

# Geophysical Methods for Pipeline Corrosion Mapping

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## Abstract

New geophysical methods have been developed to assist with estimates of pipeline corrosion. Induction methods developed for mineral exploration are now available for determination of metal thickness with precision comparable to ultrasonic measurements. The commercial tesTAU method is available either as an in-line pigging system or for external scans on exposed pipe regardless of coating material. Additional external geophysical methods are recommended to assist with a comprehensive risk analysis based on soil corrosivity. Both galvanic and electromagnetic (EM) methods can be used to provide estimates of conductivity and chargeability data related to ion mobility and electrolyte activity.

## Introduction

Measurements of pipeline corrosion are an essential element for any adequate risk analysis of major sub-surface utilities. Apart from direct detection of pitting, faults and fractures, observations of wall condition are required to confirm indirect estimates of longevity based on soil properties and burial history. Pipeline segments have been previously exhumed to provide physical samples for this purpose. However there is a significant cost as well as some physical damage associated with cutting coupons for laboratory analysis. In contrast, cost-effective geophysical methods can be mobilised to provide an almost continuous profile along the pipeline with minimal physical impact.

The methods and strategies currently available for the inspection of urban pipeline systems have been reviewed by De Silva et al (2002); these methods provide critical data for pipeline renewal, asset integrity, and water conservation programs. The scale of the problem and the current research priorities are reflected in the expenditures reported by Davis et al (2003). For Australia the annual cost for pipeline maintenance and replacement programs has been estimated to exceed Au\$250 million p.a. (on 1998/99 data) and over US\$330 billion pa worldwide (e.g. Eden 2001). These sums do not include the cost of repair for catastrophic failures involving washouts, road collapse and building damage (>Au\$10m for one single sewer collapse in central Melbourne). In these circumstances new inspection technologies and advances in associated interpretation techniques can offer substantial economic benefits as well as assisting with water conservation programs.

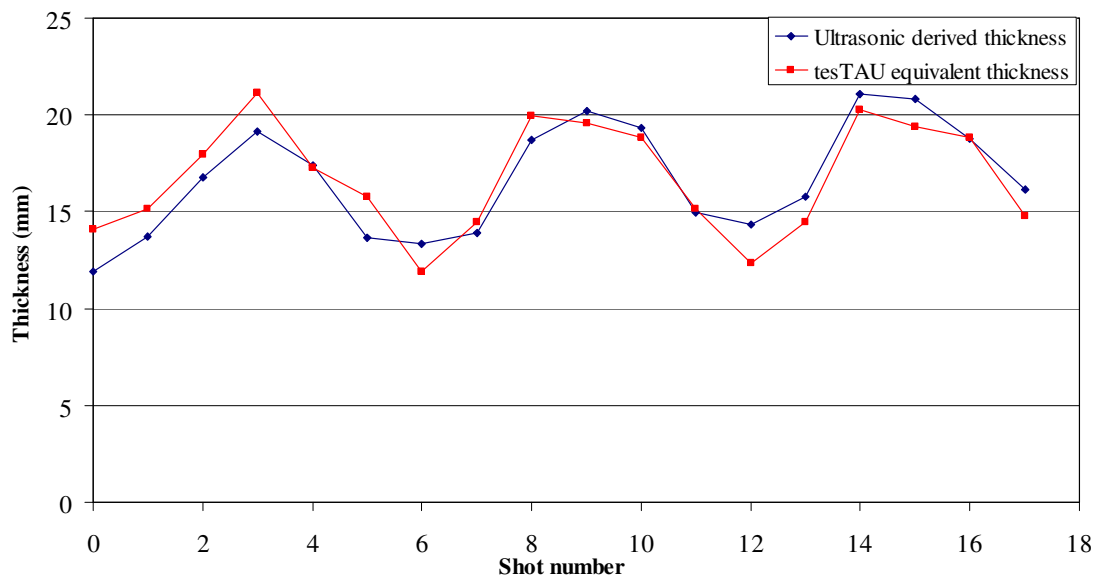
Several different geophysical survey methods are available for detailed imaging of sub-surface utilities. In particular electromagnetic induction (EM) and ground penetrating radar (GPR) techniques have been used extensively for direct detection of pipeline location and structural integrity surveys. However the results are often highly site specific with significant variations in penetration and resolution. In addition simple imaging tools are often insufficient for a comprehensive risk analysis based on material properties, construction methods, bedding, environmental factors, and age of emplacement. Consequently several new indirect geophysical inspection methods have been developed specifically to provide ancillary data for adequate evaluation of soil and groundwater conditions ultimately responsible for pipeline corrosion. A comprehensive risk analysis will require a combination of methods for direct inspection of wall condition and surface mapping of soil properties and bedding condition.

## Pipeline Induction Surveys

Pigging systems provide the most direct indication of pipewall condition. Consequently there has been considerable interest in the development of remote-field (RFT) induction sensors or eddy current systems for pipeline and other engineering applications. There are now several instruments on the market to determine material thickness of ferrous and non-ferrous metals. These sensors typically operate at a single frequency, which is tuned depending on material thickness and composition.

As an alternative to the RFT method, the tesTAU system has been developed for pipeline surveys; it is based on observations of the near-field eddy current decay induced using an array of sensor elements. The tesTAU system has been extensively tested by key providers in Australia; it provides a detailed image of pipeline topography, pitting and thinning with sensitivity better than 1 mm (e.g. Sadler et al 2003). Commercial surveys have been conducted on major pipelines in Singapore and Australia with cut-ins providing access to run lengths exceeding 250 m. External scans can be conducted where pigging is not a suitable option.

The tesTAU method is based on well-founded physical principles used extensively in the mineral exploration industry. It represents a significant technological advancement over RFT; it is specifically designed to overcome environmental variables that mask the true response related to actual wall thickness variations. In effect the near-field transient tesTAU system generates the equivalent of a wide range of frequencies, which negates the need for tuning. Pulsed eddy current systems of this type are readily distinguished from fixed frequency systems in that they provide an ‘absolute’ determination of wall thickness at each location, whereas RFT methods only determine point defect size. An example of the correlation between ultrasonic and calibrated tesTAU data illustrating its accuracy in determining wall thickness is provided in Figure 1.



**Figure 1.** Comparison between tesTAU and ultrasonic derived thickness measurements. The slight mismatch is associated with statistical variability due to the very localised nature of ultrasonic data compared to the tesTAU ‘footprint’. Three circumferential scans obtained at different locations have been merged together. The cyclic nature of the data is due to consistent thickness variations attributed to the manufacturing process.

## tesTAU Surveys

The tesTAU pigging technique has a significant advantage over other techniques including magnetic flux leakage (MFL), ultrasonic, and RFT systems in that it is relatively immune to the presence and variability of lining/coating material. Conversion to actual wall thickness does, however require knowledge of electrical conductivity, thereby requiring calibration for specific materials. Monash GeoScope has established an extensive database of calibration curves for common pipe materials and reliable *equivalent thickness* values can be obtained using this database. Alternatively, calibration curves can be established directly using a 300 mm × 300 mm coupon of the material under investigation. Individual ‘spot’ measurements using an ultrasonic system can also provide calibration information and are routinely used as part of the inspection process.

Regardless of any specific calibration, it should be noted that valuable information critical to assessing pipeline integrity can be obtained directly from the tesTAU raw data. Apart from providing a visual indication or pipeline image, the results can be statistically processed and individual pipe lengths assigned a quality grade based on the statistical variability. This grading is possibly more useful for inclusion into failure modelling packages and is immune to subtle changes in material properties that adversely affect absolute thickness conversions based on a single pipeline sample or previous laboratory investigations.

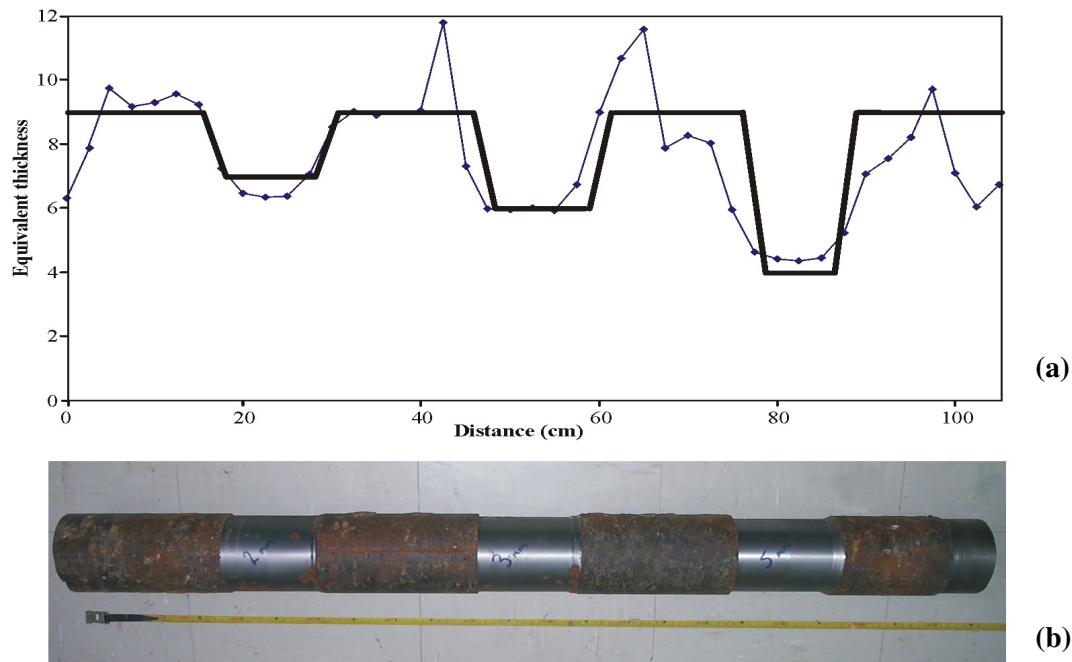
The tesTAU system is available using identical sensor assemblies for both in-pipe and external configurations. This flexibility allows translation of any available calibration information between the different acquisition platforms. Similar data quality is obtained between in-pipe and external platforms with some exceptions due to the presence of thick internal lining.

## tesTAU Resolution

Depending on the pipe diameter, multiple sensors are arranged around a central delivery platform to maintain a sensor centre to centre spacing of 60 mm. Individual sensors have a ‘*footprint*’ of 50 mm × 50 mm. The sensor *footprint* essentially refers to the minimum dimension required for an anomaly, or thickness change, to be resolvable. It should be stressed that smaller anomalies are detectable, and this is clearly evident in data collected to date, however, the response is averaged and therefore the calibrated thickness reflects the average pipe wall thickness over the sensor *footprint*, not a spot, or minimum, thickness.

Sample density along the pipe is dependent upon available time to complete the survey. Ideally, two to three samples should be acquired over the minimum anomaly size of interest. For example, to detect a 100 mm diameter defect in a 100 m survey length requires 2,000 samples over the pipe length. This would take approximately 45 minutes, including signal averaging, which is required to improve data quality and therefore anomaly recognition. Survey speed can be increased, although only at the expense of anomaly detection sensitivity; this parameter requires consultation with the client as it is related to survey expectations and outcomes.

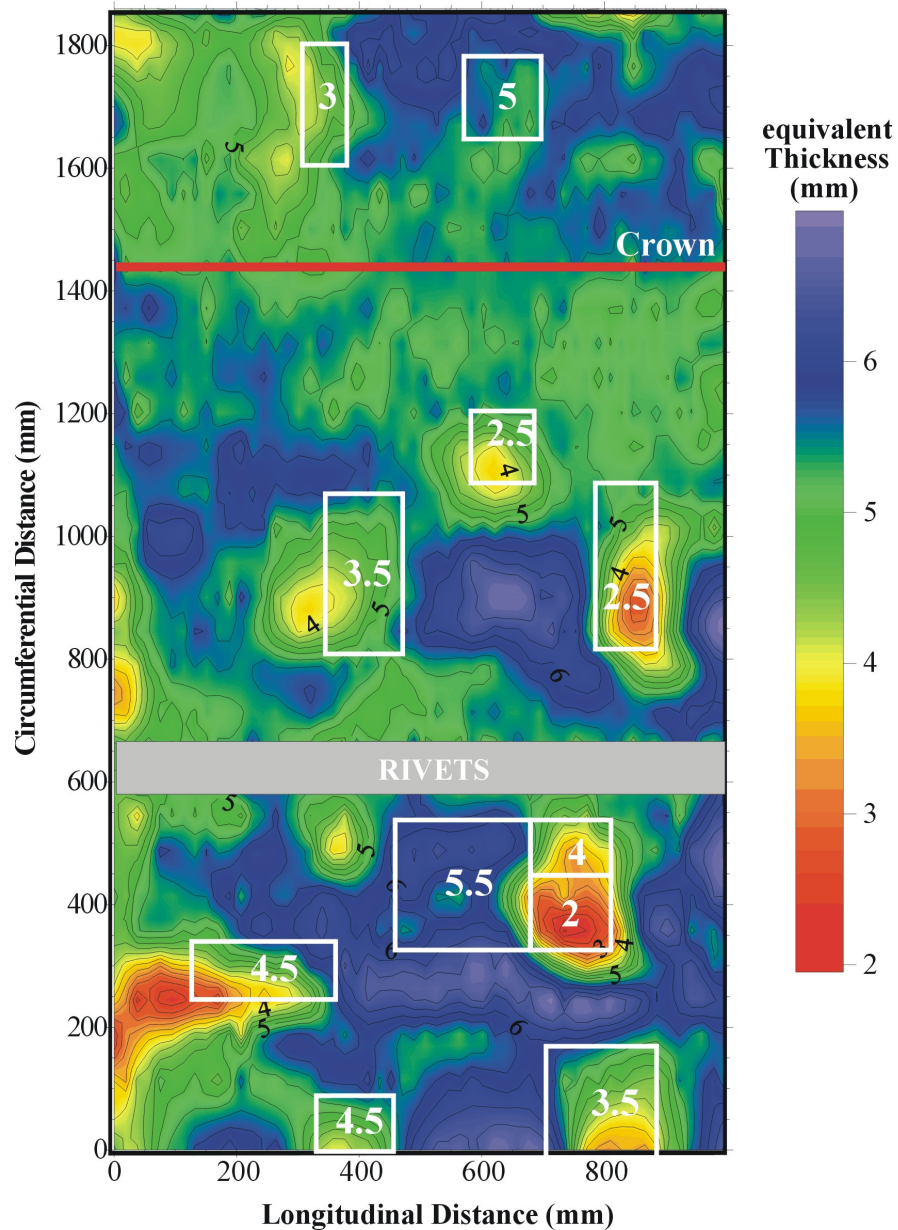
Typical examples of tesTAU data are provided in Figures 2, 3 and 4. They demonstrate different sensor configurations: an internal rapid scanning reconnaissance configuration, a high-resolution internal scan, and a high-resolution external scan, respectively. Data presented in Figure 2 were collected from within a test section of DN100 CICL water pipe with three external machined zones of thinning; the original wall thickness being 9.0 mm. The survey was completed using an axial sensor configuration. The three zones are clearly evident and further, it is possible to comment on the extent of thinning based purely on signal amplitude.



**FIGURE 2:** (a) The blue curve represents the calibrated equivalent thickness and the heavy black line is the actual wall thickness. (b) Photograph of the CICL test pipe used to conduct this test. It should be noted that because of the limited pipe length, 'end effects' have distorted the first and last two to three data points.

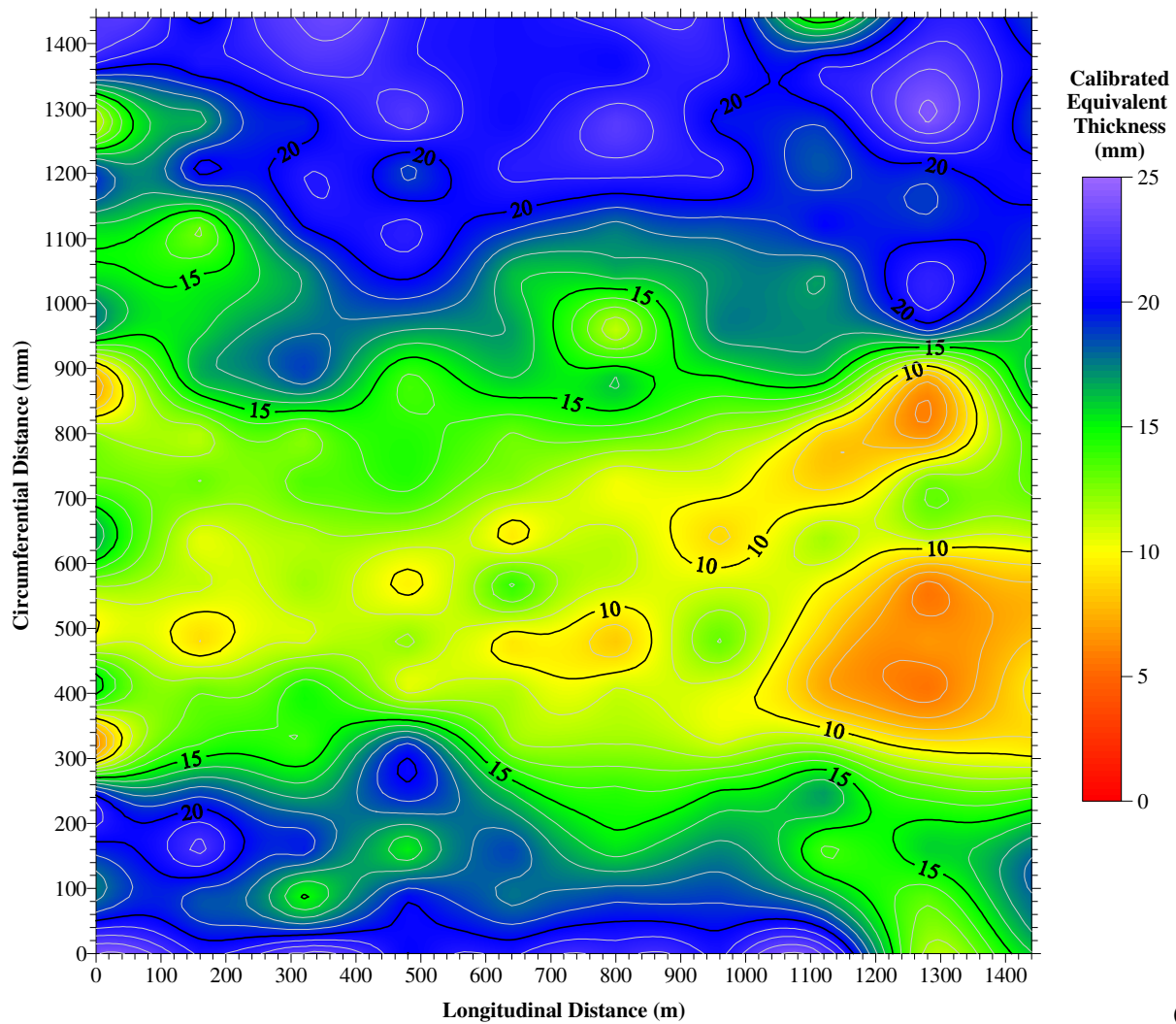
To improve tesTAU data interpretation beyond anomaly detection and estimates of lateral extent requires calibration information derived from the pipe from which data were collected. If this is not possible then estimates can be used. However, because of compositional variations in cast iron this may degrade equivalent thickness determinations. This is a problem for all induction-based sensors but statistical methods are available to demonstrate internal consistency and conformity with an extensive database. Figure 3 was constructed from an internal tesTAU scan of a limited length of exhumed wrought iron water main. Using existing calibration information, data were converted to *equivalent thickness* values. Not only have all machined anomalies been located, accurate estimates of remaining wall thickness have been derived. In addition to the manmade anomalies, it is also possible to identify the extent of natural corrosion along the pipe crown.

The last example is of tesTAU data collected externally from a DN450 CICL water main (Figure 4a). Results have been independently reviewed and found to have a mean error of 0.7 mm and a standard error of 3.2 mm relative to physical defect measurements. Given that typical anomalies in the CICL are approximately 40 mm in diameter (smaller than the tesTAU *footprint*) this outcome again demonstrates the accuracy of the tesTAU system. In addition to the colour images that do effectively convey defect location, key statistical parameters are also provided (Figure 4b). It is these values that should be used to accurately quantify pipe condition.

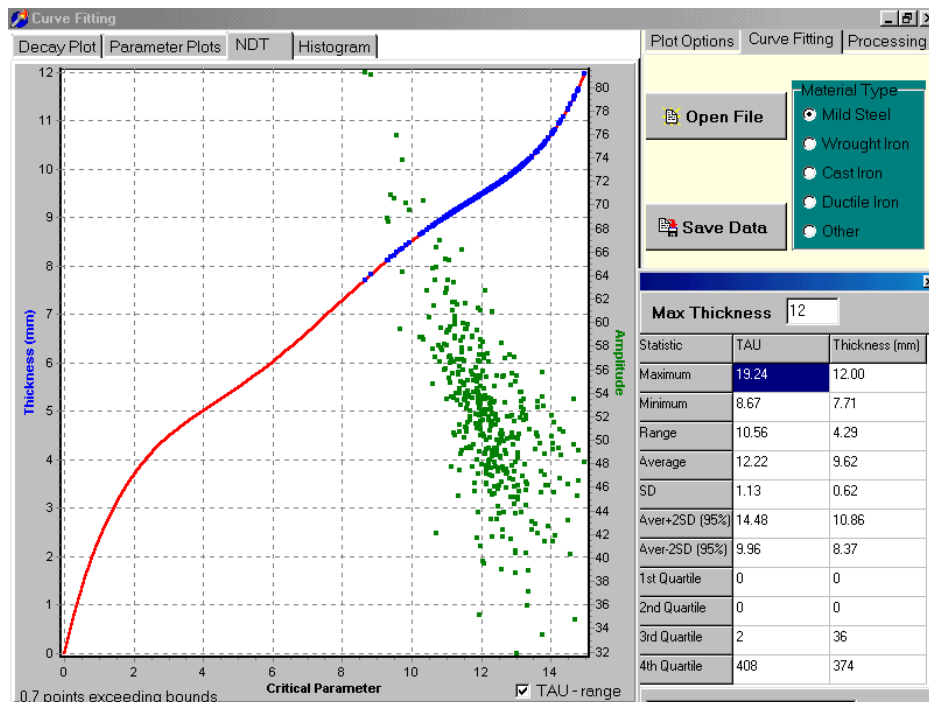


**FIGURE 3:** (a) A length of 610 mm wrought iron water main. (supplied by City West Water). Multiple defects were created; the numbers indicate the defect depth. (b) *Equivalent thickness* plot of the wrought iron pipe. Note that the numbers in white are the quoted remaining wall thickness. Some distortion in actual anomaly location has occurred because of the variations in survey speed, which was not monitored. In addition, data at either end of the pipe still contain spurious responses associated with the circumferential band of rivets.





(a)



(b)

**Figure 4:** (a) An example of results obtained from a DN450 CICL water main. (b) Screen shot of the processing program. A table of statistics is included within the client report as a more accurate description of the wall condition.

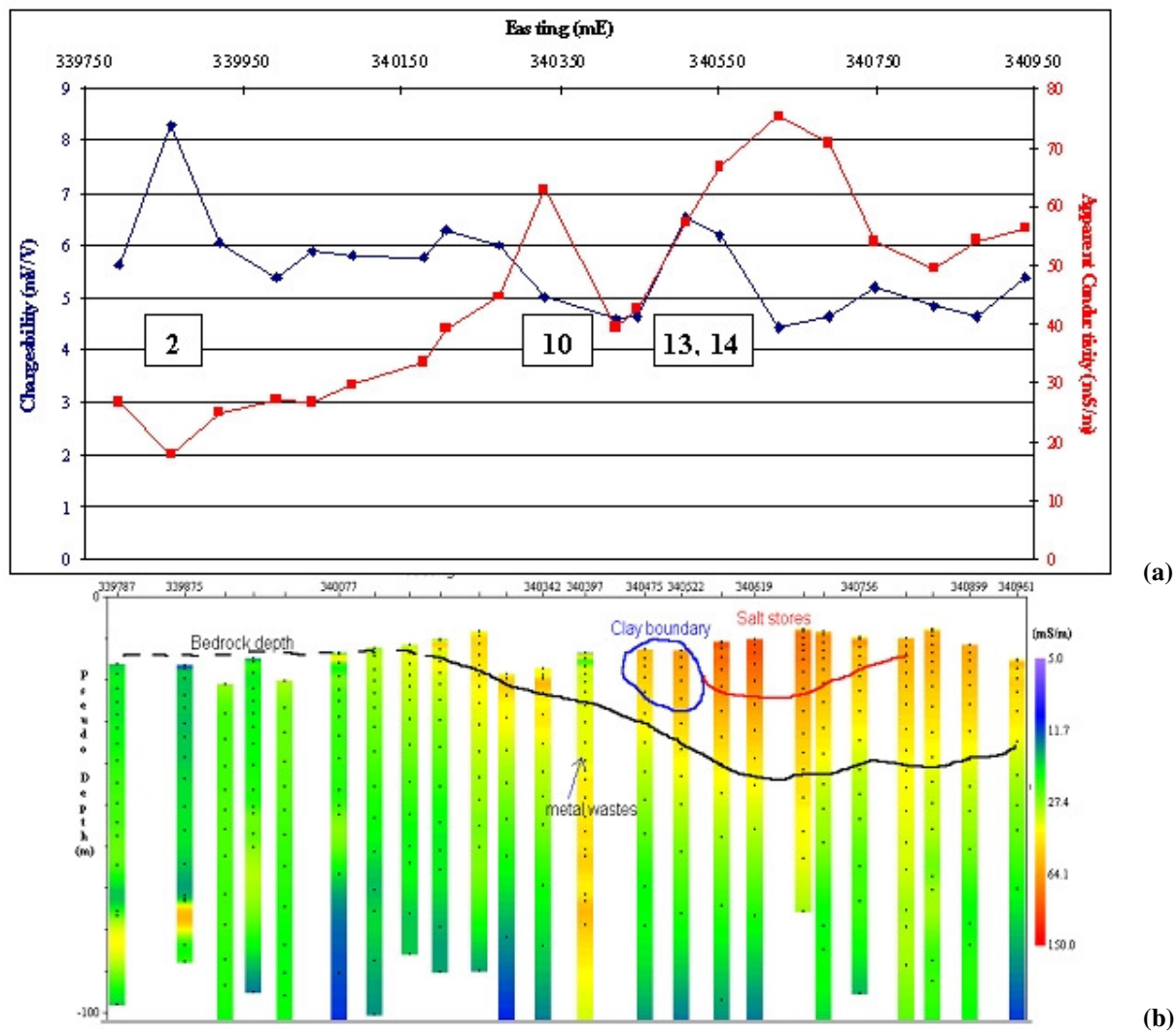
## Soil Mapping

Apart from pigging systems a considerable range of geophysical data can be obtained using external survey techniques to determine ground properties ahead of any remediation program. Soil properties are now commonly described in terms of linear polarization resistance (LPR). These surveys have the advantage that they provide rapid coverage of major utilities with low physical impact (e.g. Davis et al, 2003). Geophysical surveys can provide a useful adjunct to LPR measurements by increasing data density and providing additional information on bedding depths and pipeline location. Under favourable circumstances geophysical surveys can provide an indication of electrical properties in soil modified by local corrosion and water infiltration.

In order to obtain reasonable estimates of local corrosion rates for adequate risk analysis it is essential to identify the soil and groundwater conditions at any specific location. Deterioration of ferrous pipelines is dependent upon electrochemical properties of the soil. There have been extensive studies on the rates of corrosion for cast iron pipe in different soil types (Romanoff, 1957 and 1964, Rossum, 1969). These studies have linked soil pH, soil resistivity (inverse of conductivity), soluble sulphates and chloride ion content among others to a 'corrosivity index' of soil. However, detailed investigations of this type are generally impractical for routine operations and indirect geophysical methods have been developed to provide equivalent data. In particular, soil condition and corrosion potential are now frequently summarised in terms of an electrochemical property described as the Linear Polarisation Resistance (LPR).

The LPR method is designed to provide estimates of soil corrosivity based on small samples extracted for laboratory analysis. These small samples are assumed to provide a reasonable average for the soil conditions along the whole pipeline. However, direct determinations based on new geophysical methods may provide the capacity for a more comprehensive risk analysis at any location. Several geophysical methods have been deployed to provide suitable data. In particular resistivity surveys are directly related to soil properties including porosity, salinity, and water content. Relevant data can also be obtained using TEM induction methods or quasi-static galvanic methods. Apart from estimates of resistivity (or conductivity) these methods can provide an indication of chargeability or induced polarization (IP) related to electrolyte activity. An example of information that can be derived from investigating both resistivity and its frequency dependency is provided in Figure 5, where it is possible to differentiate conductive clay from a salt lens. This would not be possible using galvanic resistivity information alone.

IP effects observed using galvanic methods for mineral exploration are usually assumed to involve the migration and accumulation of external charge carriers at a physical interface (electrode polarisation) or electrochemical associations in complex media (membrane polarisation). However the total internal field induced by a electric dipole also contains charge displacement effects associated with many other non-galvanic processes including planar deflection of electrons held in atomic orbit, distortion of molecular bonds, and the reorientation or rotation of polar molecules (e.g. water, Bleaney & Bleaney 1963). Variations in amplitude and time-constant for the resulting IP effect are consistent with systematic trends in water content (and consequently charge density). Key parameters influencing the complex resistivity are potentially related to those responsible for variations in soil corrosivity and therefore, would represent a major innovation in pipeline survey methods.



**Figure 5:** (a) Additional information derived from a key IP parameter allows differentiation of a highly conductive anomaly into a clay body adjacent to a perched saline lens. (b) Advanced electromagnetic systems allow construction of cross-sections describing resistivity versus depth.



## Conclusions

We recommend a multi-faceted approach to pipeline NDT surveys. Past experience has demonstrated that a single technique may not provide enough information to accurately assess every fault in any given utility. Survey variables including material type, protective lining thickness, and sensor-wall offsets combine to create a complex testing environment, particularly during in-pipe inspections which are far removed from laboratory based calibration measurements. In some circumstances external access is readily available and hand-held observations can provide sufficient information. However more elaborate methods are normally required based on a combination of pigging and surface surveys.

The tesTAU system measures two important statistical parameters that can be incorporated into data reduction algorithms; these reduce potential ambiguities associated with measuring wall thickness in an extremely complex environment. These surveys provide the most detailed information available for observations of pipeline corrosion. External testing indicates resolution better than 1 mm for depth estimates on a 50 mm footprint. The results can be used for direct justification of pipeline remediation strategies or to provide independent confirmation of statistical models for risk analysis. External readings provide a suitable substitute for ultrasonic testing which can be adversely affected by coating materials.

Additional indirect geophysical surveys show great promise in providing an indication of soil properties which can determine rates of corrosivity. The additional geophysical data could be used to extrapolate information from existing soil samples or point-source LPR data and provide independent estimates with better sample density and negligible surface impact. Apart from providing high-density linear profiles between physical samples, geophysical surveys can be used to generate a vertical profile of sub-soil condition including an indication of bedding materials. Under favourable circumstances corrosion products retained within the soil may be identified through local variations in chargeability.

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