RAPID AND ECONOMICAL EVALUATION OF CONCRETE TUNNEL LININGS WITH IMPULSE RESPONSE AND IMPULSE RADAR NONDESTRUCTIVE METHODS

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KEYWORDS: Concrete tunnels, grouting, nondestructive testing (NDT), Impulse Response, Impulse Radar

ABSTRACT

Concrete tunnel linings, whether pre-cast or cast in place, are designed to distribute external soil pressures as uniformly as possible through the tunnel shell. To this effect, the contact between the lining and the surrounding soil is usually assured by grouting the annular space between. Any voiding in the grout at this interface negates the purpose of the grout. This paper describes the use of nondestructive testing to examine the efficiency of tunnel lining grouting programmes, with particular emphasis on results obtained by the Impulse Response and Impulse Radar methods. The rail, water supply and sewer tunnels discussed in this article vary in diameter between 1 m and 5 m, and emphasis is placed on the rapid results obtained by these methods.

INTRODUCTION

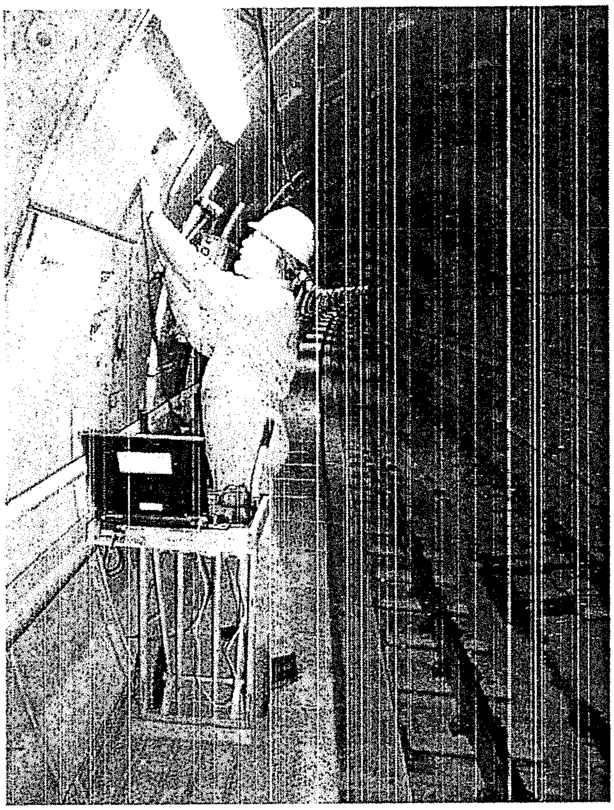
One of the principal functions of concrete tunnel linings is to transmit stress from the surrounding soils evenly throughout the structure. This is usually achieved by pressure grouting the annular interface between the soil and the lining with hydraulic cement-based grouts. Quality control of the grouting efficiency is very difficult, since the final product cannot be visually checked. In the case of very long tunnel sections, spot coring is slow and costly, as well as providing a very limited view of the total picture. The advantage of some form of nondestructive testing control programme is obvious; however, this approach must give confidence to engineers that all zones of significant loss of stress transfer through the grout/concrete interface have been detected.

The two-pronged testing approach described in this article involves the use of the nondestructive Impulse Response and Impulse Radar techniques for the research of poorly grouted areas.

IMPULSE RESPONSE TEST METHOD

The Impulse Response method was developed from the Vibration method for pile integrity testing (Davis and Dunn, 1974) and has been known variably as the Transient Dynamic Response (TDR), Mobility or Impedance method for the last 25 years. The method has been extended to the inspection of concrete structures other than piles, particularly plate-like elements such as floor slabs, walls and large cylindrical structures (Davis, 2003). The detection of voids or poorly compacted areas below or behind plate-like structures is one principal application of the method, and was first used in tunnel construction to evaluate the quality of grouting behind linings in the construction of the English Channel Tunnel.

A low-strain impact sends stress waves through the tested element. The impactor is usually a 1-kg sledgehammer with a built-in load cell in the hammerhead. The maximum compressive stress at the impact point in concrete is directly related to the elastic properties of the hammer tip. Typical peak stress levels range from 5 MPa for hard rubber tips to more than 50 MPa for aluminium tips. Response to the input stress is normally measured using a velocity transducer (geophone). This receiver is preferred because of its stability at low frequencies and its robust performance in practice. Both the hammer and the geophone are linked to a portable field computer for data acquisition and storage (Figure 1).



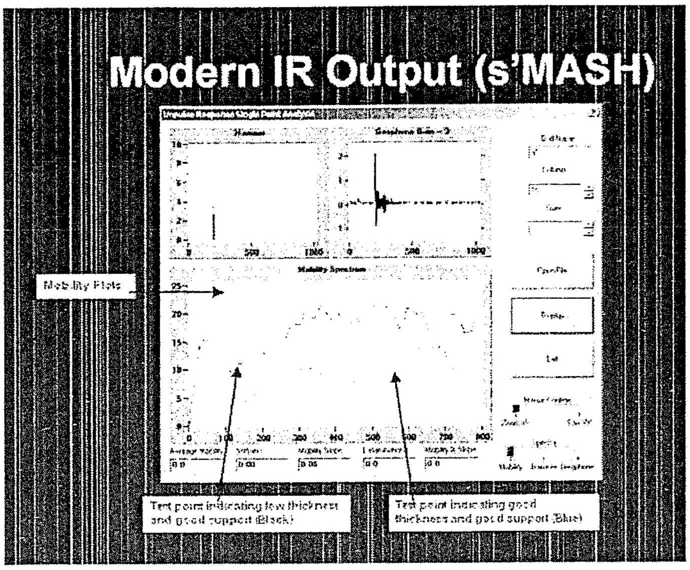


Figure 1. Impulse Response Test Unit and Typical Output

When testing plate-like structures, the Impact-Echo method (Sansalone and Streett, 1997) uses the reflected stress wave from the base of the concrete element or from some anomaly within that element (requiring a frequency range normally between 3 and 40 kHz). On the other hand, the Impulse Response impact generates a compressive stress approximately 100 times that of the Impact-Echo test. This greater stress input means that the plate response to the Impulse Response impact in a bending mode over a very much lower frequency range (0-1 kHz) can be exploited, as opposed to the reflective mode of the Impact-Echo test.

Both the time records for the hammer force and the geophone velocity response are processed in the field computer using the Fast Fourier Transform (FFT) algorithm. The resulting velocity spectrum is divided by the force spectrum to obtain a transfer function, referred to as the *Mobility* of the element under test. The test graph of Mobility plotted against frequency from 0 to 800 Hz contains information on the condition and the integrity of the concrete in the tested elements, obtained from the following measured parameters:

- *Dynamic Stiffness:* The slope of the portion of the Mobility plot below 50 Hz defines the compliance or flexibility of the area around the test point for a normalized force input. The inverse of the compliance is the dynamic stiffness of the structural element at the test point. This can be expressed as:

  Stiffness *f [concrete quality, element thickness, element support condition]*
- *Mobility and Damping:* The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). The mean mobility value over the 100-800 Hz range is directly related to the density and the thickness of a plate element. A reduction in plate thickness corresponds to an increase in mean mobility. As an example, when total debonding of an upper layer is present, the mean mobility reflects the thickness of the upper, debonded layer (in other words, the slab becomes more mobile). Also, any cracking or honeycombing in the concrete will reduce the damping and hence the stability of the mobility plots over the tested frequency range.

- *Peak/Mean Mobility Ratio:* When debonding or delamination is present within a structural element, or when there is loss of support beneath a concrete slab on grade, the response behavior of the uppermost layer controls the IR result. In addition to the increase in mean mobility between 100 and 800 Hz, the dynamic stiffness decreases greatly. The peak mobility below 100 Hz becomes appreciably higher than the mean mobility from 100-800 Hz. The ratio of this peak to mean mobility (voids ratio) is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

IMPULSE RADAR METHODOLOGY

The impulse radar technique employs high-frequency electromagnetic energy waves for rapidly and continuously assessing a variety of characteristics in concrete structures. The principle of operation is based on reflection of electromagnetic waves from varying dielectric constant boundaries in the material being probed. The impulse radar equipment is self-contained, compact, and portable. The system consists of the main radar unit, antenna and transducer cable. All data is stored in the main radar unit, by means of a computer hard drive (ACI 228.2R, 1998; Lim, 2001).

A single or double contacting transducer (antenna) transmits and receives radar signals. High frequency, short pulse electromagnetic energy is transmitted into the element (concrete, grout, soil). Each transmitted pulse travels through the material, and is partially reflected when it encounters a change in dielectric constant. The receiving section of the transducer detects reflected pulses. The location and depth of the dielectric constant boundary is evaluated by noting the transit time from start of pulse to reception of reflected pulse. Boundary depth is proportional to transit time. Since the instrument electronically detects concrete to air, water, grout and/or soil interfaces as dielectric constant boundaries, the impulse radar method is capable of assessing a variety of reinforced concrete, masonry and environmental characteristics. The similarity between cement grout and concrete dielectric constants results in good transmission of radar waves through sound concrete/grout interfaces at the back of tunnel lining segments, whereas voiding or poor bonding at that interface gives a strong radar reflection.

CASE HISTORIES

Sewer Tunnels, St. Louis, Missouri, USA

Following severe flooding from the Mississippi river in 1993, nondestructive testing played a part in the evaluation of the sewer pipes immediately to the west of one of the pumping stations in St. Louis, Missouri. Considerable subsidence of the ground above the sewer had been observed between manholes No.2 (M2) and No.3 (M3), beneath the railway lines which run north to south across the sewer line. The sewer tunnel is at approximately 6 m below ground level, and the subsided area is at approximately 40 m to the east of M2. The original tunnel lining is brick, forming an oval section, 1.2 m x 0.9 m. The tunnel had recently been lined between the two manholes with a proprietary plastic, inflatable liner. The original tunnel lining had not been modified to the east of M3.

Nondestructive testing was performed inside the tunnel, over a distance of:

- 30 m to the east of M2,
- 30 m to the west of M2, and
- 30 m to the west of M3.

Initial Impulse Response testing was performed at stations at 3-m intervals along the tunnels, usually with four test points at the 2, 4, 8 and 10 o'clock positions around the lining perimeter at each station. If anomalies were detected, the area in question was then tested over closer test spacing. The Impulse Response survey showed that the brick-lined portion east from M2 towards the pump station was in good condition, with no voiding behind the brick lining. The lining stiffness values were very evenly distributed, and ranged between 0.02 and 0.09 MN/mm. The plastic lined section to the west of M2, towards the railroad tracks, became progressively much less stiff than the section to the east of M2. Stiffness values as low as 0.002 MN/m were recorded, and the mobility of the lining increased with distance from the manhole. This indicated that the soil support to the tunnel was becoming softer to the west. No voiding was observed, and support conditions around the tunnel perimeter were uniform. The plastic lined section the east of M3 had average stiffness values of between 0.01 and 0.02 MN/mm from the manhole to 18 m to the east of M3. The average mobility values in this zone were constant, and no voids were observed. From 20 m to 30 m, however, the stiffness and average mobility values became more erratic, with stiffness values between 0.02 and 0.24 MN/mm (Figure 2), indicating very variable support from the soil behind the lining. In those areas where the stiffness values dropped below 0.005 MN/mm, the tunnel support was very weak. This suggested that the area of subsidence 9 m beyond the last test point was as a result of this lack of soil support.

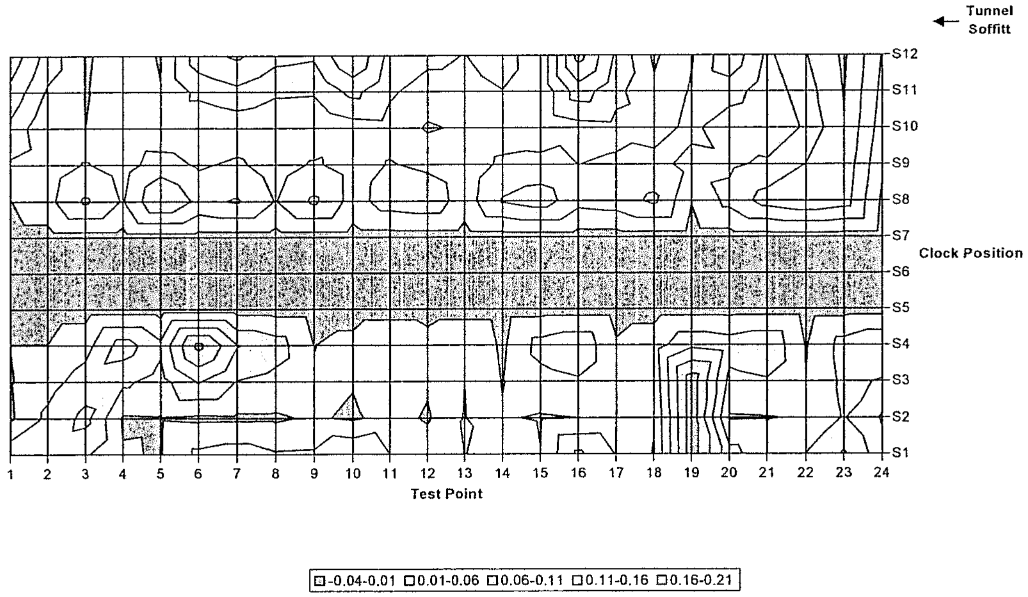


Figure 2. Dynamic Stiffness of Brick-Lined Tunnel

Sewer Tunnels, Chicago, USA

A short section of the crown of a concrete sewer tunnel collapsed approximately 90 m to the north of a manhole access. The sewer had been bypassed, and a period of relatively low water flow in the tunnel, up to 900 mm maximum depth, allowed the Impulse Response testing reported here. The tunnel is horseshoe shaped, approximately 2.1 m x 1.9 m in section. The lining was constructed in the 1920s by compacting concrete inside a wood formwork as the tunnel was advanced. The approximate thickness of the lining is 300 mm, and the tunnel crown is approximately 6 m below the existing road along the tested portion. Manholes in the road above the tunnel gave access to the sewer, with approximately 75 m between each manhole. An Impulse Response test grid was established at 1.5-m intervals along test rows at 1, 2, 3, 4, 8, 9, 10, 11 and 12 o'clock positions around the tunnel lining, over row lengths of 35 m either side of each manhole.

Increases in Mobility above that expected for a given concrete thickness and quality indicated deterioration in the structure. Additionally, defects such as honeycombing and cracking in the concrete were observed. The dynamic stiffness of the concrete around the test point is a function of the lining quality and the support offered to the liner by the soil behind. If voids are present behind the liner, they reduce the stiffness of the test point, as well as producing a high mobility at low frequency.

For 300-mm thick concrete in good condition, the following ranges of parameters are to be expected:

- Average mobility: between 7 and 10 $\times 10^{-7}$ m/N/sec over 200 to 800 Hz
- Dynamic stiffness, E: greater than 0.1 MN/mm.

The majority of test results showed the concrete in the tunnel lining to be sound and integral. Occasional zones of low density concrete were present, particularly in the shoulders of the tunnel. Very few incidents of voiding behind the lining were recorded, and only one delamination of the concrete lining was noted.

Water Supply Tunnel, Buenos Aires Argentina

Nondestructive testing was performed in this tunnel under construction to evaluate the extent of voiding behind the tunnel lining and the structural integrity of the lining (Figure 3). The tunnel is approximately 17 km in length. Pre-cast concrete segmental linings with grout behind the lining were used, and the tunnel has a projected 100-year life. The soil profile for most of the tunnel is hard silt and clayey silt, with the water table located at approximately half tunnel height. During liner installation, it was reported that some grouting problems occurred, leading to voids behind the liner. Both Impulse Radar and Impulse Response testing methods were used to determine the extent of voiding behind the liner. Field investigation was performed in five different sections, with testing at seven locations in each section. Test locations were orientated looking downstream at 12:00, 1:30, 3:00, 4:30, 7:30, 9:00 and 10:30 o'clock.

Impulse Radar testing detected voids ranging from relatively small and localized to large areas where structural integrity could be of concern. Figure 4 is an example of a radar trace showing voiding in the grout behind the liner. Void thickness varied from less than a cm to the full depth of the grout.

The three parameters measured at each Impulse Response test point were the average mobility, the dynamic stiffness and the voids ratio. In the case of a tunnel lining where the hoop stress has not been developed around the ring, individual segment stiffness values are relatively constant around the tunnel circumference, and any loss of support behind the segment is measured as an increase in voids ratio. Poor segment support typically produces voids ratio values greater than 2. On the other hand, if the tunnel segments are behaving as a fully interlocked unit with full hoop stress development, the stiffness reflects the locked-in ring stresses, and varies proportionally around the circumference. In this case, the voids ratio value remains close to unity, and any loss of support behind the lining segment (such as inadequate or no grout) is measured by changing values of the average mobility. This is the case at this site, where the measured values of voids ratio all fell below unity, and the ring stiffness varies around the tunnel circumference.

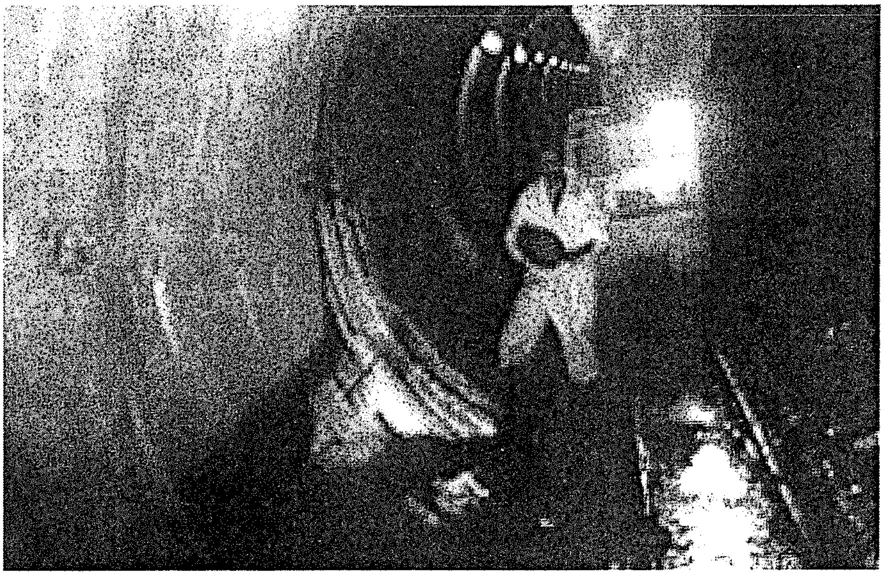


Figure 3. Buenos Aires Tunnel

The average mobility value for reinforced concrete plates 200-mm in thickness with good support conditions usually falls between 16 and 20 (x 10e-7 m/N/sec). Any significant rise in theses measured values is either attributable to thinner concrete section, or to loss of support such as voiding in the grout behind the rings. Where the average mobility is greater than 22, it is probable that voiding is present behind the ring segments. Good agreement was found between the Impulse Response average mobility test results greater than 22 and the location of voiding by Radar.

Figure 4. Radar Data showing Voiding Behind the Liner Extending Through Three Liner Rings.

CONCLUSIONS

The case histories in this article demonstrate that the Impulse Response method is a rapid and effective test method for the evaluation of precast or cast-in-place tunnel linings and their support quality. The method is presently in use for the detection of voiding in the grouted support to precast lining units in metro tunnels under construction in Denmark, and is proving to be very successful. Recent advances in Impulse Radar technology combined with Impulse Response offer a fast and economical solution to evaluating tunnel linings and their support.

REFERENCES

1. American Concrete Institute Report ACI 228.2R-98, "*Nondestructive Test Methods for Evaluation of Concrete in Structures*". ACI, Farmington Hills, Michigan, 62 pp.
2. Davis, A. G. and C.S. Dunn, 1974. "From Theory to Field Experience with the Nondestructive Vibration Testing of Piles," *Proc. Instn Civ. Engnrs,* Part 2, **57**, Dec., 571-593.
3. Davis, A.G., 2003. *"The Nondestructive Impulse Response Test in North America: 1985-2001"*. NDT & E International (Elsevier Science), Vol. 36, 185-193.
4. Lim, M.K., 2001. *"NDE Using Impulse Radar to Evaluate Material Properties in Concrete Structures"*. 9th International Conference on Structural Faults and Repair, Ed. M. C. Forde, London, UK, 9 pp.
5. Sansalone, M. and W.B. Streett, 1997. *"Impact-Echo: Nondestructive Evaluation of Concrete and Masonry"*. Bullbrier Press, Ithaca, NY.