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The nondestructive impulse response test in North America: 1985–2001

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Abstract

The nondestructive impulse response test is commonly used in civil engineering for proving the integrity of concrete bored cast in place piles (drilled shafts). Engineers are less familiar with its extended application to the testing of other reinforced concrete structural elements such as floors, pavement slabs, bridge decks, fluid-retaining tanks and tall structures such as chimneystacks and silos. Since 1985 much of this application development has taken place in North America. This article reviews these developments, and uses case histories to illustrate application of the method to the investigation and evaluation of structures.

Keywords: Impulse response test; Concrete structures; Impact-echo test

1. Introduction

The impulse response (IR) test method is a nondestructive, stress wave test, used in the evaluation of machined metallic components in the aircraft industry. Its application to concrete structures in civil engineering is less well known, and the method has received far less publicity than the newly developed impact-echo test [12]. Both tests are described in the American Concrete Institute Report ACI 228.2R-98, 'Nondestructive Test Methods for Evaluation of Concrete in Structures' [16].

The IR method (also referred to in earlier literature as the *transient dynamic response* or *sonic mobility* method) is a direct descendant of the forced vibration method developed in France in the 1960s for evaluating the integrity of concrete cast in place bored piles (commonly known as *drilled shafts* in North America) [1,2]. Paquet at the French Building Research Center (CEBTP) [4] applied for and obtained a patent in 1974 covering the application of the fast Fourier transform (FFT) algorithm to the vibration pile integrity test. He envisaged a short-duration impact force to the pile head such as a hammer blow (white noise), collecting the response to that impact with a velocity transducer as in swept frequency testing, and then converting the force and velocity time domain responses to the frequency domain. No digital processors were available for this at the time of his patent; however, the first CEBTP 'shock' apparatus (méthode impulsionelle) was used on construction sites in 1977 [5]. All the advantages of forced vibration frequency analysis were maintained and pile preparation was greatly reduced and simplified.

Advances were made in 1985 with the arrival of relatively portable personal computers (PC) with analog to digital (A/D) data acquisition cards, high sampling rates, onboard pre-trigger facilities and vastly increased data storage capacity. This allowed data analysis in the relative calm of the office after testing, with increased confidence in the final result. This breakthrough also influenced the development of the IR method in other fields besides pile testing.

Since that time, the method has been applied to diverse concrete problems in structures such as voiding and loss of support beneath concrete pavements, the integrity of chimney stacks and silos, debonding of bridge deck overlays, delamination caused by reinforcing steel corrosion, integrity of fluid-retaining tanks and radioactive storage units, and the consolidation of mass concrete. A dichotomy has appeared in the method's use between North America and the rest of the world. While quality control testing of new piles has remained the major application in Europe and Asia, very little IR testing is done on new piles in North America, principally as a result of the FHWA study on bored pile integrity testing published in 1993 [8]. That report concluded that the cross-hole sonic logging method [3] with pre-placed tubes in the pile shaft is the surest quality control test method for bored piles, since the loss of the IR signal from the shaft base in deep piles is detrimental to full test analysis.

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On the other hand, plate-like structure testing (pavements, bridge decks and walls) has expanded in North America, while remaining relatively unknown in the rest of the world. To illustrate this, equipment development as a result of market pressures in Europe has concentrated on portable units for pile testing with built-in features for pile response simulation, whereas equipment development in North America has focused on rapid testing for the storage of data from grid test points over large areas such as bridge decks and industrial floor slabs, with immediate display of IR parameter contour maps for each tested area. Most of the articles on IR testing published in the USA in the last decade deal with the method's application to structural integrity testing, rather than to piling.

The basic theory of dynamic mobility developed up to 1985 has not changed; however, its range of applications to different structural elements has increased to incorporate the following problems:

- Voiding caused by slab curling and pumping beneath concrete highway pavements, dam spillways and floor slabs [6].
- Delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimney stacks and silos [9].
- Low density concrete (honeycombing) and cracking in concrete elements [9,11,15].
- Depth of alkali silica reaction (ASR) attack in bored pile pylon foundations [14].
- Debonding of asphalt and concrete overlays to concrete substrates [10].
- Stress transfer through load transfer systems across joints in concrete slabs [7].

This article outlines the application of the impulse response method in North America to a wider range of concrete structural issues than bored pile testing.

2. Test method description

The IR method uses a low-strain impact to send 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 (Fig. 1).

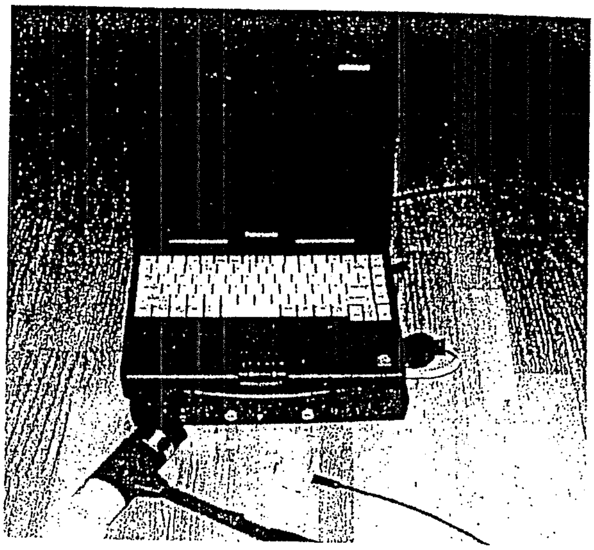

Fig. 1. Example of modern IR test equipment.

When used for pile testing, a low-strain impact on the pile head generates an axial bar wave (compression stress wave), and the velocity transducer coupled to the pile head registers the pile response. The theoretical interpretation of this application is well established [2,13] and parameters such as pile length and pile dynamic stiffness are measured. Fig. 2 shows a theoretical test mobility response for a bored pile [2].

2.1. Structural element testing

When testing plate-like structures, the impact-echo method [12] 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). The IR test impact generates a compressive stress approximately 100 times that of the I-E test. This greater stress input means that the plate responds to the IR hammer impact in a bending mode over a much lower frequency range (0–1 kHz for plate structures), as opposed to the reflective mode of the I-E test.

Both the time records for the hammer force and the geophone velocity response are processed in the field computer using the 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:

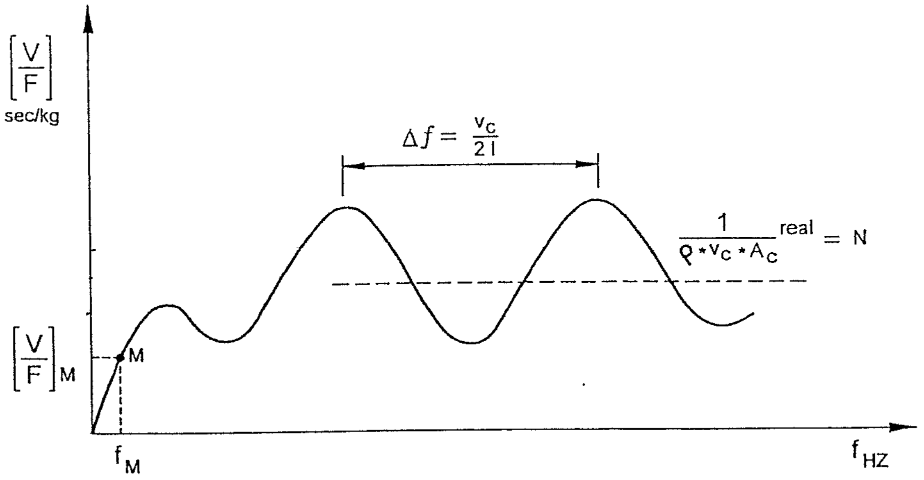

Fig. 2. Theoretical IR mobility response spectrum from pile testing.

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 to 800 Hz. The ratio of this peak to mean mobility is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

Figs. 3 and 4 show typical test responses from slab structures, illustrating responses from sound concrete and poor concrete consolidation.

3. Development in North America, 1985–2001

The first attempt to use IR testing for concrete slabs was in 1981 for the new Djakarta, Indonesia airport runway, when concrete consolidation problems appeared during

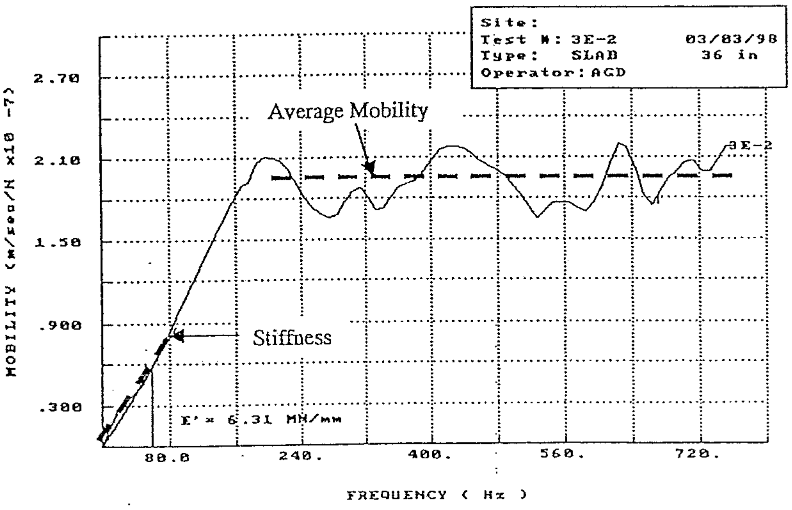

Fig. 3. Typical mobility plot for sound concrete.

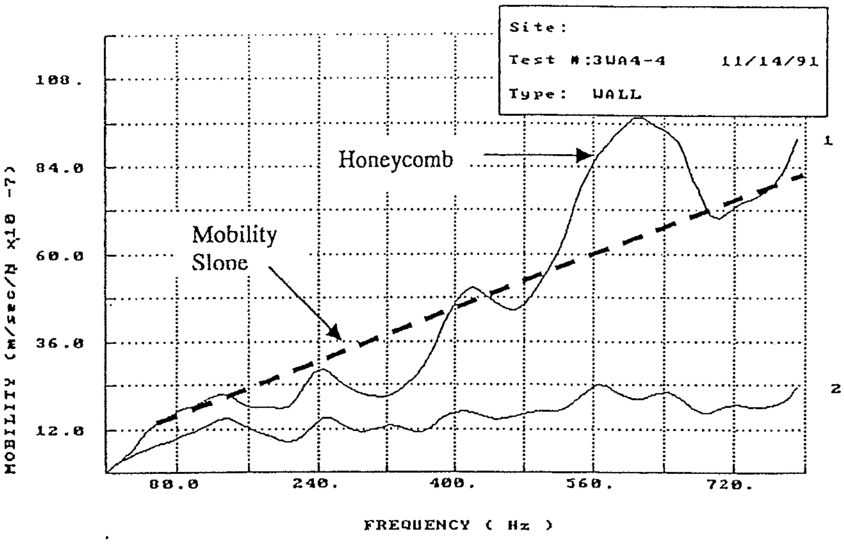

Fig. 4. Mobility plots for sound and honeycomb concrete.

construction. CEBTP built a trial slab at their Paris headquarters with void inclusions and consolidation defects, and an IR test grid on the trial slab showed that defects could be detected in this way. Testing in 1985 on Interstate Highway 40 in Arkansas and US Hwy 69 in Oklahoma extended the method possibilities to the detection of voiding and poor support in the sub-base materials below pavement slabs [6]. During this testing, it was established that the radius of influence of the 1 kg hammer blow was typically of the order of 600 mm around the point of impact. The geophone was not sensitive to the hammer impact beyond this distance.

After 1985, development of the IR method in North America concentrated on rapid acquisition and storage of data from testing large concrete surfaces, with computer extraction of the IR stiffness and mobility parameters for each test result. Contour plots of variations in these parameters were shown to be useful for the condition

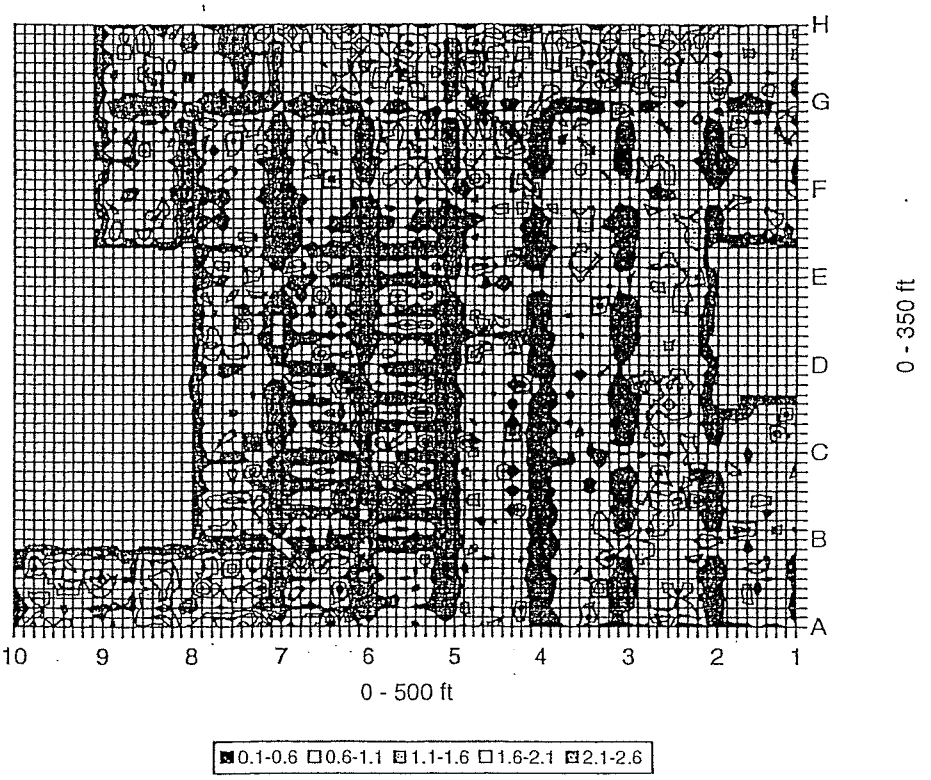

Fig. 5. Stiffness contour plot for large warehouse floor.

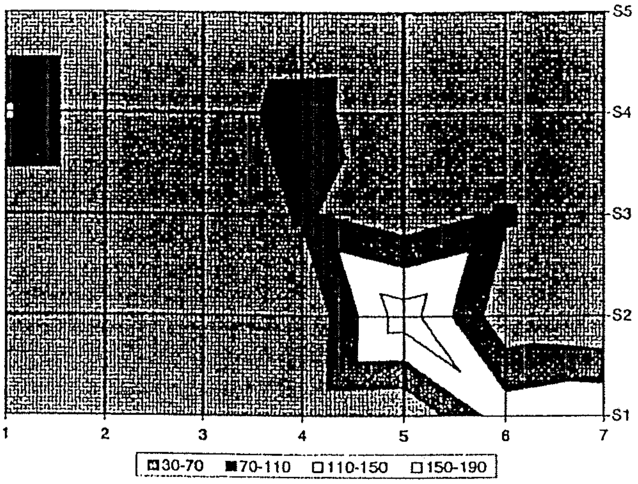

Fig. 6. IR data contour plot for cooling tower wall.

evaluation of these large areas, enabling rapid selection of zones with anomalous behavior for more detailed examination by other destructive or nondestructive test methods. Test points can be set out on a grid pattern, with test grid spacing usually between 300 and 900 mm, depending on the detail required for analysis of the tested structure. An example of such a dynamic stiffness contour plot for a large industrial floor slab is shown in Fig. 5. Low stiffness values are concentrated in the vicinity of construction joints.

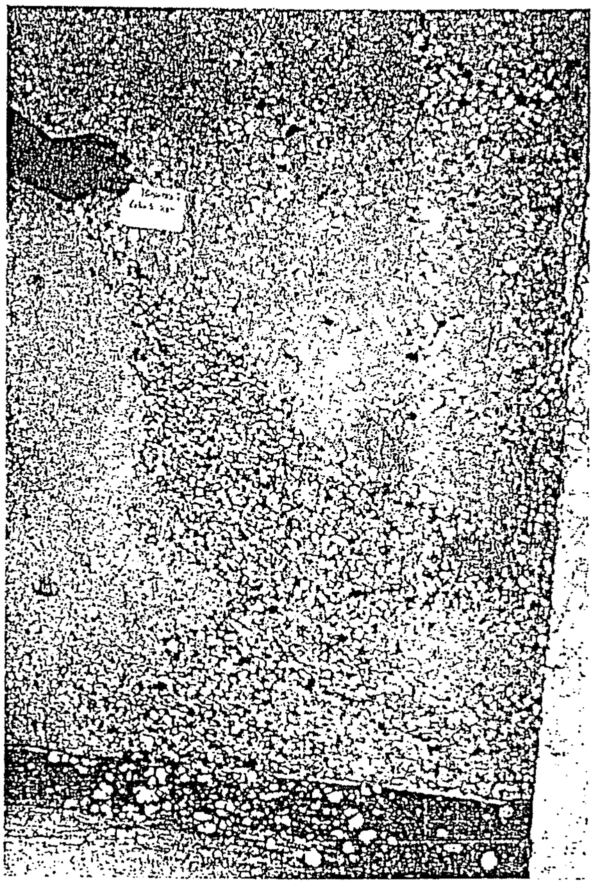

Fig. 7. Exposed cooling tower wall after IR testing.

The following case histories illustrate several different possible applications for the IR test method in the evaluation of concrete structures.

3.1. Mechanical Cooling Tower, Chicago

A mechanical-draft cooling tower with four cells included 300 mm thick reinforced concrete walls 15 m high. The walls were lined with 2 mm thick plastic coating to prevent excessive water loss through the concrete. After 2 years in service, blisters were observed on the walls, and when pierced, showed zones of saturated, poorly consolidated concrete. IR testing of the concrete through the lining mapped out zones of honeycombed concrete (Fig. 6), and gave an accurate estimate of repair quantities. All zones with poor concrete consolidation located by IR were confirmed during the repair program when the old liner was removed. Fig. 7 is an example of the good match between a disclosed poorly consolidated area and the IR mapping of the same area prior to exposure. The speed of testing and analysis meant that no facility downtime was necessary, resulting in great savings for the owner.

3.2. Bridge Arches, Rhode Island

This bridge consists of two approach spans and five arched spans. Each arched span includes a north and south arch. The arches are cast-in-place reinforced concrete structures built between 1934 and 1936. Center-span arches are 18 m high and span 48 m across the river below. The bridge deck was

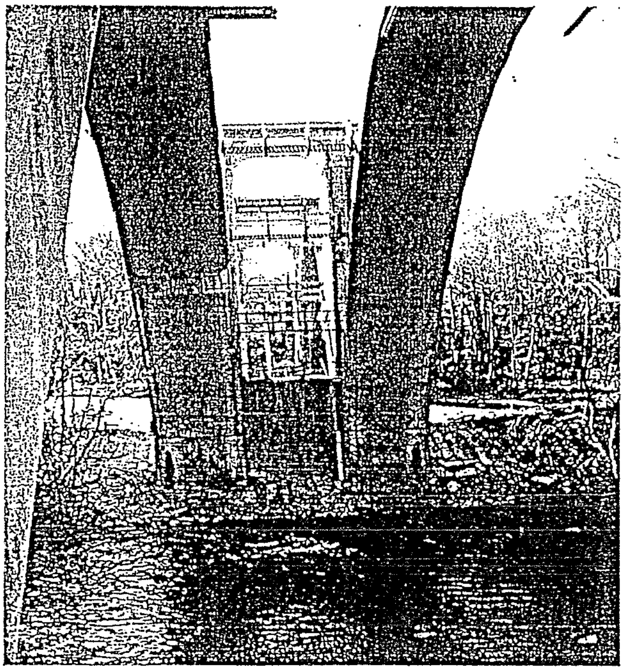

Fig. 8. Center-Span Arches, Rhode Island.

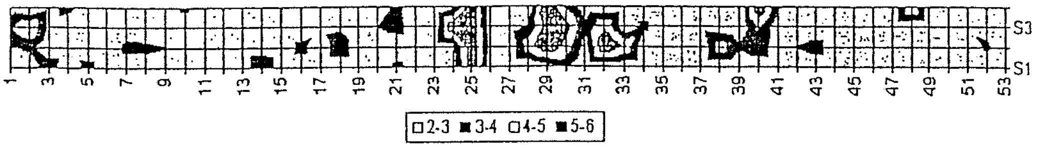

Fig. 9. Mobility slope contours for Bridge Arch, Rhode Island.

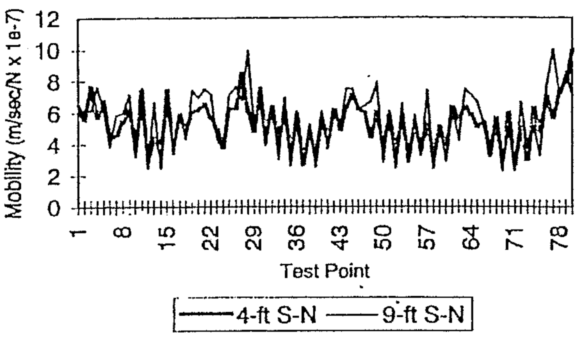

Fig. 10. Mobility plots, Bridge Deck, Washington State.

considered to be too deteriorated to be saved, and was removed for reconstruction (Fig. 8). Areas of low quality concrete were detected in the center-span arches during deck demolition. Coring in several locations indicated that the low quality or damaged concrete areas were not all readily visible. Selected areas of the arch had been removed for patching, and some of the removed areas had been filled while others remained open. The IR test was the primary test method used in this survey. After preliminary analysis of the IR data, areas of the arch were selected for impact-echo (I-E) testing to confirm IR results as well as to locate the depth and extent of anomalous areas. The arches were marked with a 1 m square grid for testing purposes on the top surfaces.

The location of possible poorly consolidated or low quality concrete at this site included a review of both the average mobility and the mobility slope values for each test point. Test areas showing high mobility slope were further analyzed using the I-E test method to determine the depth and extent of problem areas. Several areas were then selected for coring using the correlation established between the IR and I-E methods. Both arches exhibited high values of mobility slope in limited zones in the center section as well as in some areas close to the deck support columns and keyways, as shown in Fig. 9. The consistency of average mobility and mobility slope plots indicated that the problems within the arch were restricted to very limited areas of poor consolidation. The presence of severe cracking or delamination would have shown up as discrepancies in the above mentioned plots. Delamination and/or cracking would be indicated by sharp rises in the IR peak/mean mobility ratio, which were not present.

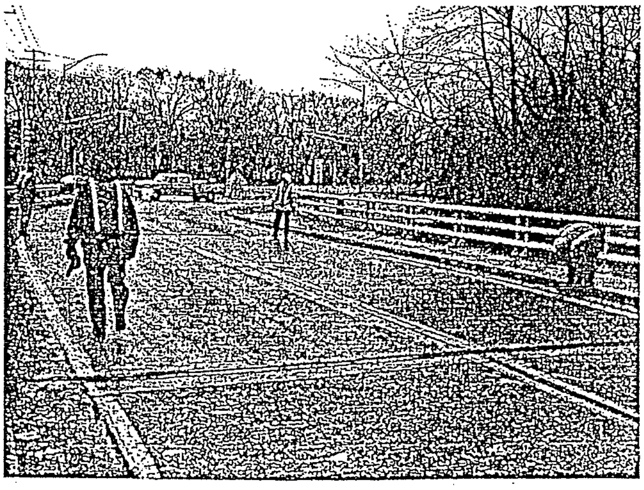

Fig. 11. Pre-stressed Box Beam Bridge, Chicago.

Fig. 12. Underside of bridge in Fig. 11.

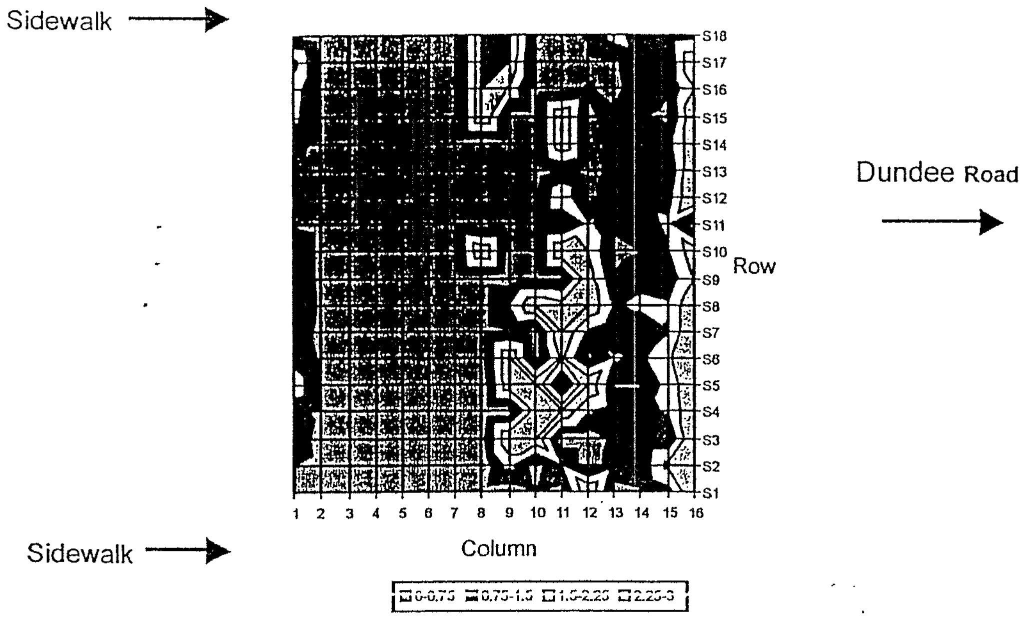

Fig. 13. Stiffness contour plot for bridge in Fig. 11.

3.3. Bridge Deck, Washington State

This 120 m long reinforced concrete bridge deck with a 25 mm thick asphalt overlay appeared to be in good condition. The deck had been cast integrally with transverse beams spaced at 3 m across the four main arch spans, and has three transverse expansion joints at approximately 9, 60 and 111 m from the south end of the deck. Two sets of steel tram rails were still present in the deck, in the center lanes in both directions. IR tests were made to evaluate the integrity of the concrete below the asphalt. The great advantage of IR testing in this case is that it is possible to test through asphalt overlays of limited thickness (up to 50 mm) when ambient temperatures are low enough to preserve relatively high asphalt stiffness. Two test rows were selected at 1.2 and 2.75 m from the east curb, with test intervals every 1.5 m along the deck.

No concrete delamination was located in the deck, with all peak/mean mobility ratios below the critical value. The 'saw-tooth' plot of average mobility in Fig. 10 reflects the spacing of the integrally cast transverse beams at 3 m. When the test point was above or very close to a transverse beam, the IR mobility was between 50 and 70% of that for a test point between the two beams. One test point alone gave a high mobility slope value, indicating probable deterioration in the concrete in the immediate vicinity, subsequently proved by coring.

3.4. Pre-Stressed Box Beam Bridge, Chicago

A common form of pre-stressed beam bridge structure on USA highways relies on cross-rods and grouted keyways between the beams to form a single span bridge (Fig. 11). Each hollow core beam is usually between 20 and 30 m long and 900 mm wide (Fig. 12). IR testing was performed on one of these bridges through a 100 mm thick concrete overlay, with much greater mobility and lower stiffness on one half of the bridge (Fig. 13). In the half of the bridge with higher stiffness the transverse rod system is functioning as designed. However, in the other half of the bridge the opposite is true; either the transverse rod system was not properly installed or not present. It was reported that during recent renovation of the bridge, the repair crew had problems with one of the rods. IR testing showed the ability of the method to detect changes within the bridge, such as a loss in functionality of the transverse rod system. This loss can be detrimental to the bridge load carrying capacity. The speed of IR testing makes it a valuable tool for testing bridges of this type.

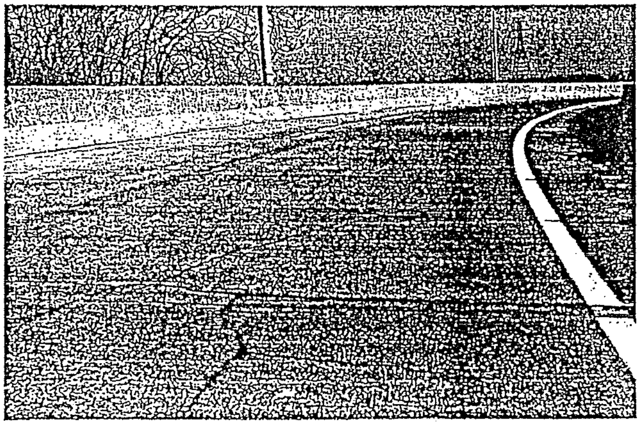

Fig. 14. Bridge Ramp Overlay, Illinois.

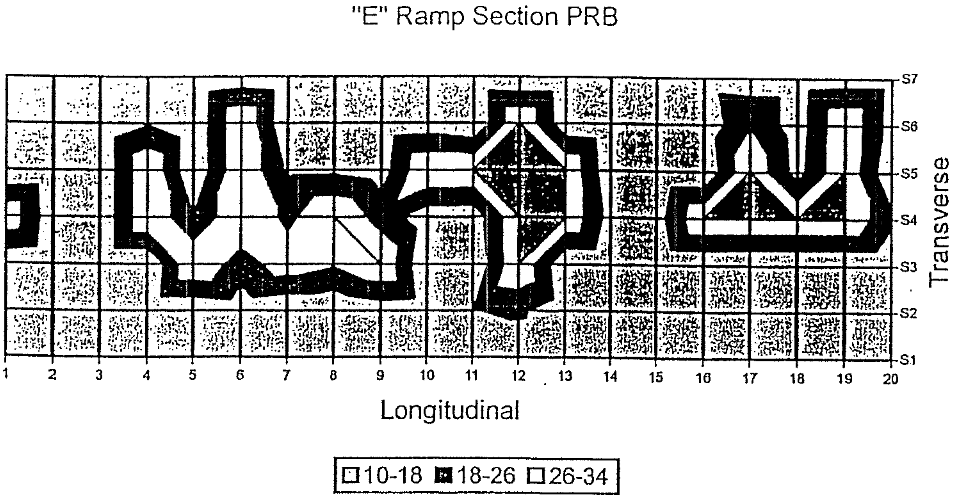

Fig. 15. Mobility plot for Bridge Ramp Overlay in Fig. 14.

3.5. *Concrete Overlay on Freeway Entrance Ramp, Illinois*

An existing reinforced concrete approach ramp to a freeway was overlain with a 75 mm thick silica fume unreinforced concrete. Surface cracking appeared six months after construction, with debonding of the overlay becoming apparent at certain locations on the slab (Fig. 14). IR testing was employed to determine the exact extent of the debonding over the whole 300 m long deck by using the mobility contour plot (Fig. 15). Testing was completed in 3 h, minimizing traffic closure. An estimate was made of those areas of the ramp with incipient debonding problems by analyzing the IR stiffness and mobility slope contour plots. This helped in selecting the repair solution and the quantity of deck overlay to be replaced.

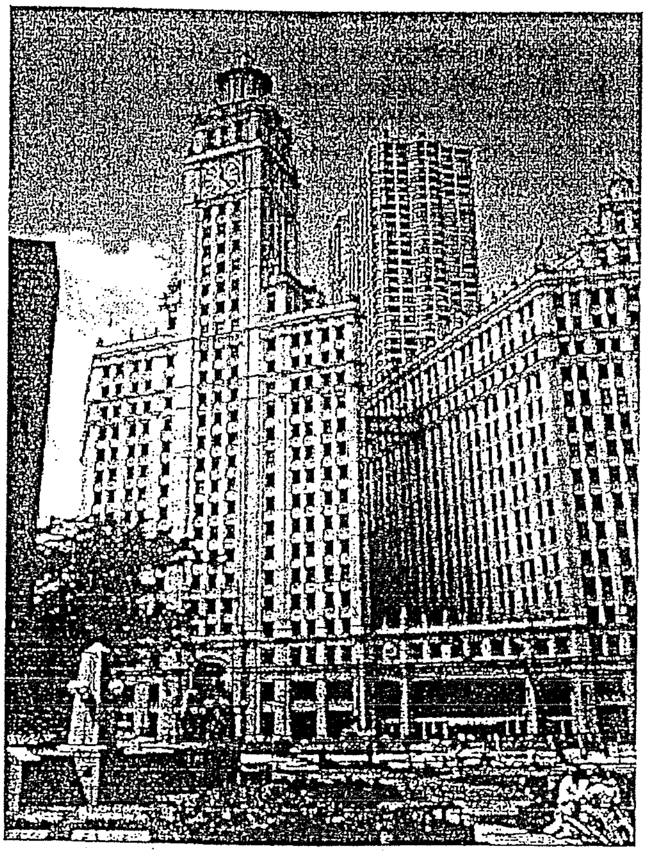

Fig. 16. Wrigley building, Chicago.

3.6. *Terra Cotta Façade, Chicago*

Vertical cracking distress was observed in terra cotta clad steel column covers and mullions on the Wrigley Building, Chicago (Fig. 16), constructed in 1926. IR tests were conducted from the fourth to the 13th floor. The tested columns and mullions were representative of similar elements around the entire perimeter of the building where the problem of vertical splitting or cracking of the terra cotta cladding was confirmed. IR detected features such as debonding of units from their supporting masonry, and nonvisible internal delamination or splitting within the terra cotta. The stiffness recorded for each terra cotta unit was plotted versus the position or height of the unit from the fourth floor upward (Fig. 17). For the column cover, the residual stiffness measurements indicated very strong concentrations of high compressive stress directly above and below the position of the steel shelf angles supporting the terra cotta at each floor line.

4. Conclusions

While best known for its application to the integrity testing of piles, this article illustrates that the nondestructive impulse response test method can play an important role in the evaluation of other reinforced concrete structures such as floor slabs, pavements, bridge decks and piers, fluid-retaining structures, chimneystacks and silos. With modern