Identification of Different Shallow Foundations Using 3D Electrical Resistivity Modeling

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Abstract
The electrical resistivity method has been successfully used to detect shallow buried foundations, almost, by using 2D electrode arrays. Basic geometry foundations (e.g., buried walls) have been investigated, although, more complicated foundation designs (e.g., stepped footing, pile group with a pile cap) are widely used in the construction industry. Investigation of these complicated foundation types, and engaging 3D surveys, therefore, are required. Multiple 3D electrical resistivity forward modeling was used to simulate different foundations (isolated simple footing, isolated stepped footing, combined simple footings, and pile group with a pile cap). The generated data sets then inverted using a robust inversion algorithm where RES3DINVx64 was used to perform the inversion process for the 3D models. The results from the 3D inverse modeling, suggest the pole-dipole and dipole-dipole arrays for all the investigated foundations.

Keywords: Electrical resistivity; 3D inversion modeling; Buried foundations

1. Introduction

The electrical resistivity method is one of the common geophysical methods. It has been successfully applied to investigate targets in different disciplines, for example, Abed et al., (2021) successfully utilized the resistivity method to image natural cavities in the desert area in Hit, Iraq. For ground contamination, Thabit and Khalid (2016) applied the method to image the distribution of the contamination. For historical buried targets, such as; ancient foundations, the method has been utilized in many case studies, see, for example, (Abu-Zeid et al., 2006; Al-Saadi et al., 2018; Giocoli et al., 2019). Recently, the resistivity method has also been used to detect concrete foundations, such as; bridge pillars (Gündoğdu et al., 2020).

The electrical resistivity can be performed by using 2D or 3D surveys. The 2D surveys image with a deployed profile (i.e. X-direction) with depth (i.e. Z-direction), and assume no changes on the Y-direction which might be the most important limitation of the 2D surveys. The 3D surveys overcome the 2D surveys in this regard, where resistivity data is also recorded in the Y-direction. To conduct a comprehensive investigation of a complex subsurface condition, the 3D surveys are the most suitable (Loke and Barker, 1996). For the 3D surveys, current and potential electrodes are needed and should be arranged in a specific electrode array (or sometimes called electrode configuration), for example, Wenner array, dipole-dipole array, and pole-pole array (Keary et al., 2002). Each array has certain advantages and limitations, for example, the Wenner array has a good signal-to-noise ratio and better DOI: 10.46717/igj.55.2B.10Ms-2022-08-26
resolution in the vertical direction compared to pole-pole array. Therefore, in order to differentiate the arrays abilities, several studies have been conducted by comparing array efficiency, for example, to detect a buried brick wall (Eissa et al., 2019), although, only 2D resistivity data sets were performed in their study.

For any construction, foundations are important parts, and these days most of the foundations are made of concrete or reinforced concrete. The main goal of using the foundations is to transfer the construction’s load to a competent layer of rock or soil. To achieve this goal various types of foundations have been attempted. For weak soils, differently designed footings might be used, for example, stepped footings. In the case of the construction cannot being built on shallow foundations, deep foundations (e.g., piles) can be an alternative option. Several kinds of piles are available, for example, pile cap and piled raft, where a group of piles can be driven into the ground with a cap placed on the top, (Murthy, 2002). Therefore, this study aims to qualitatively evaluate synthetic 3D electrical resistivity datasets to eliminate different and more complicated design foundations (e.g., isolated footings, combined footings, and a pile cap foundation). The objective of this study, therefore, 1) to perform 3D forward modeling to generate synthetic electrical resistivity datasets, 2) to use five popular electrode arrays in the forward modeling (Wenner, Wenner-Schlumberger, pole-pole, pole-dipole, and dipole-dipole), 3) to replicate the data generation for four different foundation types (isolated simple footing, isolated stepped footing, combined simple footings, and a pile cap foundation), 4) to invert all the datasets, from the 3D modeling, by using the robust inversion algorithm, and 5) to assess the tested electrode arrays to reconstruct the foundations details, such as depth, size, and shape.

2. Synthetic Models (3D forward modeling)

The RES3DMODx64 ver. 3.06, Geotomo software (2014), is the forward modeling package that was used to generate the apparent resistivity values using the finite difference algorithm. A square grid of 31 electrodes in X-direction and 31 electrodes in Y-direction, electrode spacing is 0.25 m and two nodes between any pair of electrodes were applied in the 3D forward modeling. Four foundation types were modelled in the 3D surveys; isolated simple and stepped footings, combined simple footings, and the upper part of pile group foundation with a pile cap on the top, were all modeled within a homogenous background of 20 Ω.m of resistivity value, all the foundations were modeled with a resistivity value of 200 Ω.m (Fig.1). The arrays, Wenner (W), Wenner-Schlumberger (WS), dipole-dipole (DD), pole-pole (PP), and pole-dipole (PD) were used to investigate the tested foundations.

Each model has ten horizontal slices, slices number 1, 9 and 10 were modeled entirely with a resistivity value of 20 Ω.m, where no foundation. Slices 2 through 8 show the foundations buried in the hosting background. Fig.1a, on slices 2 through 5, the columns of the footings are shown, on slices 7 and 8 the spread (i.e., the base) of the footing is represented. Fig.1b, on the slices 2 to 5, the columns of the combined footings are represented while on the slices 7 and 8 the combined spread (i.e., combined base of the two footings) is represented. For the pile group foundation, as shown in Fig.1c, the cap of the pile foundation is represented on slices 2 and 3, and the upper part of the piles is represented on the slices 4 through 7.
Fig. 1. 3D forward models, a) isolated simple footing (right) and isolated stepped footing (left), b) combined simple footing, and c) pile group. All dimensions are in metre, z is the depth range of each layer.

3. Results

The RES3DINVx64 ver. 3.15 (Geotomo software, 2019), was used to invert all the 3D data sets. The 3D data sets were generated for four different foundation types, an isolated simple footing, an isolated stepped footing, a combined simple footing, and a pile group foundation. The robust inversion algorithm was used to invert all the data sets by applying the finite difference method. Each 3D data set is presented in ten horizontal slices, to reduce the figure number; the vertical slices are not represented.

The inverted models of the isolated simple and the stepped footings are shown in Fig. 2a through Fig. 2e. All the used arrays were successful in resolving the buried footing foundations. The footings’ columns were imaged separately and the stepped footings generate a bigger anomaly compared with simple footing. The bases of the footings, layers 7 and 8, almost, are reconstructed as one anomaly with an obvious higher and bigger resistivity response on the side of the stepped footing. Most of the used arrays show the high resistive extension downward deeper than the actual position of the footings, this phenomenon noticeably appears on the inverted images from the pole-pole, pole-dipole, and dipole-dipole arrays.
Fig. 2. 3D inverse models, a) W array, b) WS array, c) PP array, d) PD array, and e) DD array, for isolated simple and isolated stepped footings. For the position and geometry of the footings, see Fig. 1. The figure continued on the next page.
Fig. 2. (continued).

Inversion results of the combined footings are represented in Fig. 3a through Fig. 3e where the footings are recognized on all the utilized arrays with some differences. The columns of the footings were separately imaged and, on each array, they generate a similar response. The combined base of the footings produces an anomaly that nearly is evenly distributed underneath the footings’ columns. The Wenner array does not show a resistive extension beneath the footings, see Fig. 3a, however, pole-pole and pole-dipole arrays, as shown in Fig. 3c and d, not only produce that but also generate bigger ones.
Fig. 3. 3D inverse models, a) W array, b) WS array, c) PP array, d) PD array, and e) DD array, for combined simple footings. For the position and geometry of the footings, see Fig. 1. The figure continued on the next page.
Fig. 3. (continued).

Fig. 4a through Fig. 4e shows the resistivity inverted models of the pile group foundation. The response of the foundation is reconstructed on all the applied arrays. The arrays were able to resolve the geometry of the shallow cap in terms of its shape, location, and orientation, where the rectangular shape along the x-axis clearly imaged. The anomaly of the cap stretched downward on deeper depths than the actual geometry of the foundation on most of the arrays except the dipole-dipole. With exception of the dipole-dipole array, the piles were not imaged to the deeper slices. The DD array was able to image two high resistive anomalies located at the end of the cap which might indicate the piles, see Fig. 4e, slices 4 and 5.
Fig. 4. 3D inverse models, a) W array, b) WS array, c) PP array, d) PD array, and e) DD array, for a pile cap foundation. For the position and geometry of the footings, see Fig.1. The figure continued on the next page.
The RMS error of all the inverted resistivity models is listed in Table 1. The highest RMS error values are obtained from the pole-pole inverted datasets, whilst the dipole-dipole generates the lowest RMS error values. All the RMS errors values are less than 1%.

**Table 1. The RMS error values obtained from the inverted datasets.**

| Array Foundation                          | Wenner | Wenner-Schlumberger | Pole-pole | Pole-dipole | Dipole-dipole |
|------------------------------------------|--------|---------------------|-----------|-------------|---------------|
| Isolated simple and isolated stepped footings | 0.47 % | 0.51 %              | 0.77 %    | 0.40 %      | 0.39 %        |
| Combined simple footings                 | 0.46 % | 0.51 %              | 0.84 %    | 0.40 %      | 0.36 %        |
| Pile cap foundation                      | 0.54 % | 0.55 %              | 0.61 %    | 0.59 %      | 0.47 %        |

4. Conclusions

In this study, a simulation of four different foundations using 3D forward modeling was carried out. In addition, five popular conventional arrays were used in the simulation, they are: Wenner, Wenner-Schlumberger, pole-pole, pole-dipole, and dipole-dipole. The abilities of the 3D simulations,
of the five arrays, to retrieve the target’s depth, size and shape were qualitatively compared with the actual design of the targets.

In the 3D models, all the arrays can detect the targets with some differences. The columns of the separated footings were imaged with almost circular shape anomalies at shallower depths. The stepped footing was imaged in a bigger anomaly compared with simple footing. The bases of the footings were almost combined in one anomaly, which indicates to the poorly detected low resistivity background between the footing bases. In the case of the combined footings, the columns have fairly the same anomaly size and the base was imaged as a whole unit. For the pile group foundation, all the arrays were unsuccessful to determine the pile, however, the pile cap was imaged on all the tested arrays.

The misfit in the determination of the depth, size, and shape of the investigated targets emphasizes the importance of prior information about the investigated site and the data should be carefully interpreted.

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References

Abed, A.M., Thabit, J.M., Al-Menshed, F.H., 2021. An attempt to image um el-adam cavity structure in the karst terrain at hit area, Western Iraq. Iraqi Geological Journal, 54(1A): 44–54.

Abu-Zeid, N., Botteon, D., Cocco, G., Santarato, G., 2006. Non-invasive characterization of ancient foundations in Venice using the electrical resistivity imaging technique: NDT E International, 39(1), 67–75.

Al-Saadi, O.S., Schmidt, V., Becken, M., Fritsch, T., 2018. Very-high-resolution electrical resistivity imaging of buried foundations of a Roman villa near Nonnweiler, Germany: Archaeological Prospecting, 25(3), 209–218.

Eissa, R., Cassidy, N., Pringle, J., Stimpson, I., 2019. Electrical resistivity tomography array comparisons to detect cleared-wall foundations in brownfield sites: Quarterly Journal of Engineering Geology Hydrogeology, 53(1), 137–144.

Giocoli, A., Hailemikael, S., Bellanova, J., Calamita, G., Perrone, A., Piscitelli, S., 2019. Site and building characterization of the Orvieto Cathedral (Umbria, Central Italy) by electrical resistivity tomography and single-station ambient vibration measurements. Engineering Geology, 260, 105195.

Gündoğdu, N.Y., Demirci, İ., Demirel, C., Candansayar, M.E., 2020. Characterization of the bridge pillar foundations using 3d focusing inversion of DC resistivity data: Journal Applied Geophysics, 172, 1–10.

Keary, P., Brooks, and M., Hill, I., 2002. An Introduction to Geophysical Exploration, third edition, Blackwell science, Great Britian.

Loke, M.H., Barker, R.D., 1996. Practical techniques for 3D resistivity surveys and data inversion 1: Geophysical Prospecting, 44, 499–523.

Murthy, V., 2002. Geotechnical engineering: principles and practices of soil mechanics and foundation engineering, Eighteenth edition, Marcel Dekker, New York.

Thabit, J.M., Khalid, F.H., 2016. Resistivity imaging survey to delineate subsurface seepage of hydrocarbon contaminated water at Karbala Governorate, Iraq. Environmental Earth Sciences, 75, 1–7.