TDR 2006

Purdue University

Full-Scale Field Testing of Surface Waves – TDR Technique in Integrity Evaluation of Large-Diameter Bored Piles

Terrence Tang and Albert T. Yeung

Ref.: Tang, Terrence and Yeung, Albert T., "Full-Scale Field Testing of Surface Waves – TDR Technique in Integrity Evaluation of Large-Diameter Bored Piles", Proc. TDR 2006, Purdue University, West Lafayette, USA, Sept. 2006, Paper ID 45, 10 p.,
https://engineering.purdue.edu/TDR/Papers

Full-Scale Field Testing of Surface Waves – TDR Technique in Integrity Evaluation of Large-Diameter Bored Piles

Terrence Tang[1] and Albert T. Yeung[2]

[1] Managing Director, Supreme Instrument Ltd., 2/F Tai Po Chamber of Commerce Building, 4-8 Shung Tak Street, Tai Po, New Territories, Hong Kong; PH: +852 2330 1023; FAX +852 23305885; email: supinst@netvigator.com.

[2]Associate Professor, Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong; PH: +852 2145 7384; FAX: +852 2559 5337; email: yeungat@hku.hk.

Abstract

The technique of time domain reflectometry (TDR) has many non-destructive testing and performance evaluation applications in civil engineering. However, in the absence of a second returning conductor for the electromagnetic waves, the applicability of TDR techniques in the integrity monitoring of geotechnical engineering structures constructed in the subsurface, such as soil nails, prebored socketed steel H-piles, large-diameter bored piles, etc., is quite limited. A new surface wave – time domain reflectometry (SW-TDR) technique has been developed to overcome the problem. The technique does not require the installation of a second conductor along the length of the structure under evaluation. It uses uni-polar surface electromagnetic waves as the probing waves, in lieu of the usual TEM wave mode, to determine the length of the embedded metallic conductor and to evaluate the integrity of the materials surrounding the conductor.

The development of the new SW-TDR technique is presented in this paper. Full-scale field evaluation of the technique on two large-diameter bored piles was performed to: (1) detect and delineate defects in the concrete around steel reinforcement bars; and (2) determine the pile length as constructed. Defects were implanted in the bored piles without prior knowledge of the testing personnel. The deductions from the TDR test results were compared to the as-built records. Details of the full-scale evaluation, results of measurements, interpretations of wave profiles, and evaluation of the technique for integrity monitoring of subsurface geotechnical structures are also presented in this paper.

Key Words

Surface electromagnetic waves; Integrity evaluation of subsurface structures; Full-scale field evaluation; Integrity evaluation; Large-diameter bored piles

Introduction

There are many innovative applications of time domain reflectometry (TDR) measurements in non-destructive evaluation of infrastructure performance in civil engineering [1–6]. In particular, there are many applications in geotechnical engineering for *in-situ* measurements and monitoring [7–14]. At least 2 parallel conductors are required for the propagation of electromagnetic waves in the TEM wave mode in ordinary TDR measurements. However, most geotechnical engineering structures constructed in the subsurface, such as soil nails, prebored socketed H-piles, large-diameter bored piles, etc., do not possess a second conducting path for electromagnetic waves. The addition of a second conductor along the length of the structure under evaluation may appear to be a plausible solution. However, this approach has many limitations. The electrical impedance of such a combined system will depend on the separation distance between and the surface conditions of the original conductor and the second conductor, in addition to the properties of grouting/concrete mix between the 2 conductors. It would be impossible to monitor the performance of the grouting/concrete mix not in close proximity of the conductors. The guidelines established by the Geotechnical Engineering Office, the Civil Engineering and Development Department, the Hong Kong Special Administration Region Government for the use of time domain reflectometry (TDR) to determine the length of installed soil nails [15] requires the placement of an insulated wire along the length of the steel reinforcement bar during soil nail installation. The installation of the insulated wire has to be under close supervision of the resident site staff to ensure it is of the same length as the reinforcement bar and there is no fault-playing on the wire. As a result, the subsequent reinforcement bar length verification by the TDR method using the reinforcement bar/wire system becomes a meaningless bureaucratic exercise, as the length of the reinforcement bar has already been carefully measured in the first instance and is already known. The measurement thus offers no additional information on the length of the installed soil nail, resulting in a waste of time and effort. Therefore, the need to develop a non-destructive evaluation technology for geotechnical engineering structures constructed in the subsurface without the need for the prior installation of a second conductor during construction is evident.

Principle of Surface Waves – TDR Technique

An innovative TDR technique has been developed using step surface electromagnetic waves as the probing waves, in lieu of the conventional TEM wave mode. The surface waves are uni-polar in nature and their behavior in many aspects is similar to that of transmission line and displacement current in extended capacitive circuits. During the test, high-frequency step-like surface electromagnetic waves are excited and let propagate onto a metal conductor embedded in the geotechnical structure. The metal conductor serves as a waveguide for the surface electromagnetic waves. The metal conductor can be the steel reinforcement bar in a soil nail, the reinforcement cage in a large-diameter bored pile, or the steel I-section in a socketed steel H-pile, etc. The waves propagate along and in the immediate vicinity of the steel reinforcement bar at a velocity governed by the dielectric properties of the surrounding grout/concrete materials. As the concrete mix/grouting should be quasi-uniform along the reinforcement bar in the geotechnical structure, any variation in electrical impedance between the reinforcement bar and the surrounding soil would be caused by the variations of the properties of the grouting/concrete mix.

Interested readers should refer to Jordon and Balmain [16], and Ling et al. [17, 18] for a more detailed description of the propagation of surface waves.

When the surface waves reach locations where local electrical impedance differs from the characteristic impedance of the metallic conductor, part or all of the wave energy will be reflected. The polarity and magnitude of the returning waves depend on the nature of impedance variation. The variation of electrical impedance can be caused, for example, by the presence of voids around the steel reinforcement bar, e.g., honeycombs in reinforced concrete, a change of material surrounding the steel reinforcement bar, e.g., intrusion of loose soil into concrete or grout, or the end of the steel reinforcement bar. The potential and current magnitudes of the surface waves along the reinforcement are recorded simultaneously during the wave transmission and reflection process. From the potential and current profiles, the impedance profile is calculated. The length of the metallic conductor and the integrity of the surrounding materials can be deduced by analyzing these wave profiles.

For integrity evaluation of geotechnical structures using steel reinforcement bar as the waveguide, the electrical impedance per unit length of the conductor, Z, is given by

$$Z \approx \sqrt{\frac{L}{C}} \tag{1}$$

where L = inductance per unit length; and C = capacitance per unit length. The propagation velocity of the surface electromagnetic wave, v, is given by

$$v = \frac{1}{\sqrt{LC}} \tag{2}$$

The coefficient of wave reflection, ρ, at the impedance discontinuity is given by

$$\rho = \frac{Z_i - Z_0}{Z_i + Z_0} \tag{3}$$

where Z_i = local electrical impedance; and Z_0 = characteristic electrical impedance of the conductor.

When there is a void or an increment in grout thickness around the steel reinforcement bar, the local capacitance per unit length will decrease, resulting in an increase in electrical impedance as given by Eq. (1) and a positive wave reflection as given by Eq. (3). On the other hand, when there is a decrement in grout thickness around the steel reinforcement bar, or soil in contact with the steel reinforcement bar, the local capacitive effect will be increased, resulting in a decrease in electrical impedance and a reverse (negative) wave reflection. Partial wave transmission and partial wave reflection thus take place at every interface of impedance discontinuity. When the waves arrive at the end of the conductor, all the wave energy will be reflected. The theoretical impedance profile of a steel reinforcement bar embedded in sections of different materials is depicted in Fig. 1 to illustrate the working principle of the technique.

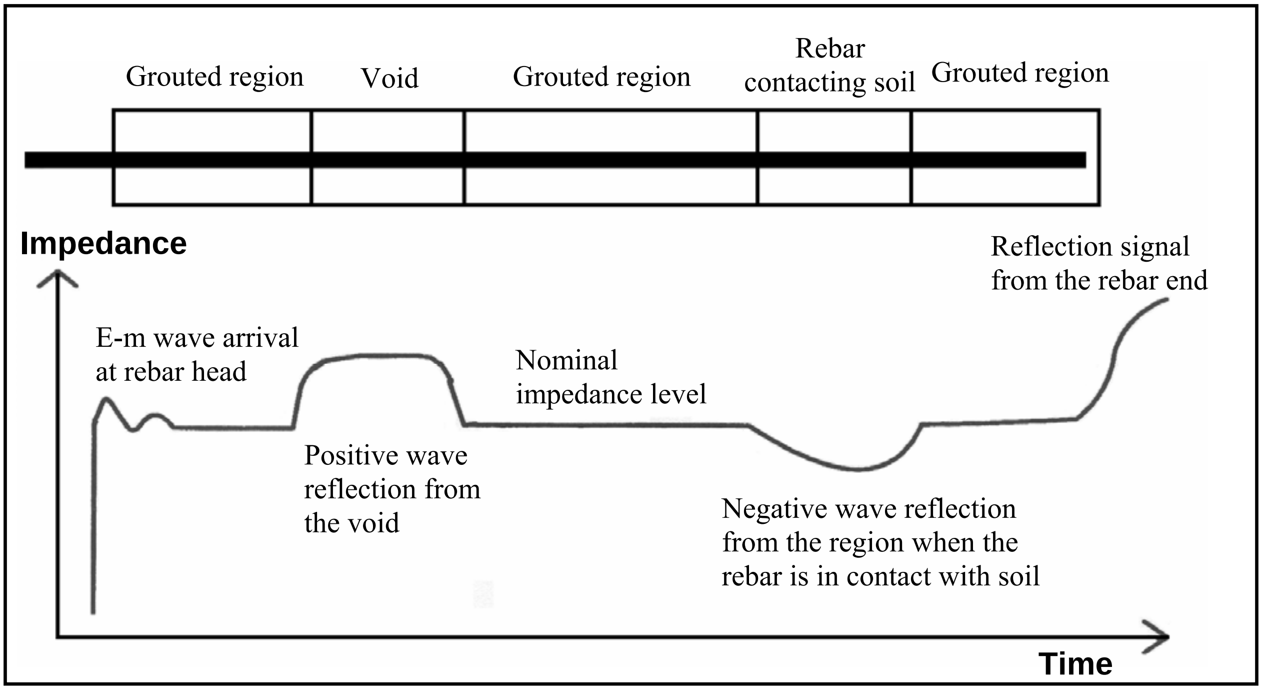

Fig. 1 Theoretical Impedance Profile of a Steel Reinforcement Bar Embedded in Sections of Different Materials

Integrity Evaluation of Large-diameter Bored Piles

Full-scale field testing of the technique on two large-diameter bored piles was performed to: (1) detect and delineate defects in the concrete around reinforcement bars; and (2) determine the pile length as constructed. Two large-diameter bored piles were selected for this evaluation program. One bored pile was used to evaluate the technique for concrete defect detection and delineation and the other one was used to evaluate the technique for pile length determination.

Instrument Development

An instrument was specifically developed with a special circuitry for excitation and detection of surface electromagnetic waves of frequency of several hundred hertz for this type of evaluation. The recording time resolution is 500 ps (1 ps = 10^{-12} s), corresponds to a length measurement accuracy of approximately 2 cm, which is considered adequate for most geotechnical engineering applications.

Detection and Delineation of Voids in Concrete

The bored pile used for void detection and delineation was 2.2 m in diameter. It is part of an earth retaining structure abutting an uphill slope. The steel reinforcement cage was constructed of forty-five 40-mm diameter vertical steel reinforcement bars. Part of the cage was covered with polystyrene foam boards so that additional steel reinforcement bars can be connected to the bored pile after excavation to construct wall panels. The ability of the technique to detect and delineate these artificial voids in the concrete was evaluated. The testing personnel had no knowledge of the *defects* prior to submission of test results.

The vertical 40-mm diameter steel reinforcement bars of the bored pile served as the waveguide for the surface electromagnetic waves. A plan showing the arrangement of these steel reinforcement bars is depicted in Fig. 2. The wave signals received at the top of the steel reinforcement bar would compose of all the reflection signals including reflections caused by laps of steel reinforcement bars, anomalies along the reinforcement bar due to variation of material conditions around the bar, and returning waves from end of the bar. SW-TDR measurements were made on Rebar 13, 17, 29, and 41. The results obtained from Rebar 13 as shown in Fig. 3 were also used for the velocity calibration of surface electromagnetic waves. The results obtained from Rebar 17 are very similar to those of Rebar 13.

It can be observed in Fig. 3 that the total wave time span measured was 597 ns. As the length of the reinforcement cage is 13.37 m, the wave velocity is thus calculated to be 4.479×10^7 m/s. The wave reflection caused by a reinforcement lap at 1.5 m from the cage head is also recorded in the SW-TDR wave diagram. Two other recorded wave reflections are caused by local increment of concrete cover thickness around the reinforcement bar. The lowering of impedance values at the pile toe indicates the rock socket length of the pile is 3.1 m.

SW-TDR results obtained from Rebar 29 and 41 are very similar. The results obtained from Rebar 41 are depicted in Fig. 4. Periodic variations of impedance occur at the upper half of the pile, indicating locations of the installed foam boards. The identified locations are in good agreement with the design locations. The rock socket length of the pile deduced from the results is 4.01 m. The variation of rock socket length at different locations of the pile is in good agreement with the geologic conditions.

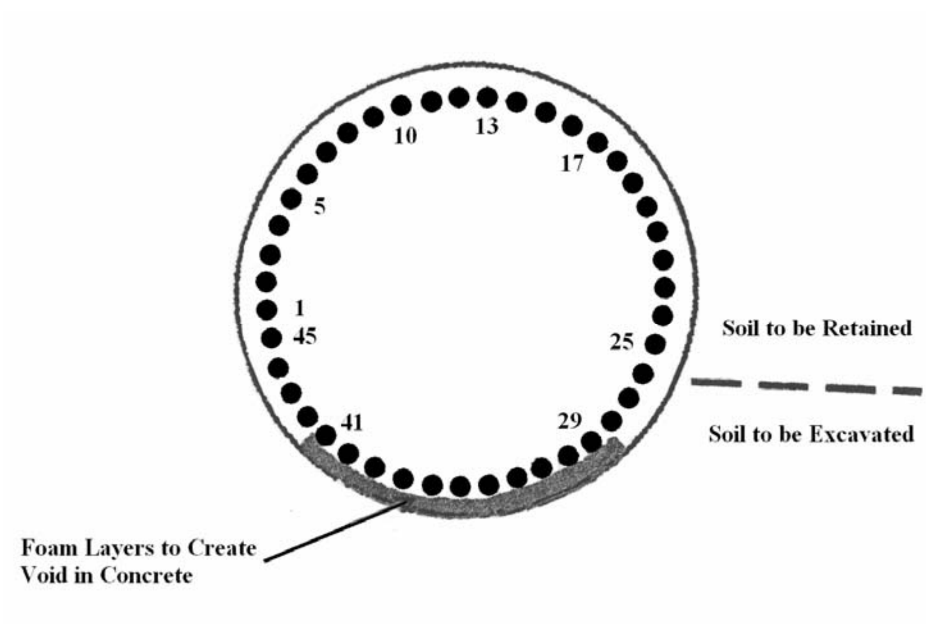

Fig. 2 Plan of the Large-diameter Bored Pile for Void Evaluation

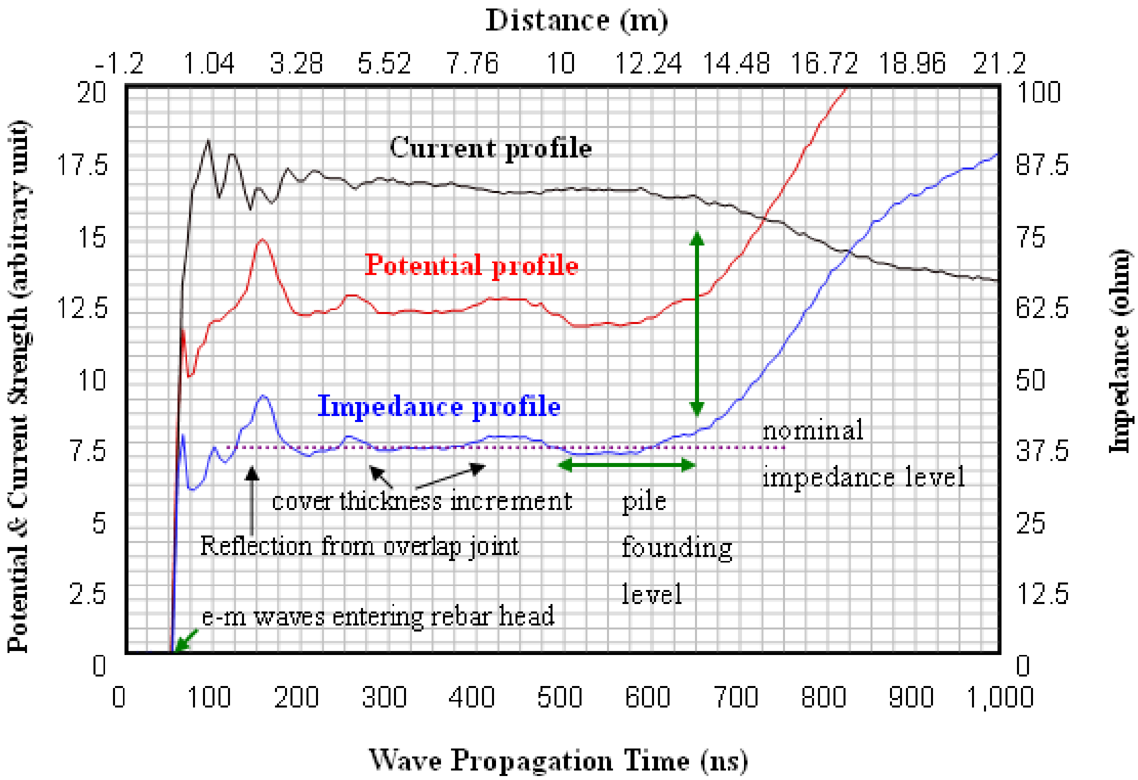

Fig. 3 SW-TDR Wave Diagram of Rebar 13 of "Void Evaluation" Bored Pile

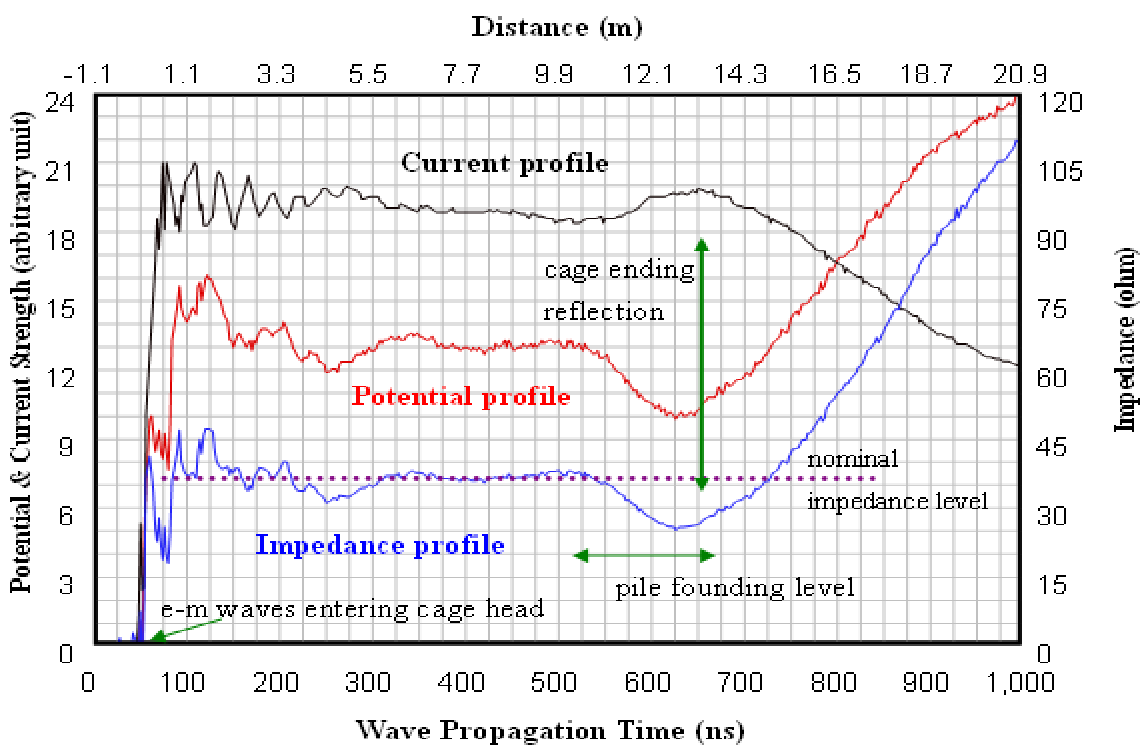

Fig. 4 SW-TDR Wave Diagram of Rebar 41 of "Void Evaluation" Bored Pile

Determination of the Length of a Constructed Bored Pile

The length of the reinforcement cage practically gives the length of a constructed bored pile. Therefore, the ability of the SW-TDR technique to evaluate the length of reinforcement bar embedded in concrete was evaluated in this program. During the test, a specifically prepared dummy rebar was added to the reinforcement cage of the large-diameter bored pile. The dummy bar was constructed by three reinforcement bars: the top two reinforcement bars were constructed as usual with an adequate lap length, while the intersection between the intermediate and lower reinforcement bars were separated by a PVC sleeve. The insertion of this PVC sleeve was to discontinue the electrical conductivity between the intermediate and the lower reinforcement bars. The head of the upper reinforcement bar is located at 1.5 m above the ground surface.

Details of the dummy bar were carefully measured and recorded but not made known to the testing personnel. During the measurement, the SW-TDR instrument was place on the ground surface. The measured potential, current, and impedance profile of the dummy rebar were depicted in Fig. 5. It can be observed that a positive spike-like increase in impedance occurred at approximately 12 m from the top of the upper bar, indicating the end of the bar. When the surface waves arrived at the end of the intermediate bar, they were strongly reflected, indicating the electrical disconnection between the intermediate and the lower bar. The time for this impedance reflection was measured to be 911 ns. Using the reference wave velocity of 4.479×10^{7} m/s, the total length of the upper and intermediate bars is determined to be 20.4 m. The measured length agrees very well with the recorded length of 20.37 m.

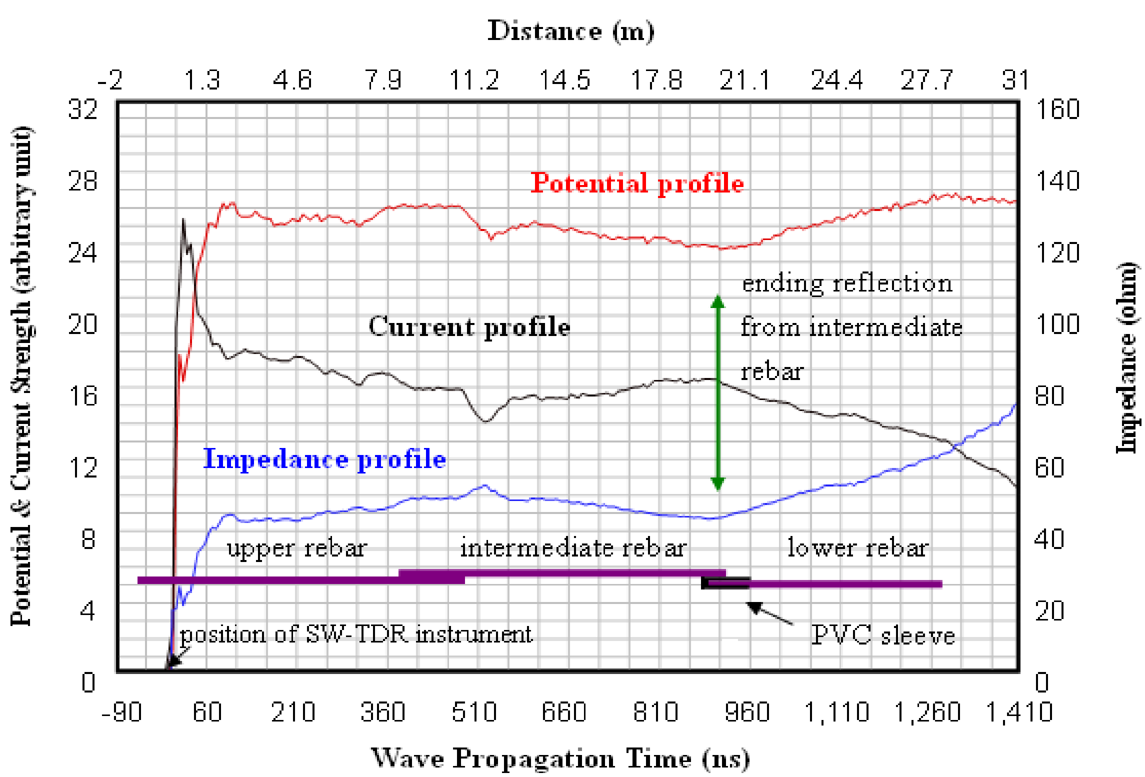

Fig. 5 SW-TDR Wave Diagram of the Dummy Rebar in the "Length Evaluation" Bored Pile

Conclusions

The following conclusions can be drawn from this full-scale field evaluation of the SW-TDR technique:

(1) The SW-TDR technique is an innovative *in-situ* and non-destructive technique that is able to detect and delineate the defects in the reinforced concrete of large-diameter bored piles.

(2) The SW-TDR technique is able to determine the length of the steel reinforcement bar in constructed large-diameter bored piles.

(3) The technique is feasible and suitable for practical uses in field quality control of subsurface geotechnical structures with steel reinforcement bars or other similar metallic conductors.

(4) The results obtained from the technique may require experienced personnel to interpret the wave reflections.

References

[1] Su, M. B. (1990). "Fracture monitoring within concrete structure by time domain reflectometry." *Engineering Fracture Mechanics*, 35(1-3), 313-320.

[2] van der Aa, J. P. C. M., and Boer, G. (1997). "Automatic moisture content measuring and monitoring system based on time domain reflectometry used in road structures." *NDT & E International*, 30(4), 239-242.

[3] Okanla, E. I., Gaydecki, P. A., Manaf, S., and Burdekin, F. M. (1997). "Detecting faults in posttensioning ducts by electrical time-domain reflectometry." *Journal of Structural Engineering*, ASCE, 123(5), 567-574.

[4] Stein, J., Laberge, G., and Levesque, D. (1997). "Monitoring the dry density and the liquid water content of snow using time domain reflectometry (TDR)." *Cold Regions Science and Technology*, 25(2), 123-136.

[5] Liu, W., Hunsperger, R. G., Chajes, M. J., Folliard, K. J., and Kunz, E. (2002). "Corrosion detection of steel cables using time domain reflectometry." *Journal of Materials in Civil Engineering*, ASCE, 14(3), 217-223.

[6] Chajes, M., Hunsperger, R., Liu, W., Li, J., and Kunz, E. (2003). "Time domain reflectometry for void detection in grouted posttensioned bridges." *Design of Structures 2003*, Transportation Research Record 1845, Transportation Research Board, Washington, D.C., 148-152.

[7] Siddiqui, S. I., Drnevich, V. P., and Deschamps, R. J. (2000). "Time domain reflectometry development for use in geotechnical engineering." *Geotechnical Testing Journal*, ASTM, 23(1), 9-20.

[8] Tang, T. (2004). "Underground and foundation works monitoring using surface wave time domain reflectometry technique." *Recent Advances in Geotechnical Engineering*, Proc. 24th Annual Seminar of Geotechnical Division, Hong Kong Institution of Engineers, Hong Kong, 69-76.

[9] Yu, X., and Drnevich, V. P. (2004). "Time domain reflectometry for compaction control of stabilized soils." *Soil Mechanics 2004*, Transportation Research Record 1868, Transportation Research Board, Washington, D.C., 14-22.

[10] Drnevich, V. P., Ashmawy, A. K., Yu, X., and Sallam, A. M. (2005). "Time domain reflectometry for water content and density of soils: study of soil-dependent calibration constants." *Canadian Geotechnical Journal*, 42(4), 1053-1065.

[11] Lin, C. P., and Tang, S. H. (2005). "Development and calibration of a TDR extensometer for geotechnical monitoring." *Geotechnical Testing Journal*, ASTM, 28(5), 464-471.

[12] Tang, T., and Yim, K. P. (2005). "The surface wave - time domain reflectometry (SW-TDR) technique for checking the length and grout integrity/concrete cover of installed underground steel reinforcement of ground anchors, soil nails, concreted steel H-piles and bored piles." *Safe and Green Slopes*, Proc. 25th Annual Seminar of Geotechnical Division, Hong Kong Institution of Engineers, Hong Kong, 305-321.

[13] Lin, C. P., Tang, S. H., and Chung, C. C. (2006a). "Development of TDR penetrometer through theoretical and laboratory investigations: 1. Measurement of soil dielectric permittivity." *Geotechnical Testing Journal*, ASTM, 29(4), 306-313.

[14] Lin, C. P., Chung, C. C., and Tang, S. H. (2006b). "Development of TDR penetrometer through theoretical and laboratory investigations: 2. Measurement of soil electrical conductivity." *Geotechnical Testing Journal*, ASTM, 29(4), 314-321.

[15] Cheung, W. M. (2005). " Use of Time Domain Reflectometry to Determine the Length of Steel Soil Nails with Pre-Installed Wires," Technical Note TN 3/2005, Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong Special Administrative Region Government.

[16] Jordan, E. C., and Balmain, K. G. (1968). *Electromagnetic waves and radiating systems*. 2nd Edition. Prentice-Hall, Englewood Cliffs, N.J.

[17] Ling, R. T., Scholler, J. D., and Ufimstev, P. Ya. (1998). "The propagation and excitation of surface waves in an absorbing layer." *Progress in Electromagnetics Research (PIER)*, Vol. 19, 49-91.

[18] Ling, R. T., Scholler, J. D., and Ufimstev, P. Ya. (1998). "Errata on: The propagation and excitation of surface waves in an absorbing layer." *Journal of Electromagnetic Waves and Applications*, 14(10), 1465.

Biographical Information

Dr. Terrence Tang is a physicist by profession. He obtained his B.Sc. degree in physics from the University of Manchester Institute of Science and Technology (UMIST) in the U.K. in 1978 and Ph.D. degree in atmospheric physics from the same university in 1982. Having completed further research and development work in science and technical fields for 2 years, he found his own company, Supreme Instruments Ltd. in 1984 in Hong Kong, and has held the position of Managing Director since then. Dr. Tang is very experienced and knowledgeable in measurement techniques and instrumentation. Application of the latest and developing innovative technologies on various difficult measurement problems is one of his main professional interests.

Dr. Albert T. Yeung is currently an Associate Professor of the Department of Civil Engineering of The University of Hong Kong. He received his BSc(Eng) degree in civil engineering with First Class Honors from The University of Hong Kong, his MS and PhD in geotechnical & geoenvironmental engineering from the University of California, Berkeley. Before joining the faculty of civil engineering at The University of Hong Kong, he served as Assistant Secretary for Financial Services and the Treasury (Financial Services) of the Financial Services and the Treasury Bureau of the Hong Kong Special Administrative Region Government, Chief Engineer of Black & Veatch Hong Kong Limited, and Assistant Professor of Civil Engineering at Texas A&M University of College Station, Texas, and Northeastern University of Boston, Massachusetts. His notable awards include Peter H. K. Chan Award of the Hong Kong Institution of Engineers (HKIE) 2001, Samuel Arnold Greeley Award of ASCE 1999, Arthur Casagrande Professional Development Award of ASCE 1996, Kumagai Prize of HKIE 1994, Dow Outstanding New Faculty Award of the American Society for Engineering Education 1994, Select Young Faculty Award of the Texas Engineering Experiment Station 1993, among many others. Among many professional commitments, he is now the President-Elect of the ASCE Hong Kong Section and a member of the Civil Discipline Advisory Panel of the HKIE. He is the author or a co-author of more than 100 publications.