

# Nondestructive Testing of Concrete Leg Foundations

Transpower New Zealand uses a method to optimize existing foundations before increasing transmission line capacity.

By Ian Flatley, Transpower New Zealand, and Huw Williams, Testconsult UK

**T**ranspower New Zealand, which owns and operates New Zealand's national grid, is embarking on a period of new building and upgrading of existing assets to meet growing demand. During this time, Transpower is also considering the future use of 400 kV and various new transmission-line options to meet growing load projections.

Transpower's transmission system comprises 170 substations and 12,000 km (7450 miles) of transmission lines. It is comparable in size to the system in the United Kingdom. The main ac transmission voltage is 220 kV, and the majority of the system was built in the 1950s through the 1980s.

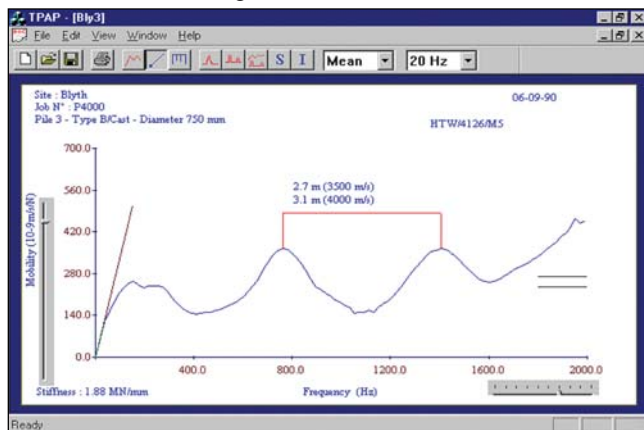
To satisfy the short-/medium-term load growth, Transpower recently completed an aerial line survey of almost half the transmission system, with 5600 km (3480 miles) of line being surveyed to an accuracy of 150 mm (6 inches). This exercise has enabled the development of tactical upgrades to identify cost-effective transmission-line solutions for capacity issues.

Transpower is considering solutions that include increasing the number of conductors, increasing the height of conductor supports, using insulated crossarms, converting suspension insulators to "floating strains" and modifying tower structure. All these solutions increase the mechanical loads experienced by the tower. Therefore, further engineering analysis is required to ensure the tower can safely resist the new loading.

Tower foundations are often overlooked. Simplistic assumptions are made that the foundations were built exactly as designed and that as-constructed records are 100% accurate. This may not be the case as in earlier years basic estimates were often made of in-situ soil strengths and of foundation capacities. Construction alterations and the lack of as-constructed data further complicate efforts to confirm the load-bearing and uplift capabilities of existing foundations.

However, many towers have been installed with a degree of capacity redundancy, as considerations other than mechanical loading become the limiting criteria for locating a tower. Therefore, it is possible that these structures are able to carry loads in excess of the original design loading.

Recently, Transpower and Testconsult (Cheshire, United Kingdom) completed field trials to determine the effectiveness of nondestructive testing (NDT) techniques for assessing concrete foundations of tower legs. These trials, commissioned by Transpower as part of a wider study on upgrading assets to increase transmission system capacity,



An example of a typical mobility response curve.



Line mechanic checking foundations on the ISL-KIK B line during trial.



**In this excavated foundation, note the overbreak approximately 1 m below the ground line.**

were undertaken on foundations of various types and depths in differing soil conditions on New Zealand's North and South islands.

### **Transmission Tower Foundations**

Transmission line tower foundations are relatively unique, given the need to provide uplift capacity as well as traditional load bearing. Bored foundations often incorporate a "bell" or enlargement at the toe of the pile to increase this uplift capacity. Difficulties in forming this enlargement in loose noncohesive soils have resulted in undesirable foun-

ation movement such that strengthening programs have been required. As the bell is buried in soil well below ground level, detecting the bell has proved difficult and often impracticable.

Having established the need to accurately determine the embedded length of the tower foundation in addition to the presence of a bell, Transpower conducted a search of the technologies that could determine the integrity of transmission line structures. This was necessary because New Zealand's electrical regulations specify that when a structure is modified, it must be able to withstand modern design loads.

New Zealand's terrain varies considerably from loose volcanic soils to recent alluvial gravels and complex cohesive clays. Transpower initiated a trial to test multiple existing technologies against a diverse range of soil conditions, structure loading and foundation types. Conventional transient dynamic response (TDR) testing is generally applied to new foundations before tower construction commences.

The trial had three objectives to confirm:

- That the foundation depth could be determined accurately and consistently.
- That the presence of any shaft anomalies could be detected.
- The presence or absence of a bell at the pile base.

### **NDT Techniques Applied to Concrete Foundations**

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evolution of the steady-state vibration test first developed and applied to foundation testing in 1966. At that time, a 25-kg (55-lb) vibrator was clamped to the pile head and used to excite foundations at a range of frequencies. Since that time there have been dramatic improvements and miniaturization of the equipment. The most significant single step came in 1982, when it was found that identical results could be obtained by a transient impulse on the foundation top, using a small hand-held hammer acting through a load cell in place of the heavy vibrator. Advances in microprocessing meant that the time-domain signal could be readily converted to frequency. (This technique, now known as the transient dynamic response test is well-documented in published articles and guides, such as CIRIA Report 144, "Integrity Testing in Piling Practice" (1997).)

The TDR method can analyze acoustic anomalies corresponding to the following conditions: foundation toe level, shaft restraints, overbreak (increases in shaft section),

waisting (reductions in shaft section), cracks and zones of poor-quality concrete.

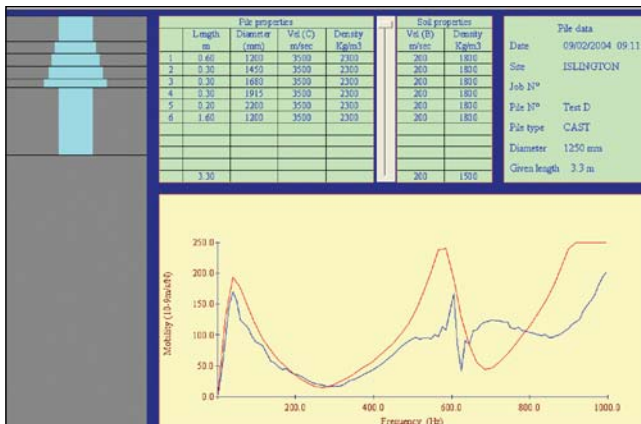
Briefly, when the top of a concrete foundation is struck with a hammer, a longitudinal bar wave travels down the shaft. When the wave reaches the base of the pile, it is reflected back up to the top. By assuming a wave speed velocity, it is possible to calculate the depth of the foundation. Reflections also can be obtained from acoustic anomalies within the shaft of the foundation. At low frequency, the response is linear, allowing measurement of the dynamic pile head stiffness.

To interpret the test results, it is necessary to make some assumptions concerning the wave propagation velocity within the pile. It is assumed that the average wave velocity of normal-quality concrete lies within the range of 3500 m/sec (11,450 ft/sec) to 4000 m/sec (13,100 ft/sec). Dense or high modulus concrete might have a slightly higher velocity than 4000 m/sec (13,100 ft/sec), and likewise, it is not impossible for concrete made with poorer quality aggregates or indeed grout piles to be lower than 3500 m/sec (11,450 ft/sec).

Length measurements are calculated from the distance between resonating peaks, produced by the foundation toe or acoustic anomalies along the shaft. Lateral soil restraints, overbreak, changes in shaft section, cracks and zones of poor-quality concrete can all produce various types of acoustic anomaly, which can be detected. The length of the foundation is given by:

Length Measurement:  $L = C/2Df$

where: C = velocity of longitudinal waves in concrete,



**Simulation result and corresponding impedance profile – Leg D, confirming mid-shaft enlargement.**

$D_f$  = distance between two resonating peaks.

The dynamic pile head stiffness is measured at low frequencies, when the head of the foundation and surrounding soil are moving as one unit and the head of the foundation is the reciprocal of the slope of the initial part of the curve.

**Dynamic Pile Head Stiffness:**  $E' = 2 P_{fm}/(V/fm)$

where:  $f_m$  = frequency at point of measurement,

$V$  = velocity.

The concrete density, or conversely the cross-sectional area of the foundation (if concrete strength is known), can be calculated from the mean height  $N$  of the resonating part of the curve using the following formula.

Mobility :  $N = 1/rCA$

where:  $r$  = density of concrete,

$C$  = velocity of longitudinal waves in concrete,

$A$  = pile cross-sectional area.

The TDR method is now used globally as a quality-assurance tool for assessing new-build foundations. The late 1990s saw advances in interpretation techniques with software processing of TDR data, and the interpretation of results is now more evident and can be used in many cases by engineers not experienced in NDT methods.

### NDT Theory to Field Experience

In New Zealand, a variety of different concrete foundation types exist, depending on soil conditions, location and the type of tower. During the trial, tests were carried out on most foundation types, including short and long foundations with belled and un-belled shafts, cylindrical bored foundations and hand-dug rectangular foundations founded in cohesive and noncohesive soils. This comprehensive trial was to determine the system in real-site conditions, both for accuracy of results and the practicality of working in difficult locations. During the trial, a total of 340 tower leg foundations were tested on eight lines and at two depots. In addition, foundations were excavated at four locations to confirm the results of the testing.

### Field Tests

- At Islington Substation, near Christchurch, four redundant test foundations were tested and analyzed. All foundations were nominally 1250 mm (49 inches) in diameter with unknown depth. TDR testing indicated that lengths ranged from 2.9 m (9.5 ft) to 3.2 m (10.5 ft) using a signal velocity of 3500 m/sec. (11,450 ft/sec) Subsequent excavation revealed actual lengths to be between 2.9 m (9.5 ft) to



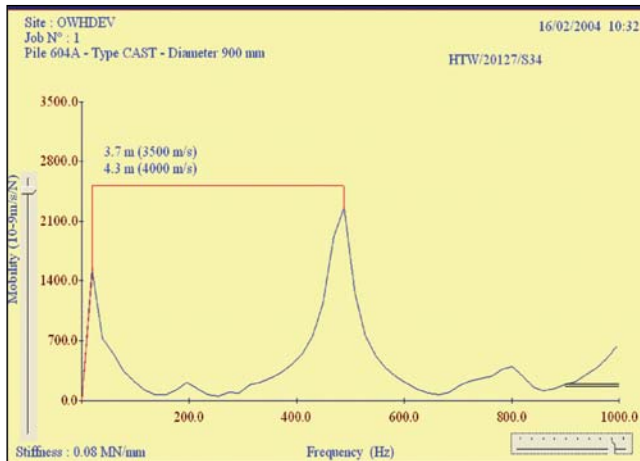
**Leg 604/A, OWH-DEV A Line, being measured for length following excavation.**

3.3 m (10.8 ft), confirming the test results. Furthermore, the simulation model and impedance profile for one foundation showed a large increase in section at approximately 1.5 m (4.9 ft). Excavation confirmed a mushroom-shaped bulge (overbreak) from 0.6 m to 1.7 m (2 ft to 5.5 ft).

- At the Omaka Training Centre, near Blenheim, 12 shallow tower-leg foundations were tested; one foundation was subsequently excavated. The test results indicated a 1.7-m to 1.9-m (5.6-ft to 6.2-ft) depth for good-quality concrete compared to the actual confirmed depth of 2 m (6.5 ft). One of the foundations was then retested with the tower disconnected. No significant difference was noted.

- The Owhata Deviation A (OWH-DEV A) transmission line, situated near Rotorua on the North Island, was originally supported on steel lattice towers. Owing to the high corrosion rates in the area, the towers for a section of the circuit were subsequently replaced with poles; hence, a number of buried tower leg foundations were re-excavated for the trial. Ground conditions are generally silty sand, ash and pumice, providing little skin friction. Ten foundations were tested, two were excavated and one previously removed from site was tested. Measured lengths again were within 100 mm, or less than 3% different from the actual length.

- The Islington-Kikiwa B (ISL-KIK B) line runs from near Christchurch on the East Coast of South Island, to Kikiwa, approximately 230 km (143 miles) north. A total of 152 tower leg foundations were tested on this line, which runs predominantly through alluvial plains and mountain ranges. Two legs of a tower near Culverden were subsequently excavated, and again measured lengths were close



**TDR test result from Leg 604/A, OWH-DEV A Line showing clear response from 3.7 m at 3500 m/sec.**

to the predicted lengths given by TDR measurements. Exposure of these two foundations also showed irregular pile shafts with a mid-shaft increase in section and slight bell at the base.

The test results from the various sites confirm that it is possible to determine the depth of both hand-dug and bored foundations with a good degree of accuracy and reliability, generally within 5% of the actual length. The ground conditions on the Glenbrook Deviation A (GLN-DEV A) line just north of Auckland (Test 3) are stiffer with more cohesive soils. The tower foundations are deeper than those checked on the South Island, ranging from approximately 3 to 12 m (10 to 39 ft). Even with these deeper piles, it was possible to obtain a clear response from the level of the pile toe, confirming the full length of the foundation.

### **Asset Owner Benefits of NDT Testing of Foundations**

The trial proved to be successful, given the high accuracy of the overall depth measurements and the potential to glean further information for significant changes in cross-section. Together with known soil properties, the results obtained from the trial show that foundation designers can, with greater confidence, predict the nature of foundation adequacy with significantly less need for expensive and time-consuming excavations. The information obtained is both reliable and accurate for current foundation design practice.

Further modeling of the TDR's impedance profile indicated the likely presence of a bell at the toe of the foundation is detectable. This enlargement of cross-section (bell) is important as such bells provide a significant increase in the strength of a tower's foundation.

The results also enable an accurate survey of the line system to be undertaken and to establish where potential exists for increasing the mechanical loads on the foundations, whereby upgrading the capacity of existing infrastructure with minimal impact and cost.

Previously, undetectable issues with bored foundations, such as necking of the pile section, cracking and under-length foundations can now be identified and mitigated. Knowledge of the pile length and section properties enables any post strengthening to be carried out economically and efficiently without the need for additional margins of uncertainty through the design process.

Upgrade work can proceed with the confidence of foundations meeting present design loading criteria. This ensures that installed works will meet stakeholder requirements for a strong, safe and efficient grid.

The TDR method was found to provide rapid and accurate data on foundation lengths, usually within 5%. Additional information on pile section can also be obtained with the use of the equipment's proprietary software and results not affected by the connection of the tower leg or applied loads to the foundations. ▀

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