A BOREHOLE MAGNETIC LOGGING TOOL FOR ESTIMATING UNKNOWN FOUNDATION DEPTHS

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Abstract

Safety inspections and assessments of built structures for maintenance or remodeling often require information about the basal depths of foundations such as piles and caissons. A borehole magnetic tool has been developed and tested to estimate pile depth in situations where such depths are unknown.

The magnetic tool operates on two fundamental assumptions. First, the foundation contains imbedded ferromagnetic material, such as reinforcement bars. Second, such ferromagnetic material generates an observable, interpretable induced magnetic field relative to the background earth's geomagnetic field. The tool consists of a flux-gate type magnetometer which measures the 3-components of the total magnetic field.

The physical modeling tests show that the vertical derivative of vertical component of the magnetic field can be interpreted and used to generate a reliable estimate of the pile depth. Errors of less than 20 cm were the norm under favorable condition. In the almost noise free condition, accurate depths were estimated even when the horizontal distance between the pile and the observation borehole was more than 3 m. Verifiable field studies indicate the borehole magnetic survey technique is one of the most accurate, fast, and reliable methods for estimating the depth to the base of foundations.

Introduction

The determination of the depth of the foundations of bridges and large buildings is not an infrequently faced task, since construction drawings can be lost or misplaced for many reasons. While there are no currently available geophysical tools for evaluating the soundness of such deep foundations with superposed structures, there are some techniques for estimating the depth of unknown foundations. These include the borehole RADAR method and parallel seismic method (Aoud and Olson, 1997), and the induced voltage tool.

In principle and under favorable conditions, the borehole RADAR tool can detect the shape or the verticality of a foundation pile. However, this technique does not work well in electrically conductive medium like clay-dominant soil. Also, gravels in the soil can also cause strong diffractions, making it difficult to get the clear reflection images of the pile.

The parallel seismic method is essentially seismic refraction performed in borehole. It can be successfully applied where the velocity contrast between the foundation and the surrounding soil is sufficient to generate interpretable head wave signal. However, gravels in the soil can also cause strong diffractions, making it difficult to get the clear "first breaks" on the refraction data.

Japanese investigators have been using a simple induced voltage tool, consisting of a horizontal coil, volt meter and depth meter, to detect the base of piles. This tool records the voltage induced by imbedded rebar in the horizontal coil as it is drawn up the borehole drilled parallel to the pile at a constant velocity. The depth corresponding to the lowermost peak observed induced voltage is assumed to represent the depth to the base of the pile. Essentially, this tool operates on the principles similar to that of the borehole magnetic tool developed by the authors.

The borehole magnetic method, described herein, is based on the fact that almost all deep foundations, except those made prior to the 20th century have reinforcement bars, steel casing, or at least imbedded steel wires. These metals are ferromagnetic and generate relatively strong induced magnetic fields. Jo et al.(1999) showed the practicability of this method.

The borehole magnetic logging tool designed by the authors, uses a flux gate magnetic sensor to measure the 3 components of the magnetic field as it is raised in a borehole in immediate proximity to

the foundation. The interpretation of the acquired magnetic field data can be done using the iterative inversion method of Cha and Suh (2000) and the simple vertical derivative method. Physical modeling tests indicate the accuracy of this method (relocation of base of pile) is about 20 cm under generally favorable conditions. In noise free conditions, satisfactory results were obtained when the distance between the pile and the survey borehole was as much as 3 m.

Borehole Magnetic Method

Deep foundation structures generally contain steel reinforcement bars or at least imbedded steel wires for the pre-tensioning. Sometimes the outer case of the pile is actually made of steel. These steel rebar, wires and casings are ferromagnetic, and generate relatively strong induced magnetic fields in response to the earth's geomagnetic field. The surrounding soil is generally non-ferromagnetic, and its associated induced magnetic fields are much smaller to those of the foundation steel. If the induced magnetic field measured within a proximal borehole is assumed to be generated by steel imbedded within the deep foundation, estimates of the depth to the base of the foundations can be generated. Figure 1 illustrates the basic concepts and the measuring system.

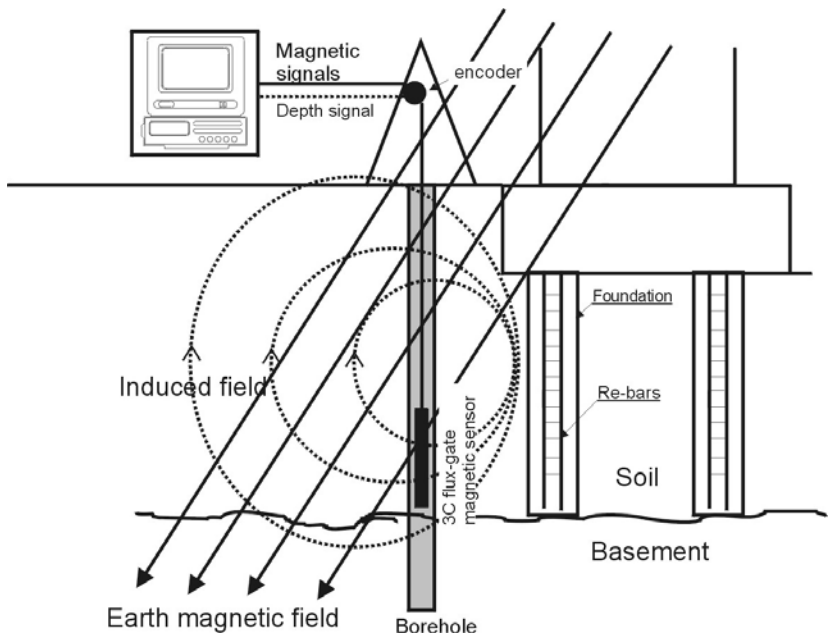

Fig. 1 Borehole magnetic survey for the estimation of the unknown foundation depth: basic concepts.

Analytical calculations based on the theoretical response of the vertical magnetic dipole (Telford et al., 1976) are shown Figure 2. Vertical magnetic dipole was chosen because it can represent many types of pile foundation such as H beam pile, pre-stressed pile, cast in place pile, and so on. The horizontal distance between the vertical magnetic dipole and the survey borehole were variously set at 1 m, 2 m, and 3 m as shown in Figure 2(a). The variation of vertical component of the induced magnetic field as a function of dipole-tool separation is shown in Figure 2(b); the horizontal induced magnetic field component curve and the vertical derivative of vertical magnetic field component curve are shown in Figure 2(c), and (d) respectively. The horizontal component curve shows local extreme values near the both ends of dipole, while vertical derivative of the vertical component shows local peaks near the both ends of the dipole regardless the variation of the separation between the dipole and the survey hole. This constitutes a very simple interpretation criterion for the depth estimation of the pile foundation.

The distortion of the vertical component and the horizontal component in the middle range of the dipole when the separation is 1m is caused by the incompleteness of the equation used, and will not happen in real situation. This discrepancy, however, does not affect our interpretation criterion since our main range of concern is around the bottom of the dipole.

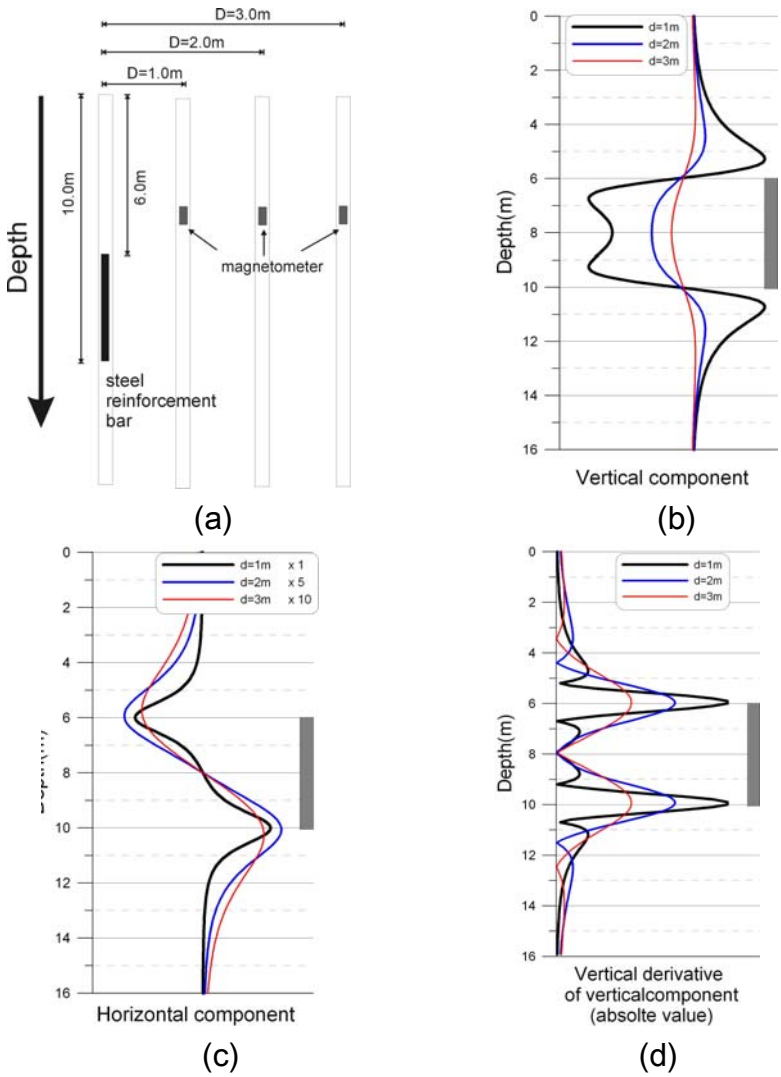

Fig. 2 (a) Numerical model lay-out. (b) Vertical component curves for the horizontal distance between the vertical magnetic dipole (steel bar) and the measuring borehole vary as 1m, 2m, and 3m. (c) Horizontal component curves for each distance and (d) vertical derivative of vertical component curves for each distance, where we can see that the peak (absolute) values are located very close to the both ends of the dipole. Vertical magnetic dipole is described as a gray bar, and each of the horizontal curves are amplified as denoted in the legend box.

Borehole Magnetic Logging Tool

Since the induced magnetic field associated with a vertical bar exhibits distinctive characteristics, the use of a triaxial magnetometer is strongly recommended. For actual field testing purposes, the authors employed a 3-component flux-gate magnetic sensor sealed inside a water proof non-magnetic housing. The diameter of the probe is about 45 mm. An encoder, located on the axis of the pulley, sends depth signals to the control unit. The 3-component magnetic measurements are recorded as a function of observation depth on a notebook PC. The borehole magnetic logging tool used for field example adapted MAG539 flux-gate sensor of Applied Physics Systems(USA).

The foundation piles are normally located in soil or weathered rock, and casing is needed to prevent the collapse. The casing should be comprised of a non magnetic material such as PVC.

Field Examples

Two sets of experimental field results are presented in Figure 3. The curves shown in Figure 3(a) are of data acquired at a site where the bridge foundation was steel piles. Both of the local peak value of the vertical derivative of vertical component and the extreme horizontal component value were recorded around 22.8 m. We guess that the degree of agreement between these two values indicates the credibility of the estimation.

The curves shown in Figure 3(b) are the results of a verification test. One customer wanted to verify the reliability of the magnetic method, so a test was conducted at a site where the depth of an H beam pile was accurately known. The real depth was 4.5 m. The peak and extreme values were recorded at depths of about 4.6 m. The horizontal distance between the center of the pile and the survey borehole was about 2 m for the case depicted in Figure 3(a), and about 1m for the case depicted in Figure 3(b).

Other methods for pile depth estimation, such as the parallel seismic method and the borehole RADAR method, also require the drilling of a survey borehole. The horizontal distance between the borehole and the pile is also critical in these situations, as resolution deteriorates with increasing separation. From a practical perspective, a separation distance of 2 m seems to provide an optimum balance between proximity and drilling limitations.

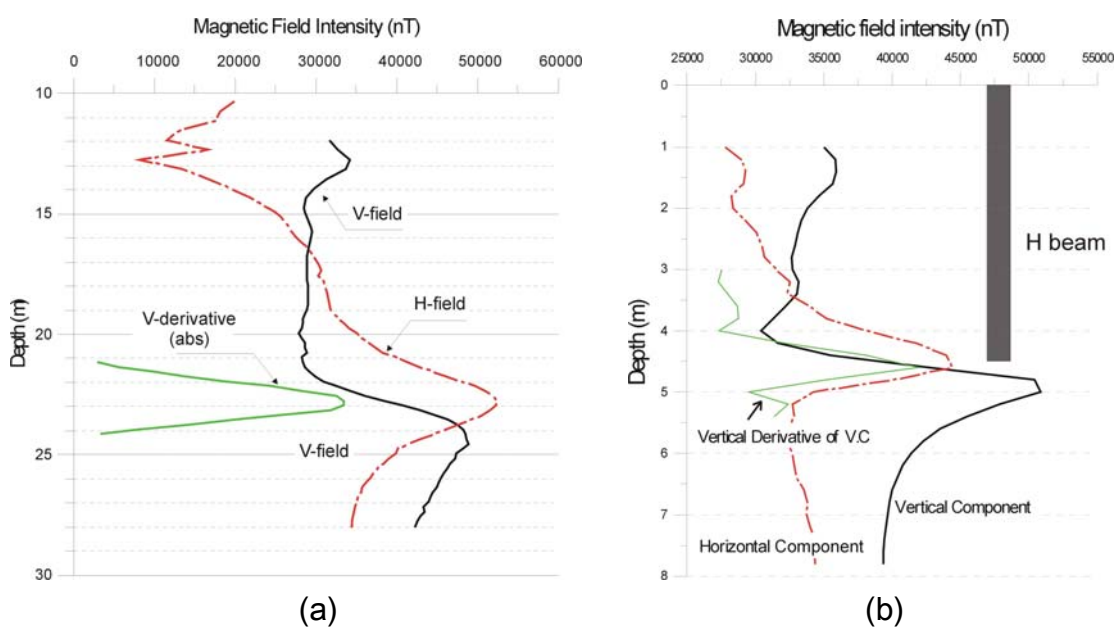

Fig. 3 (a) a field test showing the vertical component (VC), the vertical derivative of VC, and the horizontal component curves; (b) a verification test performed near an H beam pile whose depth is known to be 4.5 m.

Summary

The borehole magnetic survey tool can provide accurate estimates of unknown foundation depths, as long as the foundation has sufficient imbedded ferromagnetic material such as steel pipe piles, rebar, etc., and as long as proximal boreholes can be drilled. Pre-stressed concrete piles that have imbedded wire strings may not induce a relatively high amplitude magnetic field, and may not be a good candidate for the magnetic tool unless the horizontal separation between the pile and the borehole is fairly small < 1 m). The magnetic tool can also be used in clayey soils

and in soils containing coarse gravels where other methods may fail. However, the tool does not work well in noisy environments generally associated with proximal ferromagnetic material that is not imbedded in the foundation.

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