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Prediction of steel tower foundation specifications using non-destructive testing method

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Abstract. Transmission tower foundations play a critical role in supporting and preventing the collapse of tower structures. In Korea, 12,000 tower foundations require additional reinforcement due to the recent design standard changes for wind speed pressure as a result of climate change. However, several challenges arise when attempting to determine appropriate methods of reinforcement, especially in the case of approximately 1,500 towers that lack any records of foundation specifications. In this study, the electrical resistivity survey, one of the non-destructive testing methods, is employed to accurately determine foundation specifications, which can in turn be used to strategically develop reinforcement plans. Using electrical resistivity survey data obtained through both laboratory and field experiments, an algorithm capable of extracting foundation specifications was developed. The system was then applied to 47 transmission tower foundations. According to the results, the electrical resistivity survey achieved a prediction accuracy of 91.5% for depth of the tower foundation, 98.6% for width of the base slab, and 95.6% for thickness of the base slab. These findings suggest that the method is particularly effective at predicting the width and thickness of the base slab, with width predictions being the most accurate. This research is expected to aid in the creation of maintenance and reinforcement plans for transmission tower foundations while also enabling cost-effective specification assessments for various buried civil engineering structures.

Keywords: electrical resistivity survey; foundation; non-destructive test; specification; transmission tower

1. Introduction

Transmission towers play a crucial role in the transmission of electricity. A transmission tower is built upon a foundation that serves as a support structure to prevent the tower from collapsing. Such transmission tower foundations are designed based on the applied loads and the structural design of the transmission tower. A key external factor that affects the loads applied to a transmission tower is wind pressure (Pacheco *et al.* 2008, Wang *et al.* 2021, Wang *et al.* 2024). In Korea, the design standards for tower foundations have traditionally used wind speed pressure criteria derived from meteorological data from the 1980s. However, due to climate change, wind speed pressure criteria in Korea have recently been revised, necessitating reinforcement for approximately 12,000 transmission tower foundations. However, the detailed specifications of approximately 1,500 tower foundations have not been recorded, thus presenting a challenge when attempting to determine suitable reinforcement methods. Among the various parameters of the steel tower foundation specification, the parameters required for establishing the tower foundation reinforcement plan are the width and thickness of the base slab, and depth of the tower foundation. (Pacheco *et al.* 2008, Kyun and Lee 2015, Kyung *et al.* 2015, Wang *et al.* 2021). New technologies need to be developed so that the specifications of tower foundations can be determined to ensure reliable power transmission networks.

Technologies for the prediction of transmission tower foundation specifications can be categorized into surface and borehole investigations, depending on the point of investigation. Surface investigations employ techniques such as elastic wave refraction and reflection surveys, electrical resistivity surveys, and ultrasonic surveys. On the other hand, borehole investigations include methods like elastic wave tomography, velocity logging, and downhole elastic wave surveys. Among these methods, elastic wave surveys are widely used in construction, civil engineering, and oil and gas exploration. These techniques can be employed to effectively image subsurface structures and are thus highly useful for geotechnical investigations and subsurface structural surveys. Technologies for determining foundation specifications using elastic waves generally involve techniques such as the impact-echo method and the parallel seismic (PS) method. These methods determine the

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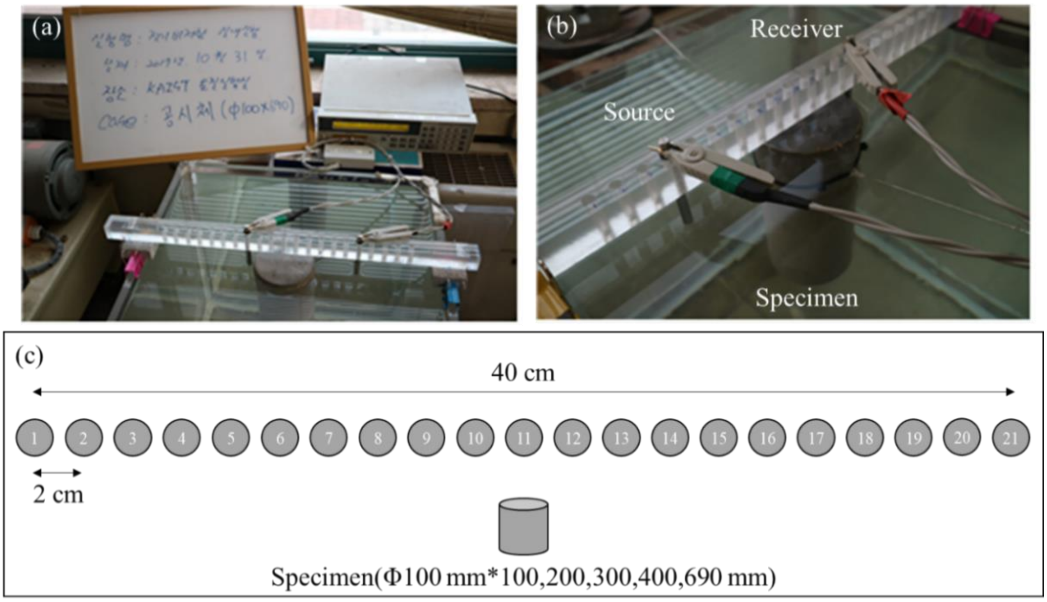

Fig. 1 (a) Photograph of the laboratory experiment setup, (b) photograph of the source and receiver sensors, and (c) schematic diagram of the experimental setup

specifications of a foundation by measuring the elastic waves that are generated when the foundation or the ground surface is struck by an impact force.

The impact-echo method estimates the embedded depth of a foundation by generating elastic waves at the top of the foundation and measuring the reflected waves from the bottom of the foundation (Pratt, D. and Sansalone 1992, Sansalone 1997, Carino 2001, Song and Cho 2009, Carino, 2015). Since this method relies on reflected waves, which often have low energy and can overlap with ambient noise, appropriate data processing is required to achieve reliable results. The parallel seismic method is a borehole investigation technique that involves placing geophones inside an adjacent borehole, then striking the foundation to measure the transmitted elastic waves and estimate the embedded depth of the foundation (Ni *et al.* 2011, Niederleithinger 2012, Souza *et al.* 2016). The PS method offers higher data reliability compared to surface investigations due to the lower energy attenuation with depth. However, the method necessitates the drilling of boreholes and is thus more expensive. Furthermore, elastic wave surveys are primarily used to gather data on the direction in which the seismic waves propagate; when applied to tower foundations, they are limited to determining the embedment depth of foundations (Colla *et al.* 2003, Aggelis *et al.* 2008, Wang *et al.* 2014, Rashidyan *et al.* 2017, Garbacz *et al.* 2017, Kumar *et al.* 2024).

In contrast, an electrical resistivity survey is performed to investigate subsurface structures in two or three dimensions (Chitea *et al.* 2019, Wang *et al.* 2020, Eissa 2021, Doro *et al.* 2022, Alao *et al.* 2024). In other words, the width and thickness of the base slab, and depth of the tower foundation required for establishing the tower foundation reinforcement plan can be investigated through electrical resistivity surveys. This technique involves using a pair of grounded electrodes to pass an electric current through the ground, then measuring the potential difference to determine the electrical resistivity distribution of the subsurface materials. Since subsurface structure exhibit complex geological and structural characteristics (i.e., heterogeneity and anisotropy), the penetration and flow of electric currents can vary significantly. Electrical resistivity surveys are extensively used not only for groundwater exploration and contamination detection, but also for various purposes in the engineering (e.g., locating underground voids, identifying faults and fracture zones, investigating mineshafts and permafrost zones) and archaeological fields (e.g., uncovering buried foundations of ancient structures in archaeological sites) (Rizzo *et al.* 2004, Cardarelli *et al*. 2010, Metwaly *et al*. 2013, Xiao *et al*. 2013, Raji and Adedoyin 2020, Chhun and Yune 2023, Olabode and San 2023, Song *et al*. 2023, Min and Yoon 2024).

This study applied an electrical resistivity survey —a non-destructive testing technique—to accurately predict foundation specification information that is required when establishing plans to repair or reinforce transmission tower foundations. We began with laboratory experiments to evaluate the feasibility of conducting electrical resistivity surveys to predict foundation specifications. An algorithm was also developed to automatically extract foundation specification information, allowing for rapid on-site results. Furthermore, a handheld system was developed so that the analysis method could be implemented in difficult-to-access locations (e.g., mountainous areas). The developed system was applied to analyze 47 transmission tower foundations.

2. Methods

The aim of this study is to predict the specifications of transmission tower foundations based on the aforementioned electrical resistivity survey. Most transmission towers are constructed by excavating the natural ground, installing the foundation in the excavated hole, and then backfilling with soil. However, unlike natural soil, it is difficult to tightly compact backfilled soil, resulting in soil that differs from the original ground. Additionally, as the installed foundation structures consist of non-soil materials, they exhibit distinct electrical properties, making them distinguishable from the surrounding ground (Chitea *et al.* 2019, Ganiyu *et al.* 2020, Wang *et al.* 2020, Eissa 2021, Doro *et al.* 2022, Oyeyemi *et al.* 2022, Alao *et al.* 2024). Therefore, investigations involving the electrical resistivity survey should consider the unique properties of transmission tower foundations and the surrounding ground, including how electric field ranges, sensor placement, and analysis algorithms are affected by factors such as the embedded depth, size, and material of transmission tower foundations.

Prior to developing an analysis algorithm, we conducted laboratory experiments to observe changes in the electric field caused by the presence of a transmission tower foundation. The experiments aimed to understand the electrical resistivity distribution resulting from variations in measurement distance and tower foundation depth. To verify and improve the algorithm, the experiments needed to be conducted under homogeneous conditions to minimize data errors. Instead of simulating actual in-situ soil conditions, the experiments were conducted in water as underwater conditions are more favorable when measuring electrical resistivity. To minimize boundary effects, the experiments were conducted in an acrylic tank (487*487*665 mm), and holes separated by 2 cm intervals were drilled along a rectangular acrylic column where the sensors could be inserted for measurements (Fig. 1). The size of the sensor is 8 mm in diameter and 100 mm in length. Concrete specimens were fabricated to represent transmission tower foundations and were submerged underwater in the tank during the experiments.

The concrete specimens were cylindrical with a diameter of 100 mm and lengths of 100 mm, 200 mm, 300 mm, 400 mm, and 690 mm, respectively. A reference case without a specimen was first conducted, followed by experiments with each specimen placed in the tank. As shown in Fig. 1, the spacing between the sensor holes was 2 cm. The experimental procedure involves selecting one sensor from Sensor No. 1 to Sensor No. 8 as the source sensor, and measuring the resistance values from Sensor No. 14 to Sensor No. 21. This process is repeated by sequentially selecting each sensor as the source up to the Sensor No. 8.

3. Results

Fig. 2 illustrates the resistivity results corresponding to sensor positions obtained through laboratory experiments with test specimens of varying sizes. Sensor No. 1 to No. 8, positioned on the left side of the specimen, were used as the source, while the resistance values were analyzed from Sensor No. 14 to No. 21 on the right side of the specimen. Each graph represents results from a different source, and the black line indicates the reference case where no test specimen is present. In the reference case, the resistance values generally diminished as the distance to the source sensor decreased. When a test specimen was present, the resistance values tended to rise as the size of the specimen and the distance to the source sensor increased. These trends were found to be consistent with theoretical electrical resistivity phenomena (Ryu *et al.* 2020).

From the laboratory experiments, the trend of resistance value changes depending on the presence the tower foundation was observed, confirming the potential for using electrical resistivity to determine the specifications of the tower foundation. It also highlighted the need for algorithm development based on theoretical principles for field application. We established a measurement database for algorithm development, and various issues encountered during the testing process were analyzed to propose solutions. The following findings were derived: ① When applying the proposed method at actual transmission tower foundation sites, it is necessary to determine the appropriate sensor size and spacing based on the foundation size. ② If the medium is soil, the required supply voltage should be considered due to the lower electrical conductivity of soil compared to water. ③ Measurement values can vary significantly depending on the applied cross-sectional area of the sensor (area submerged in water or the installation depth of the sensor in soil). Therefore, the applied cross-sectional area of the sensor must be recorded when conducting in-situ measurements. ④ Prior to field application, the electrical conductivity of the surrounding soil must be measured. Based on these findings, we developed an algorithm and a hardware system for identifying the specifications of transmission tower foundations.

4. Field applications

We aimed to develop a theoretical formula for predicting transmission tower foundation dimensions in addition to a model capable of accurately predicting transmission tower foundation shapes based on resistance value measurements.

4.1 Development of an algorithm for predicting tower foundation dimensions

The following theoretical equations were derived to investigate the ground conditions behind the tunnel face using the electrical resistivity surveys (Ryu *et al*. 2020). Based on these equations, we derived a theoretical formula that describes the extent to which an electric field generated by applying a voltage in the ground is distorted by the presence of a transmission tower foundation (Fig. 3). Current (I) is defined as the amount of charge passing through an arbitrary cross-sectional area (ds) over time. This is expressed mathematically as Eq. (1) (Reitz *et al.* 2008)

$$I = \oint \sigma E \cdot ds \tag{1}$$

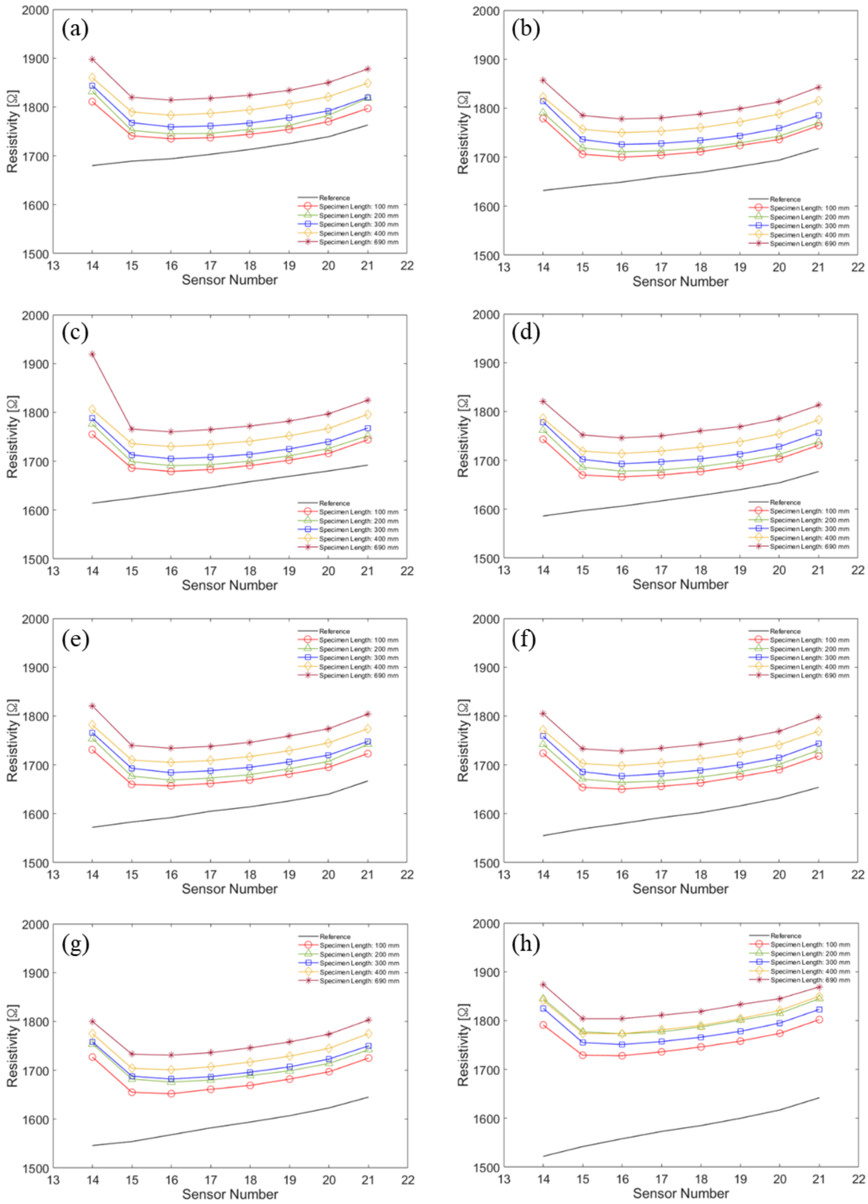

Fig. 2 Laboratory electrical resistivity experiment results based on specimen length when the source sensor is (a) Sensor No. 1, (b) Sensor No. 2, (c) Sensor No. 3, (d) Sensor No. 4, (e) Sensor No. 5, (f) Sensor No. 6, (g) Sensor No. 7 and (h) Sensor No. 8

Where, σ is the electrical conductivity, and E is the electric field. As shown in Fig. 4(a), when a transmission tower foundation is embedded in the ground, the current flowing through the ground can be expressed as Eq. (2) (Ryu 2010, Ryu *et al*. 2015)

$$I = \int_0^\infty \sigma_m E_m \pi l \, dl - \int \sigma_m E_m ds + \int \sigma_p E_p ds \qquad (2)$$

Here, σ_m is the electrical conductivity of the soil, E_m is the electric field generated in the soil, σ_p is the electrical conductivity of the tower foundation, E_p is the electric field generated in the foundation, and l is the distance from a point inside the soil to the line connecting the two sensors. The first term in Eq. (2) represents the electric field when the tower foundation is not present. The second term represents the current due to the area of the tower foundation, and the third term represents the current considering the material of the tower foundation (σ_p).

The electric field generated in the soil is expressed as Eq. (3), and the relationship between the electric field generated in the tower foundation and the soil is expressed as Eq. (4)

$$E_m = \frac{1}{4\pi\varepsilon_m}\frac{Q}{r^2}\cdot\hat{r} = \frac{Q}{4\pi\varepsilon_m}\frac{L/2}{((L/2)^2+l)^{3/2}}\times 2 \qquad (3)$$

$$E_m = \frac{K+2}{3}E_p \qquad (4)$$

Here, ϵ_m is the permittivity of the soil, Q is the amount of electric charge, r is the distance from the sensor to a

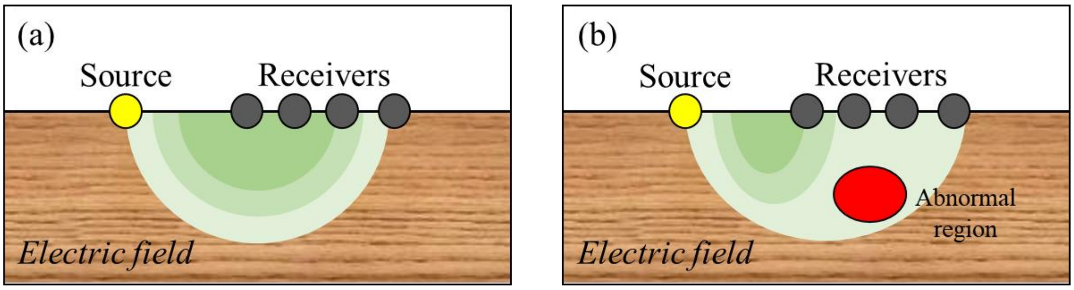

Fig. 3 Conceptual diagram of the electric field analysis method. (a) Typical electric field behavior and (b) electric field behavior in the presence of an abnormal region

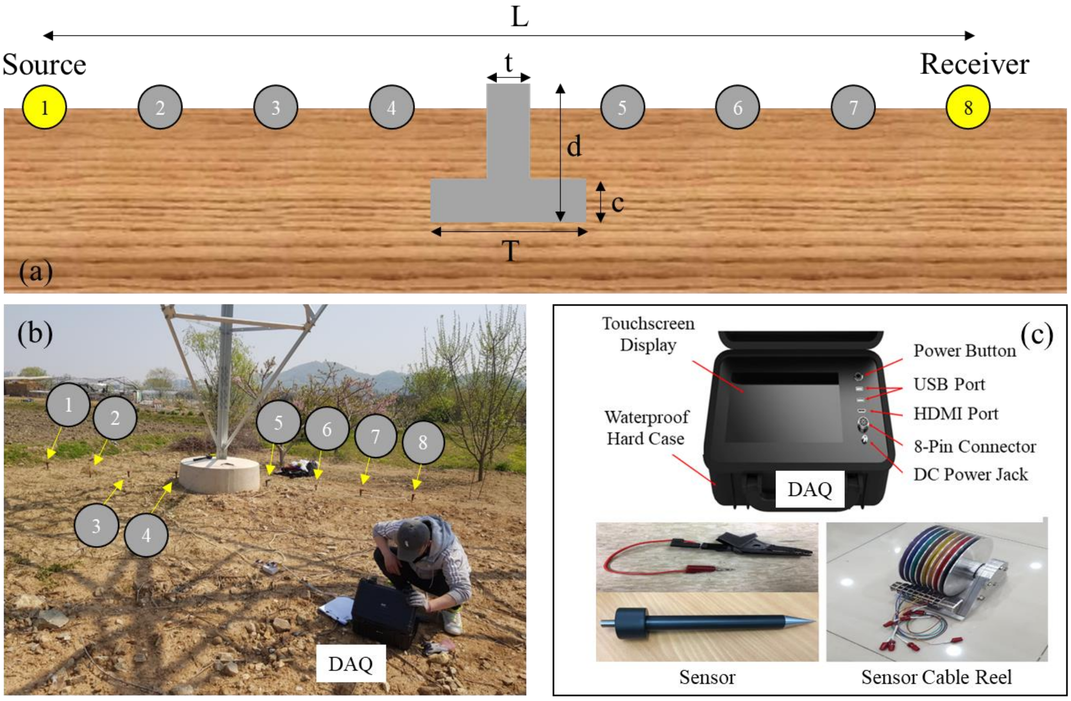

Fig. 4 (a) Conditions for field data acquisition and parameters related to transmission tower foundations, (b) installation of sensors for an in-situ electrical resistivity survey to estimate transmission tower foundation specifications and (c) hand-held system. Note that data was collected by alternating the source and receiver sensors

point inside the soil, L is the distance between the two sensors, $\hat{r}$ is the unit vector in the x-direction, and K (= $\varepsilon_p/\varepsilon_m$) is the ratio between the permittivity of the tower foundation (ϵ_p) and the soil (ϵ_m). The factor of 2 in Eq. (3) arises because an arbitrary point in the soil is influenced by both the source and receiver sensors. By substituting Eqs. (3) and (4) into the first term of Eq. (2), we obtain Eq. (5)

$$\int_0^\infty \sigma_m E_m \pi l\, dl = \sigma_m \pi \int_0^\infty \frac{Q}{4\pi\varepsilon_m}\frac{L/2}{\left((L/2)^2+l^2\right)^{3/2}}\times 2l dl = \frac{QL\sigma_m}{4\varepsilon_m}\int_0^\infty \frac{l}{\left((L/2)^2+l^2\right)^{3/2}} dl \quad (5)$$

The amount of charge (Q) is defined as shown in Eq. (6), and substituting Eq. (6) into Eq. (5) and rearranging Eq. (2) results in Eq. (7)

$$Q = 2\pi\varepsilon_m aV \quad (6)$$

$$I = \pi\sigma_m aV - \int \sigma_m E_m ds + \int \sigma_p E_p ds \quad (7)$$

Here, a is the radius of the sensor, and V is the voltage. Finally, by substituting Eqs. (3), (4), and (6) into Eq. (7), the formula for electrical resistance ($R_\perp$) is derived as Eq. (8)

$$R_\perp = \frac{1}{a\left[\pi\sigma_m - Lf_1\left(\sigma_m - \sigma_p \frac{3}{K+2}\right)\right]} \quad (8)$$

$$f_1 = \int_0^{d-c}\int_0^{t/2}\frac{1}{\left((L/2)^2+y^2+z^2\right)^{3/2}}dydz + \int_{d-c}^{d}\int_0^{T/2}\frac{1}{\left((L/2)^2+y^2+z^2\right)^{3/2}}dydz \quad (9)$$

Here, R is electrical resistance, d is the embedded depth of the tower foundation, t is the radius of the tower foundation, T is the width of the base slab, and c is the thickness of the base slab.

From Eqs. (8) and (9), the theoretical derivation confirmed the relationship between electrical resistivity and the tower foundation specifications. Considering the long

Table 1 Prediction results of transmission tower foundations (with specifications) obtained through electrical resistivity survey

No.	Location	Foundation type	Reference			This study					
			Foundation depth (m)	Width of the base slab (m)	Thickness of the base slab (m)	Foundation depth		Width of the base slab		Thickness of the base slab	
						Observed value (m)	Error rate	Observed value (m)	Error rate	Observed value (m)	Error rate
1	Jochiwon-Daehwa①	Inverted T-shaped	3.10	2.5	0.50	3.90	25.8%	2.67	6.8%	0.53	6.2%
2	Jochiwon-Daehwa②	Inverted T-shaped	3.65	2.7	0.65	3.89	6.5%	2.67	1.0%	0.68	4.0%
3	Jochiwon-Daehwa③	Inverted T-shaped	3.50	2.6	0.70	3.90	11.4%	2.67	2.8%	0.68	3.6%
4	Sinonyang-Seokgok①	Inverted T-shaped	5.45	3.3	0.85	5.75	5.6%	3.32	0.5%	0.85	0.0%
5	Sinonyang-Seokgok②	Inverted T-shaped	5.30	3.3	0.90	5.66	6.8%	3.34	1.3%	0.89	1.6%
6	Sinonyang-Seokgok③	Inverted T-shaped	5.25	3.5	0.65	5.54	5.5%	3.50	0.1%	0.65	0.2%
7	Sinonyang-Seokgok④	Inverted T-shaped	3.60	2.8	0.80	3.77	4.8%	2.82	0.7%	0.79	0.9%
8	Sinonyang-Seokgok⑤	Inverted T-shaped	5.60	3.2	0.80	3.40	39.3%	3.60	12.6%	1.20	50.0%
9	Sinonyang-Seokgok⑥	Inverted T-shaped	5.30	3.8	0.70	3.40	35.8%	3.60	5.2%	1.20	71.4%
10	Sinonyang-Seokgok⑦	Inverted T-shaped	5.05	3.1	0.65	5.44	7.8%	3.13	1.0%	0.65	0.5%
11	Sinonyang-Seokgok⑧	Inverted T-shaped	4.70	3.0	0.70	5.09	8.3%	3.02	0.5%	0.70	0.1%
12	Sinonyang-Seokgok⑨	Inverted T-shaped	3.75	3.0	0.55	4.07	8.4%	3.00	0.1%	0.55	0.5%
13	Sinonyang-Seokgok⑩	Inverted T-shaped	6.15	3.6	0.95	6.73	9.5%	3.61	0.2%	0.93	2.3%
14	Sinonyang-Seokgok⑪	Inverted T-shaped	6.50	3.6	0.90	6.73	3.6%	3.62	0.4%	0.93	3.3%
15	Sinonyang-Seokgok⑫	Inverted T-shaped	4.70	3.0	0.70	5.08	8.1%	2.98	0.7%	0.70	0.7%
16	Sinonyang-Seokgok⑬	Inverted T-shaped	5.05	3.1	0.65	5.46	8.1%	3.11	0.2%	0.65	0.6%
17	Sinonyang-Seokgok⑭	Inverted T-shaped	6.90	4.0	0.90	7.23	4.8%	4.04	1.0%	0.91	0.6%
18	Sinonyang-Seokgok⑮	Inverted T-shaped	6.90	4.0	0.90	7.22	4.7%	4.04	1.1%	0.91	0.6%
19	Boryeong-Ghwanchang①	Inverted T-shaped	4.05	2.7	0.65	4.30	6.2%	2.70	0.1%	0.65	0.0%
20	Boryeong-Ghwanchang②	Inverted T-shaped	3.60	2.9	0.60	4.10	13.5%	2.90	0.4%	0.64	6.7%
21	Singyeryong-Eunjin①	Inverted T-shaped	4.55	2.9	0.75	4.40	3.3%	2.98	2.9%	0.77	3.1%
22	Singyeryong-Eunjin②	Inverted T-shaped	3.25	3.2	0.85	3.50	7.8%	3.20	0.2%	0.82	3.5%
23	Sinokcheon-Seodaejeon①	Inverted T-shaped	3.85	2.7	0.65	4.15	7.7%	2.73	1.1%	0.63	2.5%
24	Sinokcheon-Seodaejeon②	Inverted T-shaped	3.60	2.6	0.60	3.95	9.8%	2.68	2.9%	0.61	1.7%
25	Yongwoon-Daehwa	Inverted T-shaped	2.90	4.0	0.90	3.19	10.1%	4.01	0.2%	0.90	0.0%
26	Hwaseong-Sagang	Inverted T-shaped	4.10	3.3	0.60	4.44	8.3%	3.30	0.4%	0.61	1.7%
27	Ildong-Wongok	Inverted T-shaped	3.40	2.6	0.60	4.14	21.7%	2.64	1.5%	0.60	0.5%
28	Sinonyang –Seoseoul	Inverted T-shaped	5.00	4.2	0.80	5.15	3.1%	4.25	1.2%	0.81	0.8%

computation times required for inverse analysis, deep learning techniques were applied to predict the specifications of transmission tower foundations.

A deep neural network (DNN, also referred to as deep learning) is a machine learning technique that aims to summarize key features or functions from large or complex datasets through combinations of multiple nonlinear transformations. The deep neural network used in this study consists of one input layer, four hidden layers, each with 512 units, and one output layer. The activation function of each layer is Sigmoid, with a dropout rate of 0.5. The MomentumSGD is applied as the optimizer, and the learning rate of 0.01 is applied. The input data consists of electrical resistivity values measured from seven sensors, and the output data include the width and thickness of the base slab, and depth of the tower foundation. We collected data from transmission towers with known specifications then applied deep learning techniques. Measurements were collected by arranging sensors as shown in Fig. 4. For the database, we obtained approximately 900 electrical resistance values.

Fig. 4(c) represents the hand-held system. The system is composed of a DAQ, which generates a source, processes the acquired data, and displays the results, along with eight sensors. The sensors are connected to the pack, which passes an electric current through the ground, and measures the electrical flow. The sensor has a diameter of 2 cm and a length of 24 cm (Fig. 4(c)), and the distance between the sensors is 0.8 m (Fig. 4(b)). The supply voltage is 10 to 12 V.

4.2 Results from 47 tower foundations

The results of applying the developed system to 47 transmission towers installed in Korea are presented in Table 1. These towers were installed under various conditions, including mountainous areas, flatlands, rice fields, farmland, and slopes. The dimensions of the steel tower foundation in this study are approximately 3 to 7 m in depth, 3 to 4 m in width of the base slab, and 0.5 to 1 m in

Table 1 Continued-

No.	Location	Foundation type	Reference			This study					
			Foundation depth (m)	Width of the base slab (m)	Thickness of the base slab (m)	Foundation depth		Width of the base slab		Thickness of the base slab	
						Observed value (m)	Error rate	Observed value (m)	Error rate	Observed value (m)	Error rate
29	Hwaseong-Pyeongtaek	Inverted T-shaped	4.30	5.5	0.90	4.66	8.3%	5.54	0.7%	0.91	0.8%
30	Gonjiam-Sinchungju	Inverted T-shaped	6.00	3.8	1.50	6.38	6.3%	3.85	1.2%	1.51	0.5%
31	Yulhyeon-Yongin	Inverted T-shaped	3.80	1.8	0.50	4.02	5.8%	1.80	0.2%	0.50	0.2%
32	Songtan-Anseong	Inverted T-shaped	3.45	2.5	0.80	3.76	8.8%	2.51	0.5%	0.80	0.1%
33	Poseung-Cheongbuk①	Inverted T-shaped	4.05	3.6	0.65	4.30	6.4%	3.70	1.6%	0.66	0.8%
34	Poseung-Cheongbuk①	Inverted T-shaped	4.05	3.6	0.65	4.40	8.5%	3.61	0.3%	0.66	1.1%
35	Poseung-Cheongbuk②	Inverted T-shaped	4.05	3.6	0.65	4.30	7.1%	3.60	0.6%	0.70	7.7%
36	Poseung-Cheongbuk③	Inverted T-shaped	4.05	3.6	0.65	4.50	10.6%	3.60	0.3%	0.70	7.7%
37	Poseung-Cheongbuk④	Inverted T-shaped	3.95	5.5	0.95	4.00	0.7%	5.52	0.3%	0.95	0.4%
38	Poseung-Cheongbuk⑤	Inverted T-shaped	3.95	5.5	0.95	4.00	0.3%	5.53	0.5%	0.95	0.4%
39	Poseung-Cheongbuk⑥	Inverted T-shaped	3.95	5.5	0.95	3.90	0.0%	5.53	0.6%	0.95	0.4%
40	Poseung-Cheongbuk⑦	Inverted T-shaped	3.95	5.5	0.95	4.00	1.8%	5.40	2.0%	0.90	5.3%
41	Poseung-Cheongbuk⑦	Inverted T-shaped	3.95	5.5	0.95	4.00	1.0%	5.20	5.3%	0.90	5.3%
42	Gonjiam -Yongmun	Inverted T-shaped	4.75	3.8	0.75	5.10	7.0%	3.79	0.2%	0.76	1.3%
43	Gonjiam -Icheon①	Inverted T-shaped	6.85	5.0	1.25	7.11	3.8%	5.05	0.9%	1.26	0.5%
44	Gonjiam -Icheon②	Inverted T-shaped	3.75	2.8	0.55	4.03	7.4%	2.79	0.5%	0.57	2.7%
45	Gonjiam -Icheon③	Inverted T-shaped	3.75	2.9	0.55	4.14	10.5%	2.90	0.1%	0.55	0.7%
46	Gonjiam -Icheon④	Inverted T-shaped	3.70	2.6	0.50	4.00	8.2%	2.61	0.2%	0.50	0.2%
47	Cheongwon-Osong	Inverted T-shaped	6.05	4.6	1.05	5.90	2.5%	4.40	4.3%	1.00	4.8%

thickness of the base slab. The error rates between the predicted results obtained using the electrical resistivity survey and the specifications of the transmission tower foundations are shown in Table 1. The prediction accuracy was 91.5% for depth of the tower foundation, 98.6% for width of the base slab, and 95.6% for thickness of the base slab. This indicates that when applying the electrical resistivity survey to determine transmission tower foundation specifications, the base slab width and thickness predictions are more accurate relative to the depth prediction. Notably, the highest prediction accuracy was achieved when measuring the width of the base slab.

5. Conclusions

This study applied the non-destructive electrical resistivity survey to accurately determine the specifications of transmission tower foundations. An algorithm developed based on laboratory and field experimental data was used to determine foundation specifications, and a hand-held system was designed so that the methodology can be implemented even in mountainous sites. Upon analyzing 47 transmission tower foundations, the developed system was able to achieve a prediction accuracy of 91.5% for the depth of the tower foundation, 98.6% for the width of the base slab, and 95.6% for the thickness of the base slab. Therefore, it can be concluded that the electrical resistivity survey is more useful for predicting the width and thickness of the base slab than its depth.

In addition to concrete, transmission tower foundations are often composed of steel piles, and rebar (anchors), all of which can significantly affect electrical conductivity measurements. While the electrical conductivity of concrete differs greatly compared to that of natural soil, making electrical resistivity predictions relatively straightforward, materials like steel piles and rebar exhibit distinct resistivity properties as they are conductive materials. Therefore, it is essential to consider the properties of different materials when defining and analyzing resistivity values. In addition to contributing to the development of maintenance and reinforcement plans for transmission tower foundations, the findings of this study could potentially be applied to evaluate the specifications of a wide range of buried civil engineering structures in a cost-effective manner.

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