Title: **Nondestructive Evaluation of Prestressed Concrete Bridges using Impulse Response.**

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Abstract

The Impulse Response nondestructive stress wave test method is presented for the evaluation of concrete conditions in pre-stressed and post-tensioned bridge units, such as pre-stressed hollow core beam bridge decks and post-tensioned box girders.

The first case refers to pre-stressed concrete hollow core beam bridges decks, which are frequent on state highways in the USA. These bridges span between 15 and 35 m normally, with beam widths of 900 to 1200 mm. The beams are assembled with longitudinal grouted keyways and transverse cross bolts at 1/3 and 2/3 distance along the beams. Bridge deck performance can deteriorate over time because of loss of interaction at the grouted keyways, as well as corrosion of pre-stressing wires and cross bolts. The authors carried out a preliminary nondestructive testing survey on a 3-beam deck from an existing bridge, re-assembled in the University of Illinois Structural Laboratory. This study confirmed that the s'MASH Impulse Response NDT method could detect deterioration in the bridge system, and further tests were then performed in the field on an 11-beam bridge deck in the Chicago area. The test approach used and the results of the testing are discussed in this article.

The second application concerns the evaluation of concrete quality in internally post-tensioned box girders, either cast in place or pre-cast. In the case history presented here, s'MASH Impulse Response testing located deficiencies in the girder concrete such as poor compaction and delamination, as well as loss of post-tensioning caused by patching of partial exposures after post-tensioning and formwork stripping.

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 recently developed Impact-Echo test [8]. Both tests are described in the American Concrete Institute Report ACI 228.2R-98, "*Nondestructive Test Methods for Evaluation of Concrete in Structures*" [11].

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 [1, 2].

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, on-board 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 [12].

Since 1985 the method has been applied to diverse concrete problems in structures such as voiding and loss of support beneath concrete pavements, the integrity of chimneystacks 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.

The basic theory of dynamic mobility developed before 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 [3]
Delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimneystacks and silos [5]
Low density concrete (honeycombing) and cracking in concrete elements [5, 7, 10]
Depth of Alkali Silica Reaction (ASR) attack in bored pile pylon foundations [9]
Debonding of asphalt and concrete overlays to concrete substrates [6]
Stress transfer through load transfer systems across joints in concrete slabs [4].
This article describes the application of the Impulse Response method to the evaluation of concrete conditions in pre-stressed and post-tensioned bridge units.

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 (Figure 1).

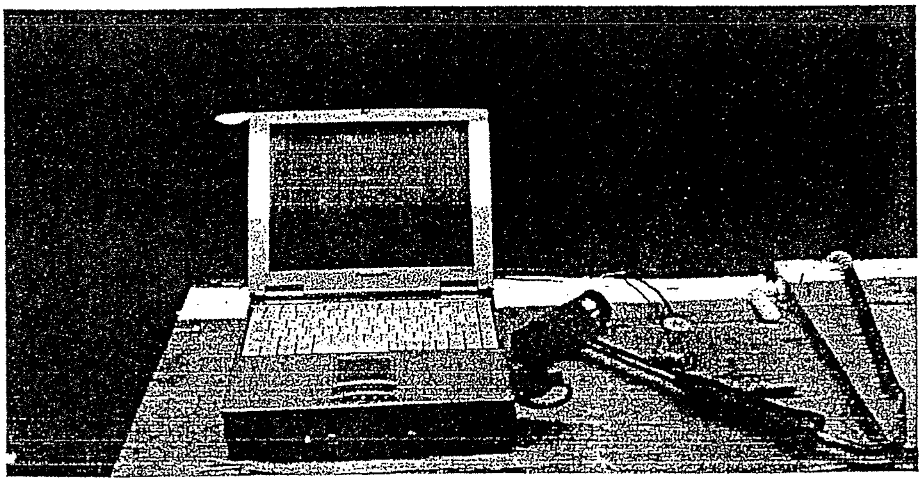

Figure 1.

When testing plate-like structures, the Impact-Echo method [8] 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 very 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 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 is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

Figure 2 shows typical test responses from structures with sound concrete and poor concrete consolidation. Recent development of the IR method has 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 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. Examples of dynamic stiffness contour plots for concrete bridge elements are given in Figures 3 and 4.

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interaction at the grouted keyways, as well as corrosion of pre-stressing wires and cross bolts.

The first case refers to IR tests on a full-scale laboratory mock-up. An existing three-beam structure owned by Illinois Department of Transportation (IDOT), was demolished and re-assembled with newly grouted key-ways and new cross bolts to form a complete single span bridge structure in the Structures Laboratory at the University of Illinois, Urbana-Champaign. Each beam was approximately 15 m long and 900 mm wide, with two layers of pre-stressing wires in the base, with concrete cover of 7 mm and 13 mm respectively. The hollow core comprises two circular sections. Each section is 280 mm in diameter and its base at 125 mm above the bottom of the beam. There were evident cracks, spalls and holes on the concrete at certain locations.

A preliminary IR test series in 1999 produced the stiffness contour plot in Figure 3. This figure shows a symmetrical concentration of high stiffness at the center, as well as at the supports at each end. The mock-up was then subjected to cyclical full service flex load + impact tests on the beams, at first with the transverse rods bolted and then with the rods released. Both outside girders were loaded, with no load on the central beam. The northern longitudinal joint showed definite signs of cracking, and the southern (stronger) joint appeared to be in much better condition. Figure 4 presents the IR stiffness contour plot at the end of these tests in 2002. A marked reduction in stiffness after flex testing in the bridge center is evident, with degradation in the integral performance of the three beams.

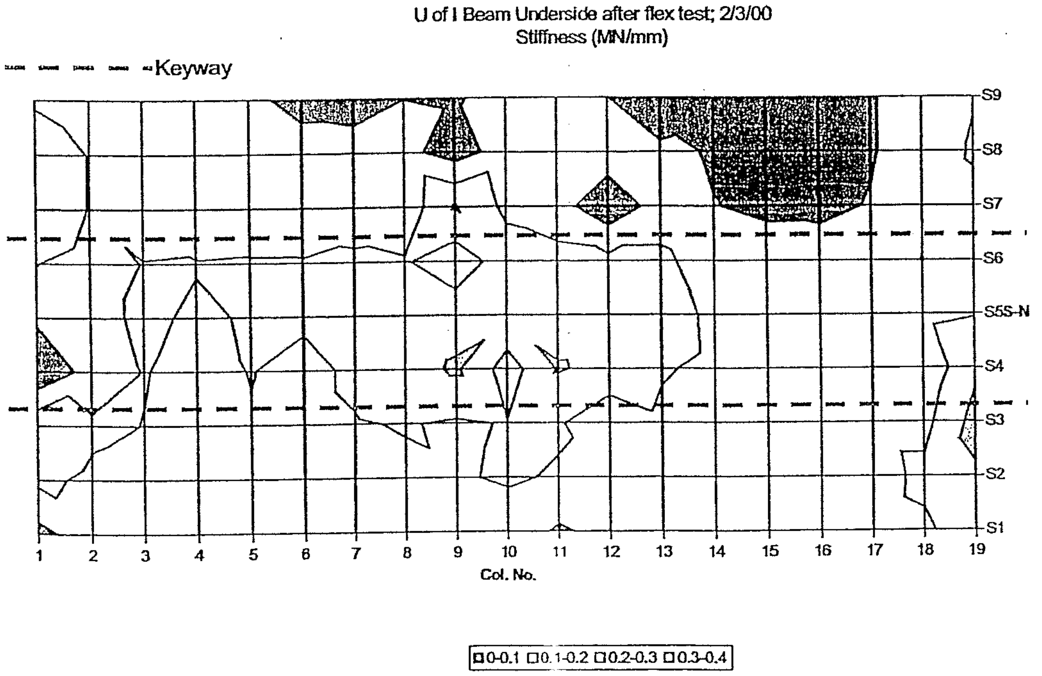


Figure 4. Stiffness After Flex Test

was followed with testing on an in-service 11-beam bridge deck in Illinois. The long, two-lane bridge deck was tested through a 40 mm concrete overlay, using d 900 mm longitudinally by 450 mm transversely (third points on each beam).

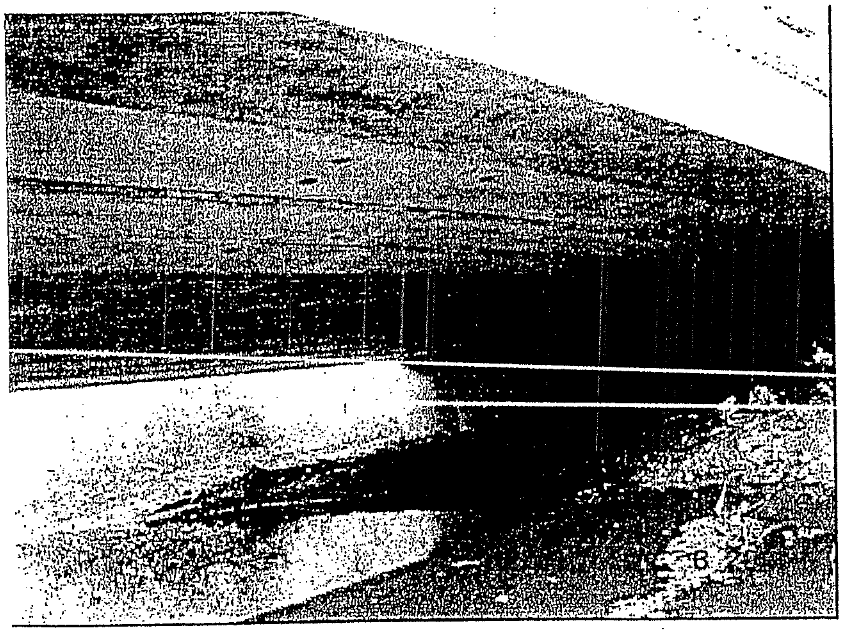


Figure 5. Underside View of Hollow Core Bridge Deck, Illinois

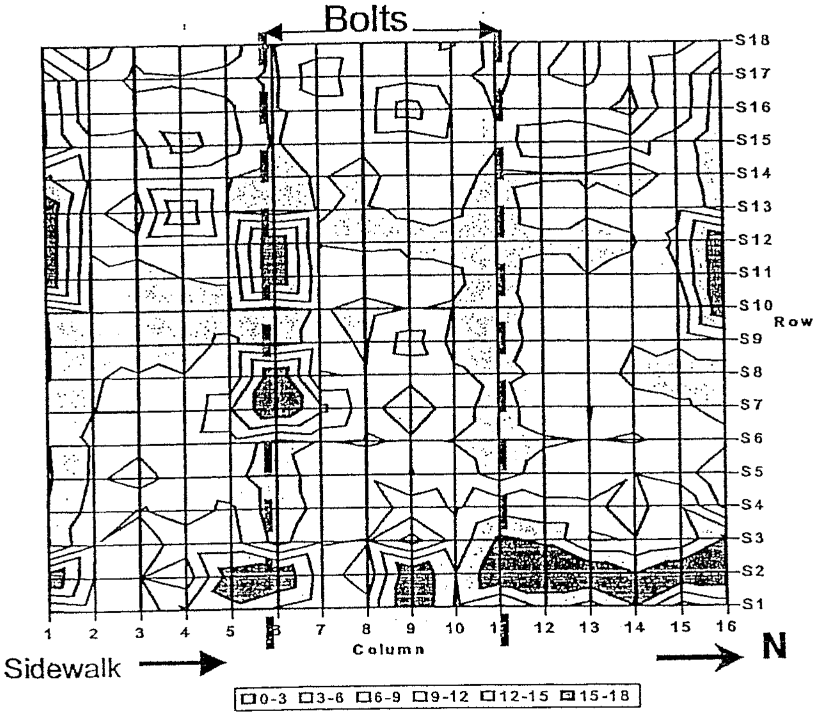


Figure 6. Average Mobility, Hollow Core Bridge Deck, Illinois

Figure 5 is the underside view of the deck, showing the keyed beams. Figure 6 is the contour plot of average mobility for the deck, with very high mobility along the southern transverse bolt, as opposed to relatively low mobility along the northern bolt line. This indicates that the transverse bolt system is functioning as designed in the northern bridge sector. However in the southern half of the bridge the opposite is true; either the bolt system was not properly installed or not present. It was reported that during a recent renovation of the bridge, the crew had problems installing one of the transverse bolts. The IR tests show this problem to be in the southern half of the bridge. Figure 6 also shows very high mobility values along the length of the easternmost beam, indicating deterioration of the pre-stress in this beam. Inspection showed that the beam in question showed signs of concrete spalling next to the adjacent beam.

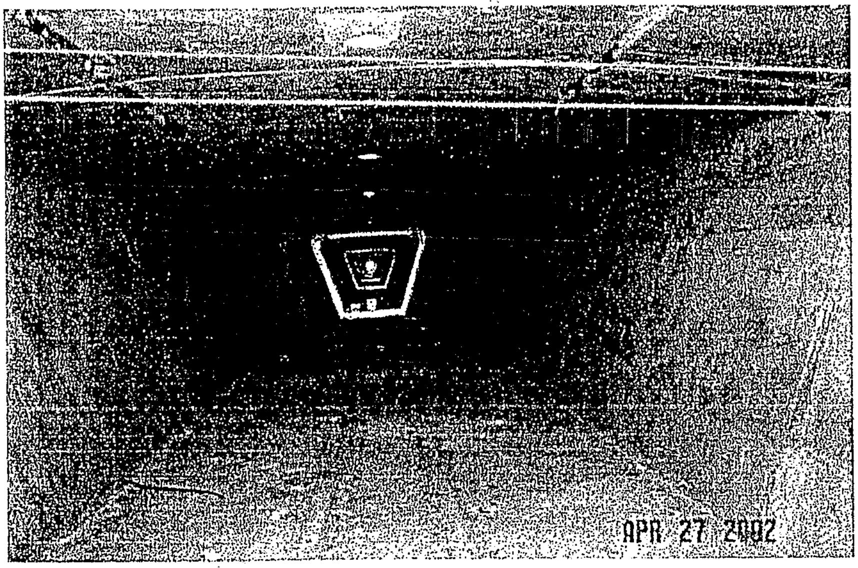
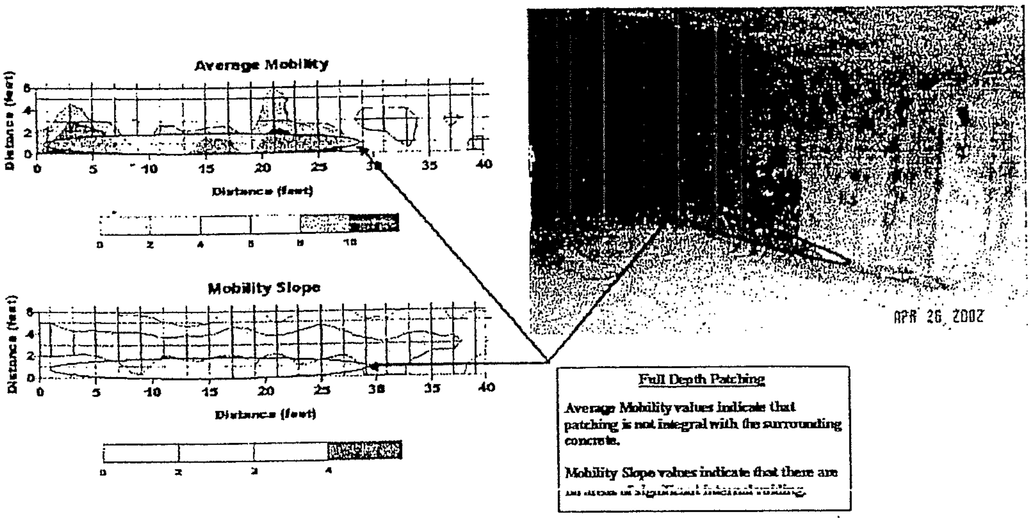


Figure 7.

Post-Tensioned Box Girders

Concrete placement deficiencies were identified in recently constructed post-tensioned concrete box girders (Figure 7), including areas of poorly consolidated concrete, cold joints and questionable concrete patch repairs. Congested steel reinforcement at girder end diaphragms and large diameter post-tensioning ducts in the girder webs complicate concrete placement. The efficiency of earlier patch repairs on the as-placed concrete was evaluated using the Impulse Response test method.

The high average mobility values in the shaded area in Figure 8 show that the patch is not integral with the surrounding concrete. However, the low mobility slope values for the shaded area indicate that there are no areas of significant voiding behind the patch. The area tested in Figure 9 revealed a zone with high mobility slope values. A finer test grid was established around this zone, and the suspect area was sized. Honeycomb concrete was discovered upon opening at this point.

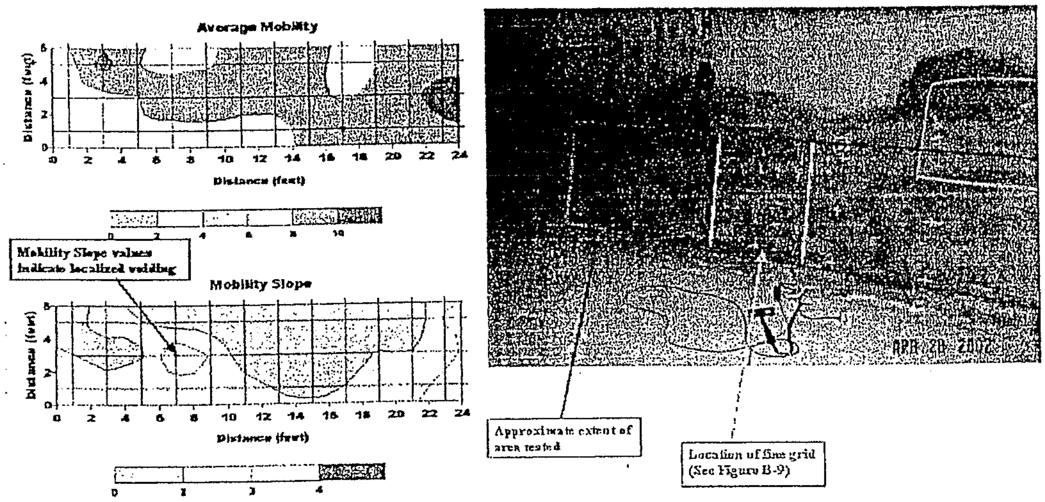


Full Depth Patching

Average Mobility values indicate that patching is not integral with the surrounding concrete.

Mobility Slope values indicate that there are an areas of significant internal voiding.

Figure 8.



Mobility Slope values indicate localized voiding

Approximate extent of area tested

Location of fine grid (See Figure B-9)

Figure 9.

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 pre-stressed bridge decks and post-tensioned box girders. With modern computer data storage and analysis facilities, the Impulse Response test can play a major role in rapid evaluation of large structures during testing on site, allowing immediate identification of problematic zones within the structure for subsequent, more detailed investigation. This results in considerable economic benefit and increased confidence for both engineers and owners.

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