Different types of transmission tower foundations are available, including inverted-T (footing), pile, mat, and single-pole. They are selectively used depending on the size of the structure, the type of load and the soil conditions (IEEE, 2001; Morinaga et al., 2002; KECA, 2003; Jang et al., 2007).

Soft soils widely exist in most coastal areas and undeveloped inland regions. For foundations constructed in soft soils, structural damage and geotechnical instability can be encountered due to insufficient foundation resistance and large differential settlements. The connected foundation is an option that can be used to improve the structural and geotechnical performance in such cases. For example, Yang et al. (2012) and Wang et al. (2014) presented connected H-shaped girders for transmission towers to prevent the instability problem of tower structures. Yuan et al. (2009) also presented tower...
foundations with protective slabs in order to reduce the differential settlements of the foundations.

The connected foundation is a type of modified foundation using secondary connection components, but without altering the main configuration of the foundation. For transmission tower structures with a connected foundation, connection beams are usually adopted and installed at each corner between the transmission tower foundations. The design guidelines and a performance analysis can be found in TEPCO (1988) and IEEE (2001). According to TEPCO (1988), connection beams are regarded as rigid components and the mechanical properties of connection beams are not taken into account for the design. IEEE (2001) also referred to the use of connection beams for the same purpose, namely, to increase foundation resistance and to decrease differential settlements.

The performance of connected foundations and more detailed design parameters were presented later for various tower and connection beam conditions (Kyung et al., 2015). The proposed design parameters included load height, connection-beam stiffness and soil conditions. It was shown that connected foundations produce more efficient load-carrying capability for higher load heights and greater connection-beam stiffness (Kyung et al., 2015). For transmission tower structures, load direction is another factor that needs to be addressed because tower structures are not generally axi symmetric and the direction of transmission power lines and wind loads can vary. Although the performance and resisting mechanism of transmission tower foundations may change with the load direction, this has not been addressed or checked in detail, particularly with regard to connection-beam properties.

In this study, the performance of connected foundations for transmission tower structures was investigated focusing on the effect of load direction. For this purpose, load tests were conducted using model transmission tower structures with connected foundations specifically manufactured for this study. Different load heights and connection-beam stiffness were considered for the model structures. Two load directions were considered in the tests, namely, 0° and 45°, in the lateral load direction. In order to check the performance of the connected foundations, field load tests using prototype-scaled transmission model structures were conducted.

2. Foundations for transmission tower structures

2.1. Types of transmission tower foundations

Various types of foundations are used for transmission tower structures to support electrical power transmission systems, including overhead power lines and steel tower frames. Inverted-T foundations or footings are often used when the design loads are relatively small and the ground conditions are sufficiently favorable. When the towers are constructed in steep slopes, hilly areas or soft soils, deep foundations, such as piers or piles, are used, although they are more costly (Kim and Cho, 1995; KECA, 2003; Jang et al., 2007).

Transmission tower foundations can be classified according to the type of dominant load component acting on the foundations. Fig. 1 shows the types of foundations that are often adopted for transmission tower structures. Inverted-T and pile foundations, shown in Fig. 1(a) and (b), correspond to axial-load foundations as the lateral loads acting on the towers are transferred as uplift and compressive axial loads on individual foundations at each corner. Mat and single-pole foundations, shown in Fig. 1(c) and (d), are moment-load foundations as moment loads develop and act on the foundations upon lateral loading on the towers. Axial-load foundations are effective in resisting lateral tower loads, yet they are vulnerable to differential settlements. Moment-load foundations are effective in reducing differential settlements, but the lateral resistance tends to be lower than with the axial-load foundations.

2.2. Design of transmission tower foundations

Lattice towers are widely used for transmission tower structures. The considered design loads for lattice tower foundations are uplift, compressive and lateral (IEEE 2001; KEPCO, 2011). The design steps for transmission tower foundations include the structural design and a stability analysis of the foundation components, which are similar to other types of foundations. For the structural design, the structure members are proportioned based on the estimated bending moments and stresses (Subramanian and Vasan thi,
For the stability analysis, the load capacity of the individual foundations is evaluated for the given soil conditions and it is ensured that the load capacity is greater than the design loads.

Fig. 2(a) shows the typical configuration of an applied load ($H$) on a tower, transferred loads ($Q$) to lower foundations and mobilized foundation resistances ($R$) for transmission tower structures for the load direction of $\theta = 0^\circ$. Given the load direction in Fig. 2(a), the front- and rear-side piles are subjected to compressive and uplift tensile forces, respectively. When the applied load ($H$) changes in direction laterally, for example, from $0^\circ$ to $45^\circ$, as indicated in Fig. 2(b), the resisting mechanism of the foundations may also change. As shown in Fig. 2(a), for a load direction equal to $\theta = 0^\circ$, each pair of front and rear foundations is subjected to compressive and uplift loads, respectively. For the load direction equal to $\theta = 45^\circ$ in Fig. 2(b), the load-carrying mechanisms of the front and rear foundations are similar to those for $\theta = 0^\circ$. The two middle foundations, however, are neutral or are subjected to compressive or uplift loads depending on the settlement profile upon loading.

The stability of transmission tower foundations can be checked based on the following design criteria (TEPCO, 1988; KEPCO, 2011):

\[ Q_{vc} \leq R_{vc,m} = \frac{R_{vc}}{FS} \quad \text{and} \quad Q_{vt} \leq R_{vt,m} \]

\[ Q_{hc} \leq R_{hc,m} = \frac{R_{hc}}{FS} \quad \text{and} \quad Q_{ht} \leq R_{ht,m} \]

where $Q_{vc}$ and $Q_{vt}$ are transferred compressive and uplift tensile loads on the front and rear sides, respectively; $Q_{hc}$ and $Q_{ht}$ are transferred horizontal loads on the front and rear sides, respectively; $R_{vc,m}$ and $R_{vt,m}$ are allowable compressive and uplift resistances, respectively; $R_{hc,m}$ and $R_{ht,m}$ are allowable horizontal resistances; $R_{vc}$, $R_{vc}$, $R_{ht}$, and $R_{ht}$ are ultimate compressive, uplift and horizontal resistances, respectively; and $FS$ is the factor of safety. Note that $Q_{vc}$ and $Q_{vt}$ in Eq. (1) should include the self-weight of the tower structure as it would increase and decrease the compressive and uplift loads, respectively. Although similar equilibrium conditions may apply to horizontal loads $Q_{ht}$ and
where $Q_{he}$, the equality of these two loads will depend on the stiffness of the superstructure and the foundations as well as on the deformation characteristics of the underlying soils. While stabilities in both vertical and horizontal directions must be guaranteed, the vertical stability against uplift loads ($Q_{vt}$) in most cases controls the design as uplift resistance and is usually smaller than the vertical compressive resistance.

2.3. Connected foundation

The connected foundation is a modified reinforced foundation using additional structural components to improve the mechanical performance of the entire foundation system. As shown in Fig. 3(a), connection beams are placed between the main foundation components to provide additional load-carrying capability and to increase structural rigidity.

According to the existing design guidelines, the resistance of the connection beams can be calculated using a simplified beam analogy, as described in the ultra-high voltage (UHV) transmission tower design method for V-type foundations, which is denoted as the UHV method (TEPCO, 1988). For the UHV method in Fig. 3(b), it is assumed that the increase in load capacity of the connected foundation is given by the additional shear resistance provided by the installed connection beam. The shear resistance between the connection beam and the main foundation can be calculated by combining the fixed- and the hinged-end support conditions at A, as indicated in Fig. 3(b). The shear resistance of the connection beam is then obtained as the following equation:

$$R_A = q \cdot s + \frac{2}{s} \cdot \frac{M}{s}$$  \hspace{1cm} (3)

where $R_A =$ shear resistance of the connection beam; $q =$ pressure due to the self-weight of the connection beam; $s =$ effective length of the connection beam $= W + 1$ (m); $W =$ edge-to-edge net contiguous length excluding the foundation width; $M =$ bending moment induced by the lateral load $= Q_{he} \cdot (h + \frac{t}{2})$; and $h$ and $t =$ height and thickness of the mat, respectively.

As a recent development, a design equation was proposed for connected foundations considering the effect of the connection beam properties, given as (Kyung et al., 2015)

$$R_{vt,c} = C_R \cdot R_{vt}$$  \hspace{1cm} (4)

where $R_{vt,c}$ and $R_{vt} =$ uplift resistances of connected and unconnected foundations, respectively and $C_R =$ resistance increase factor. It has been presented that resistance increase factor $C_R$ varies as a function of the various design parameters given as follows:

$$C_R = 1 + \left[0.1015 \cdot \ln \left( \frac{E I}{q_s \sum A_s \sum A_b} + 0.784 \right) \right] \cdot \left[ \frac{z_h / W}{3.36 + 1.05(z_h / W)} \right]$$  \hspace{1cm} (5)

where $E I =$ connection-beam stiffness; $q_s =$ pile skin friction; $A_s$ and $A_b =$ pile shaft and base areas, respectively; $z_h =$ load height; and $W =$ contiguous distance between foundations. Eqs. (4) and (5) account for the effects of the various design parameters, yet they were developed under the condition of a load direction equal to $\theta = 0^\circ$. 

Fig. 3. Description of UHV method for calculation of connection beam resistance.
3. Experimental testing program

3.1. Test description

In order to investigate the load-carrying behavior of connected foundations under various loading conditions, a series of field load tests using model transmission tower structures was conducted. The test site was located in Iksan City, Korea where soft clayey soils predominantly exist. To characterize the in-situ soil conditions at the test site, standard penetration tests (SPTs) and cone penetration tests (CPTs) were conducted. Fig. 4 shows the depth profiles of SPT blow count N and CPT cone resistance $q_c$. The top 1 m of the surface soil, shown in Fig. 4, was silty sand, which was removed before the load tests. Below the top silty sand layer, silty clays extended down to a depth of 6.8 m below which a hard silty sand layer existed.

Undisturbed soil samples were collected from the silty clay layer and tested to obtain the index and the basic properties. The soils were classified into clay with low plasticity (CL) according to the unified soil classification system (USCS). The liquid limit (LL) and the plasticity index (PI) were 44.9% and 23.3%, respectively. The total unit weight ($\gamma_t$), specific gravity ($G_s$), water content ($w$) and coefficient of compressibility ($C_c$) were 16.59 kN/m$^3$, 2.69, 43.3% and 0.4, respectively. The undrained shear strength ($s_u$) was found to be in the range of 8.4–11.1 kPa from triaxial tests using soil samples.

3.2. Model structures

Model transmission tower structures with different types of connection beams and tower heights were manufactured and adopted in the testing program. Fig. 5 shows the detailed configuration of the model structure and the instrumentation adopted in the tests. The model transmission structures were prepared assuming an idealized and simplified configuration of the upper tower and lower foundations. The upper tower structure was manufactured using steel tubular frames with four legs and a joint head (‘a’ in Fig. 5(a)). The lower foundations consisted of four individual foundations with piles at each corner. Piles were used as they are commonly used for transmission tower structures in soft soils. The upper tower frames and lower foundations were all hinge-connected, as indicated by a–d in Fig. 5(a).

Model tower structures with three different heights ($z_h$) were prepared. The considered load heights ($z_h$) were 0.5, 1.0 and 1.5 m corresponding to 1 W, 2 W and 3 W, respectively, for which W is the contiguous distance equal to 0.5 m, as indicated...
in Fig. 5(a). For the connected foundation, three different types of connection beams were used, which included a wire type with low stiffness of $EI = 0.133 \text{ N m}^2$, a medium-stiffness beam with $EI = 6.135 \text{ N m}^2$ and a high-stiffness beam with $EI = 1571 \text{ N m}^2$. These are designated as T1, T2 and T3, respectively. A total of 12 field load tests were conducted. The detailed test conditions are summarized in Table 1.

Table 1
Test conditions for field load tests.

<table>
<thead>
<tr>
<th>Connection beam type</th>
<th>Load height (m)</th>
<th>Test name</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.5</td>
<td>1W45N</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2W45N</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3W45N</td>
</tr>
<tr>
<td>0.133</td>
<td>0.5</td>
<td>1W45T1</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2W45T1</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3W45T1</td>
</tr>
<tr>
<td>6.135</td>
<td>0.5</td>
<td>1W45T2</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2W45T2</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3W45T2</td>
</tr>
<tr>
<td>1571</td>
<td>0.5</td>
<td>1W45T3</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>2W45T3</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>3W45T3</td>
</tr>
</tbody>
</table>

The model piles for the foundations were made of closed-ended steel pipes with a diameter ($B$) of 0.05 m and a length of 0.8 m. Between the model piles and the upper tower frames, 0.1 $/\text{m}^2$ steel mats were installed. A load cell was installed at the top joint head to measure the applied lateral loads, and four additional load cells were installed along the four tower frames to measure the forces transferred to the lower foundations. Thirteen LVDTs were installed at the joint head and each of the four steel mats to measure the vertical and horizontal displacements of the model structures. Lateral loads were applied at the joint head using a wire-connected winch that was installed on a reaction H-pile driven 30 m from the model structure. Load increments ($\Delta H$) of 0.05–0.1 kN were applied until the uplift displacement ($s_{vt}$ in Fig. 2) of the uplift pile reached 30 mm. For all cases, the load direction was set to $\theta = 45^\circ$.

4. Test results

4.1. Load responses and displacement behavior

Lateral load–displacement ($H$–$s_h$) curves, measured at the top joint head, are shown in Fig. 6 for different connection
beams of T1, T2 and T3 and load heights of 1 W and 3 W. The symbol ‘N’ in the figure represents the unconnected foundations. For comparison, the results for $\theta = 0^\circ$ in Kyung et al. (2015) were adopted and included in Fig. 6(a) and (b). As shown in Fig. 6, improved performances of the connected foundations are observed with the increased load-carrying capacities in comparison to those of the unconnected foundations for both $\theta = 0^\circ$ and $45^\circ$. The vertical dashed lines in Fig. 6 represent the load levels measured at an uplift displacement ($s_{vt}$) of the uplift piles equal to 10% of the pile diameters ($0.1B$) (i.e., 5 mm). The $0.1B$ criterion for the uplift pile resistance can also be found from other cases in literature (JGS, 2002; Livneh and El Naggar, 2008; Xu et al., 2009). The shape of the load–displacement curves and the post-yielding behavior for different load directions in Fig. 6 were somewhat different, which will be further analyzed.

As the foundations of transmission tower structures represent a combined foundation system, the load responses of individual foundations affect the overall performance of the transmission tower structure. Fig. 7 shows the load responses of the unconnected model structure for different load and displacement components. Fig. 7(a)–(d) represents the lateral load–displacement ($H-s_h$), the uplift load–displacement ($Q_{vt}-s_{vt}$), the compressive load–displacement ($Q_{vc}-s_{vc}$) and the lateral load–displacement ($Q_{ht}-s_{ht}$) curves of the foundations, respectively. It is noted that the lateral displacements ($s_{ht}$) in Fig. 7(d) are much smaller than the vertical uplift and compressive displacements ($s_{vt}$ and $s_{vc}$) in Fig. 7(b) and (c).

The presence of vertical loads affects the lateral resistance of the piles. Zhang et al. (2002) reported that the presence of vertical loads produces increases in the lateral resistance of piles in sand. For piles in clay, Karthikeyan et al. (2007) showed that the lateral resistance decreases with the presence of vertical load. Fig. 8 shows the lateral load–displacement curves ($Q_{ht}-s_{ht}$) for unconnected and connected foundations with different load heights of $z_h = 1$ W, 2 W and 3 W and $\theta = 45^\circ$. Note that the cases of $z_h = 1$ W and 3 W represent the lowest and the highest vertical loads ($Q_{vc}$) for the same magnitude of horizontal load ($Q_{hc}$), respectively. As shown in Fig. 8(a), the lateral load resistance becomes lower as the load height increases from $z_h = 1$ W to 3 W. This is consistent with the results by Karthikeyan et al. (2007). For the connected case in Fig. 8(b), the effect of vertical loads was not clear,
showing similar lateral load responses for different load heights. This indicates that the effect of vertical loads becomes less pronounced when foundations are connected together as connection components now carry part of the transferred loads. The same results were observed for $\theta = 0^\circ$.

Fig. 9 shows the lateral movements of unconnected and connected foundations for different load directions. For the load direction of $\theta = 0^\circ$ in Fig. 9(a) and (b), the front- and rear-side foundations tend to move farther and closer to each other, respectively, showing a trapezoidal-shaped displacement configuration. Such movements were suppressed when the connected foundation was used showing reduced lateral displacements. For the load direction of $\theta = 45^\circ$ in Fig. 9(c) and (d), the directions of lateral displacements of the front-and rear-side foundations all coincided with the load direction, while fewer movements were observed from the middle-side foundations. Similar reductions in lateral displacement were observed from the connected case.

Fig. 10 shows the vertical downward and uplift displacement ($s_{hc}$ and $s_{vc}$) profiles for $\theta = 0^\circ$ and $45^\circ$ at $H = 0.343$ kN and 0.334 kN, respectively. For $\theta = 0^\circ$ in Fig. 10(a), the uplift displacements were much larger than the downward settlements. For $\theta = 45^\circ$ in Fig. 10(b), the downward settlements increased considerably, while the uplift displacements were approximately similar to those for $\theta = 0^\circ$. The increased downward settlements can be attributed to the reduced number of foundations at the front side against the compressive load. It was two for $\theta = 0^\circ$, which became one for $\theta = 45^\circ$. No noticeable vertical displacements were observed from the two middle-side foundations in Fig. 10(b). For both $\theta = 0^\circ$ and $45^\circ$, reduced amounts of downward settlement and uplift displacement were observed from the connected foundations, and this was more noticeable for higher connection-beam stiffness.

4.2. Comparison of resistance

Fig. 11 shows a comparison of lateral load-carrying capacities for $\theta = 0^\circ$ and $45^\circ$ ($H_0$ and $H_{45}$) measured from both unconnected and connected foundations. The lateral load-carrying capacities were measured at two different uplift displacement levels of 0.02B and 0.1B ($B$ = pile diameter) as shown in Fig. 11(a) and (b), respectively. These displacement levels can be regarded as the initial loading range and the ultimate state, respectively, considering the typical load-carrying mechanism of piles.

From Fig. 11, it is observed that most of the $H_0$ values at 0.02B are somewhat larger than $H_{45}$, while $H_{45}$ becomes equal to or slightly larger than $H_0$ at higher load levels of 0.1B. This can be explained by referring to the number of foundations that resist uplift loads. As presented previously, within the initial loading range, the numbers of uplift foundations are two and one at the rear side for $\theta = 0^\circ$ and $45^\circ$, respectively. For $\theta = 45^\circ$, however, with further increases in applied load, the middle-side foundations, which were in a neutral position, become part of the uplift loads as the front-side foundation settles more. As the lateral load-carrying capacity of transmission towers is usually governed by the uplift load capacity of uplift foundations, the additional uplift resistance from the middle-side foundations at larger displacements results in increases in the overall lateral load-carrying capacity.

There are two data points in Fig. 11(b) where $H_{45}$ was noticeably larger than $H_0$. These were obtained from the lowest load height of $z_h = 1$ W with T2 and T3 connection beams. As shown in Fig. 6(a) for $\theta = 0^\circ$, no significant differences in the ultimate load-carrying capacity at 0.1B were observed between the unconnected and the connected foundations, which was different from those for $\theta = 45^\circ$ in Fig. 6(c). In fact, the differences became larger as the displacement further increased. As a result, the test cases of 1W45T2 and 1W45T3 for $z_h = 1$W showed the values for $H_{45}$ as being quite a bit larger than the values for $H_0$. For other cases, the values for the lateral load-carrying capacities were approximately similar for both load directions. These results imply that the design method for $\theta = 0^\circ$ is also applicable for $\theta = 45^\circ$ and likely to be applicable for other load directions as well.

4.3. Differential settlement

Reductions in differential settlements are another main effect of connected foundations. Fig. 12 shows a comparison of the...
differential settlements measured from the unconnected and connected foundations ($\Delta s_{v,\text{un}}$ and $\Delta s_v$) for different load directions and connection-beam stiffness. For consistency in the comparison, the values for $\Delta s_{v,\text{un}}$ and $\Delta s_v$ in Fig. 12 were all obtained at the same load level of $H_u$, that is, equal to the ultimate lateral load measured from the unconnected foundations.

As observed from Fig. 12, differential settlements for $\theta=45^\circ$ were nearly twice larger than those for $\theta=0^\circ$ for all connection-beam stiffness cases. As discussed previously, this is due to the increased downward settlements at the front side where the number of compressive foundations is one. However, the reduction ratios of the differential settlements between unconnected and connected foundations were similar for both $\theta=0^\circ$ and $45^\circ$, which were equal to 40%, 75% and 84% for connection-beam stiffness of T1, T2 and T3, respectively. As observed from Fig. 12(a)–(c), the differences in differential settlement between $\theta=0^\circ$ and $45^\circ$ become smaller as the connection-beam stiffness increases. For T3 in Fig. 12(c), the values of $\Delta s_v$ for $\theta=0^\circ$ were very close to those for $\theta=45^\circ$. This indicates that the use of a connection beam is more effective for the load direction of $\theta=45^\circ$ than for $\theta=0^\circ$, showing larger amounts of reduced differential settlements.

5. Field load tests using prototype model structures

5.1. Test description

To check and confirm the compared load-carrying behavior of connected foundations for different load directions, larger-scaled prototype transmission model structures were constructed and field load tests were conducted. The test site was located at Hwasung City in Korea. Soils at the test site consisted of two
distinguished layers of upper sandy clay, with a thickness of 4 m, and a lower silty sand layer. Near the soil surface, a thin mixed silty clayey sand layer, with a thickness of 0.4 m, existed. The depth profiles of SPT N and the soil types at the test site are shown in Fig. 13. The upper sandy clay was classified into clay with low plasticity (CL) with SPT N values smaller than 2, indicating a very compressible and soft soil condition. The total unit weight (\( \gamma_t \)), water content (\( w \)), plastic index (PI) and compressive index (\( C_c \)) for the upper sandy clay layer were 15.5 kN/m\(^3\), 69.6%, 29.2% and 0.58, respectively. The undrained shear strength (\( s_u \)) at the middle depth of the upper sandy clay layer was 8.6 kPa.

Fig. 14 shows the detailed configuration of the prototype model transmission structure constructed for the field load tests. Both unconnected and connected foundations were constructed and adopted in the load tests using the prototype model structures. The height of the model structure was 2.856 m and the contiguous distance (\( W \)) was 1.28 m. For the foundations at each corner, a square mat and four closed-ended piles were installed. The width and the height of the mat were 0.5 m and 0.085 m, and the diameter and the length of the piles were 0.102 and 4.5 m, respectively. For the case of the connected foundation, connection beams were installed with a hunched-shape interface to mat, as shown in Fig. 14. The width of the connection beams was 0.125 m; this means that the connection-beam stiffness (\( EI \)) was equal to 25% of the mat stiffness.

Lateral loads (\( H \)) were applied at the top of the model transmission tower using a hydraulic cylinder with a load increment of 50 kN. A load cell was installed between the hydraulic cylinder and the top of the tower to measure the applied lateral loads. LVDTs were installed at the edges of each individual foundation to measure the lateral and vertical displacements of the foundations.

5.2. Test results

Fig. 15 shows the lateral load–displacement (\( H-s_v \)) curves and the compared ultimate lateral load-carrying capacities (\( H_u \)) of the connected (PMT0–25% and PMT45–25%) and the unconnected foundations (PMT0-N and PMT45-N) for different load directions of \( \theta = 0^\circ \) and 45°. The field load test results for \( \theta = 0^\circ \) were also adopted from Kyung et al. (2015).
The $H-s_h$ curves were measured at the top of the model transmission tower and the ultimate lateral load-carrying capacities ($H_{u0}$ and $H_{u45}$) corresponded to the loads that caused uplift displacements ($s_{u0}$) of $0.1B$. The value of $B$ was 0.102 m, which was the diameter of an individual pile for the PMT cases shown in Fig. 14. Although 4 piles were used for each corner, the $0.1B$ criterion using individual pile diameter $B$ was adopted as this uplift displacement level was sufficiently large for the uplift capacity of individual piles to be fully mobilized. The load-carrying capacities obtained at the uplift displacement of $0.1B$ were indicated with dashed lines in Fig. 15(a). As shown in Fig. 15(a), the overall shapes and sizes of the load--displacement curves for the connected and the unconnected foundations were fairly similar. The ultimate load-carrying capacities for $\theta=0^\circ$ and $45^\circ$ in Fig. 15(b) were also similar, whereas $H_{u45}$ for $\theta=45^\circ$ were slightly smaller than $H_{u0}$ for $\theta=0^\circ$.

Table 2 shows the ratios of the ultimate load-carrying capacities of the connected ($H_u$) to the unconnected ($H_{u,un}$) foundations and those of the differential settlements of the connected ($\Delta s_v$) to the unconnected ($\Delta s_{v,un}$) foundations for different load directions. It is seen that the $H_u$ of the connected foundation increased by 56% and 51% for $\theta=0^\circ$ and $45^\circ$, respectively, compared to those of the unconnected foundations. The differential settlements also decreased markedly with the use of connected foundations, showing $\Delta s_v/\Delta s_{v,un}$ equal to 0.09 and 0.18 for $\theta=0^\circ$ and $45^\circ$, respectively.

From the results in Fig. 15 and Table 2, it can be summarized that the use of connected foundations for transmission tower structures is similarly beneficial for different load directions. While the transmission tower structure itself is not axisymmetric, changes in load direction did not produce particularly noticeable differences in the load response. Based on these results, it is suggested that a unified design methodology may be applicable for the stability analysis of transmission tower structures subjected to different load directions. However, the differential settlements were certainly different and increased as the load direction changed from $0^\circ$ to $45^\circ$. It is also indicated that the effectiveness of the connected foundations in reducing the differential settlement changes with the load direction, showing a higher reduction effect for the load direction of $\theta=45^\circ$.
6. Summary and conclusion

The connected foundation is an effective type of foundation for improving the structural and geotechnical performance of transmission tower structures in soft soils. In this study, the load-carrying behavior of connected foundations for transmission tower structures was investigated focusing on the effect of load direction. A series of field load tests was conducted in soft soil deposits using small- and prototype-scaled model transmission tower structures.

Improved performances of connected foundations with increased load-carrying capacities and reduced displacements were observed...
for both load directions of $\theta=0^\circ$ and $45^\circ$. A trapezoidal-shaped lateral displacement configuration was observed for $\theta=0^\circ$, whereas the directions of lateral displacements for $\theta=45^\circ$ all coincided with the direction of applied load. Downward settlements at the front compressive side increased considerably for $\theta=45^\circ$, while upward displacements were approximately similar to those for $\theta=0^\circ$. For both vertical and lateral displacements, the connected foundations were more effective for $\theta=45^\circ$, showing higher displacement reduction ratios, which were more pronounced as the connection-beam stiffness increased.

The lateral load-carrying capacities for $\theta=0^\circ$ and $45^\circ$ ($H_0$ and $H_{45}$) were not significantly different for either unconnected or connected foundations. Within the range of initial loading, however, the values for $H_0$ were slightly larger than those for $H_{45}$. With further increases in load and displacement level, $H_{45}$ tended to be reversely larger than $H_0$ due to changes in the number of foundations that resist uplift loads.

From the prototype-scaled model load tests, it was confirmed that the use of connected foundations for transmission tower structures is similarly effective for different load directions. It was indicated that the same design methodology may be applicable for the stability analysis of transmission tower structures subjected to different load directions. However, the amount of differential settlement becomes different as the load direction changes from $0^\circ$ to $45^\circ$. For such cases, the use of connected foundations was more effective, producing higher reduction ratios of differential settlements.

Acknowledgments

This work was supported by a Grant from Power Generation & Electricity Delivery of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by the Korean Government Ministry of Knowledge Economy (No. 20101020200060). The work was also supported by a Grant from the National Research Foundation of Korea (NRF) funded by the Korean Government (MSIP) (No. 2011-0030040).

Table 2
Comparisons of $H_s/H_{u,un}$ and $\Delta s/\Delta s_{v,un}$ with relative stiffness of connection beams for prototype model structures.

<table>
<thead>
<tr>
<th>PMT0–25%</th>
<th>PMT45–25%</th>
<th>Effect of connection beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_s/H_{u,un}$</td>
<td>1.56</td>
<td>1.51</td>
</tr>
<tr>
<td>$\Delta s/\Delta s_{v,un}$</td>
<td>0.09</td>
<td>0.18</td>
</tr>
</tbody>
</table>

References


