

Presentation: ACI Open Paper Session, Tuesday, October 27, 1998

ACI Convention, Los Angeles, California

Title: Locating Concrete Consolidation Problems using the Nondestructive Impulse Response Test.

Authors: Bernard H. Hertlein, Associate, STS Consultants, Ltd., and
Allen G. Davis, Principal Engineer, Construction Technology Laboratories, Inc.

Addresses: STS Consultants, Ltd., 750 Corporate Woods Parkway, Vernon Hills, IL 60061;
hertlein@stsltd.com, tel. (847) 279-2500 fax (847) 279-2510.
Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, IL
60077, adavis@c-t-l.com, tel. (847) 965-7500, fax (847) 965-6541.

Abstract:

The Impulse Response method is a nondestructive field test, which measures the response of concrete structural elements to impact-generated, low frequency stress-waves. This test is most commonly used for the evaluation of the integrity of drilled shafts, the investigation of concrete pavement and floor slab support conditions, and for the location of delaminations in reinforced concrete structures. This presentation will describe the application of the Impulse Response test to the location of areas of poor consolidation of hardened concrete in structures such as cooling towers, water tanks, silos, airport pavements and bridge piers when consolidation problems are not apparent at the surface. The principle of the method will be described, and the technical and economic benefits of the test will be demonstrated by case histories drawn from five different types of structure.

Presentation: ACI Open Paper Session, Tuesday, October 27, 1998

ACI Convention, Los Angeles, California

LOCATING CONCRETE CONSOLIDATION PROBLEMS USING THE NONDESTRUCTIVE IMPULSE RESPONSE TEST

Bernard H. Hertlein, Associate, STS Consultants, Ltd., and
Allen G. Davis, Principal Engineer, Construction Technology Laboratories (CTL), Inc.

1. INTRODUCTION

The Impulse Response method is a nondestructive field test, which measures the response of concrete structural elements to impact-generated, low frequency stress waves. This test is most commonly used for the evaluation of the integrity of drilled shafts, the investigation of concrete pavement and floor slab support conditions, and for the location of delaminations in reinforced concrete structures. Recent studies have extended the application of the method to the location of areas of poor consolidation of hardened concrete in structures such as cooling towers, water tanks, silos, airport pavements and bridge piers when consolidation problems are not apparent at the surface.

2. IMPULSE RESPONSE METHOD

The Impulse Response (IR) test method is used extensively in the evaluation of machined metallic components in the aircraft industry. Its application to concrete structures diagnostics is less well known, and the method has received far less publicity than the more recently developed Impact-Echo method (Sansalone, 1997).

The IR method (also referred to in earlier literature as the Transient Dynamic Response method) is a direct development of the forced vibration method developed in France in the 1960's for the evaluation of the integrity of concrete drilled shafts (Davis and Dunn, 1974). The theory of dynamic mobility developed at that time has been extended to include the following applications:

- voiding beneath concrete slabs in highways, spillways and floors (Pederson and Senkowski, 1986; Davis and Hertlein, 1987; Reddy, 1992),
- delamination of concrete around steel reinforcement in concrete slabs, walls and large structures such as dams, chimney stacks and silos (Davis and Hertlein, 1995),
- low density concrete (honeycombing) and cracking in concrete structural elements (Davis and Hertlein, 1995; Davis *et al*, 1997),

These three test methods are fully described in the ACI Report 228.2R-98¹, and are reviewed in the chapters below.

IMPULSE RESPONSE TEST METHOD

The IR test method is a nondestructive, stress wave test, used extensively 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 (I-E) test².

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 for evaluating the integrity of concrete drilled shafts, developed in France in the 1960's³. The basic theory of dynamic mobility developed at that time has not changed; however, its range of applications to different structural elements has increased to incorporate the following problems:

- Voiding beneath concrete highway, spillway and floor slabs⁴
- Degree of stress transfer through load transfer systems across joints in concrete slabs⁴
- Delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimney stacks and silos⁵
- Low density concrete (honeycombing) and cracking in concrete elements^{5,6}
- Depth of AAR attack in drilled shafts used as pylon foundations⁷
- Debonding of asphalt and concrete overlays to concrete substrates⁸

The IR method uses a low strain impact to send a stress wave 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 stress levels range from 5 MPa for hard rubber tips to more than 50 MPa for aluminum 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.

When testing plate-like structures, the Impact-Echo method 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 10 and 50 kHz). The IR test uses a compressive stress impact approximately 100 times stronger than 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

- *Damping*: The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). Any cracking or honeycombing in the concrete under test will reduce damping and hence the stability of mobility over the frequency range of 50 Hz to 1 kHz.
- *Peak/Mean Mobility Ratio*: When debonding or delamination is present within a structural element, or when there is loss of support below a concrete slab on grade, the behavior of the upper layer controls the IR response. In addition to the increase in N , the dynamic stiffness, K_d is greatly reduced, and the peak value of mobility below ~50 Hz (M_p) becomes appreciably higher than the mean mobility, N . An increasing ratio of M_p/N is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

A recent approach to the measurement of the impulse response of concrete slab structures (walls, pavements...) has been developed at the University of Texas at El Paso (Reddy, 1992; Nazarian *et al*, 1993). This method uses the flexibility spectrum from the impulse response, which is the displacement/force transfer function. For this approach, the slab is modeled as a flexible slab on an elastic foundation, and the impact is assumed to be a half sine wave. The parameters that affect the flexibility response are:

- slab thickness, h ,
- slab elastic modulus, E ,
- modulus of the support beneath or behind the slab,
- slab dimensions and shape,
- point of impact on the slab.

This modeling has allowed the separation of the stiffness function from the damping function (phase) obtainable from the IR spectrum, and has been useful in understanding the difference in spectral response between sound and poorly consolidated concrete.

3. IR APPLIED TO STRUCTURES WITH POOR CONCRETE CONSOLIDATION

Preliminary trials were run in France at the French National Building Research Station (CEBTP) in 1981 on concrete slabs built with intentional honeycombing. These trials were intended to assess the potential of the method for the location of zones of poor consolidation in the runway for the newly constructed Djakarta airport, Indonesia. When the mobility of a sound slab was compared with that of concrete with honeycomb inclusions, it was noted that the latter showed increasing mobility with increasing frequency over the frequency range 100-800 Hz, whereas the former maintained a relatively constant average mobility over the same frequency range. Typical test results showing this comparison are given in Figure 1.

At that time, the reason for this shift in the mobility was not understood, and the observation and its extension to studies of real structures were purely empirical. However, as the following case histories will demonstrate, identification of poorly consolidated concrete zones is possible by comparing the mobility plots over the entire structure, and locating those test areas with rising average mobility.

It now appears probable that the rising mobility is directly a function of change in damping of the velocity (geophone) response over this frequency range. Sound concrete offers relatively constant damping, whereas voided concrete damping reduces with increasing frequency. This was suggested in the work by Reddy (1982), and is confirmed by the plots in Figures 1-3, taken from tests on a reinforced concrete water tank wall, 300 mm thick. Figure 1 shows the constant mobility for a sound test point compared with that of a point with poor consolidation within the wall, with rising mobility. Figure 2 reproduces the mobility spectrum for the sound concrete, with the phase (imaginary) spectrum for the same test overlaid on the plot. This shows a relatively constant phase angle over the total spectrum, i.e. constant damping. Figure 3 shows the mobility spectrum for the test point with poorly consolidated concrete, together with its phase spectrum. Here it can be seen that the phase stability changes rapidly above 400 Hz, indicating a large reduction in damping at this point. It has also been observed that the slope of the mobility plot between 100-800 Hz increases with reducing concrete density. This is to be expected, since the damping of the signal will reduce even more for poorer consolidation.

The following case histories have been selected to illustrate this application.

3.1 MECHANICAL DRAUGHT COOLING TOWERS, ILLINOIS

A block of cooling towers including four downdraught chambers and a central spillway were constructed in reinforced concrete with the exterior walls faced in brick masonry. Each rectangular chamber is 15 m x 18 m x 15 m high (50 ft x 60 ft x 50 ft high), and the reinforced concrete walls are 0.3 m (1 ft) thick. The chamber interior walls were coated with a thin vinyl-based waterproofing layer, to prevent water permeation into the concrete. The vertical walls were cast in single 15-m (50-ft) lifts, with no construction joints and consequently very difficult concrete vibration conditions. The waterproof coating was not correctly applied and pin-holes quickly appeared, resulting in water ingress to the concrete walls. Large bubbles appeared in the coating after less than two years of service. When one of these sacs was pierced, loose concrete aggregate was seen to be present in the bubble. It was decided that a general inspection of the chamber and spillway walls was mandatory. The facility could not be closed down, so two chambers were taken out of service for a maximum of one week at a time. All inspection had to be completed within that time frame, and the inspection technique had to work without removing the existing coating.

IR testing was performed on all interior walls with a 900-mm (3-ft) test point grid. All testing was done with coating in place. Figure 4 shows a normal rest response with a constant mean mobility (test #3wa4-7), and a test result (test #3wa4-4) with a mean mobility increasing in

frequency. The latter result indicates the presence of low density or honeycombed concrete; the greater the mean mobility positive slope, the greater the degree of honeycombing. Areas of low concrete density (high mobility slope) were mapped out, and the coating removed at these points. Figure 5 shows a typical mobility slope map, with high values corresponding to an area of severe honeycombing; pictured in Figure 6. The full testing program required 5 days.

Most of the poor areas were concentrated in the lower third of the walls. This was to be expected, since the concrete was cast in a single 15-m (50-ft) lift, with no vibration possible in the lower region. It was decided to remove the coating entirely, repair the honeycombed areas by removing all poor concrete and patching to either partial or full depth with rapid setting concrete. IR testing was performed on each patch to check the soundness of the bond to the substrate, and a new, thicker coating was placed on the walls.

3.2 INDUSTRIAL PLANT COOLING TOWERS, South Carolina

A similar draught cooling tower system with five cells in a line and a fore bay running the length of the cells was constructed with 250-mm (10-inch) thick reinforced concrete walls. The junction of the vertical walls with the internal floor slab contained a relatively thick L-shaped water stop, together with fairly congested reinforcing steel. After-stripping of the forms, it was observed that large areas of honeycombing were visible on some of the cell walls, particularly near the bottom of the walls.

In order to examine the extent of the poor concrete consolidation, a test grid with points at 900-mm (3-ft) spacing was drawn on the exterior walls, since the cells were in operation and filled with water at that time. A complete coverage of the walls with the IR test was achieved in two days, and the results analyzed on site. Those areas considered to contain significant honeycombing were outlined with spray paint. The cells were drained sequentially, the marked areas were chipped out (usually to full depth) and these areas repaired by shotcrete. Particular care was taken with the areas around the water stops. The speed of the inspection program, as well as reducing the amount of exploratory chipping out of the concrete around potential honeycomb areas, resulted in considerable savings for the contractor and the facility owner.

3.3 INDIANA BRIDGE PIERS

A road bridge was constructed in the 1930's over the Wabash River, with seven reinforced concrete bridge piers. The deck showed severe signs of reinforcement corrosion, and it was decided to replace it. Before investing in this overhaul, a survey of the state of the piers was deemed necessary. Signs of freeze-thaw damage were visible, particularly near the water line, and a nondestructive investigation was commissioned. IR testing was performed on the pier faces on a 300-mm (3-ft) test point grid, including the pier noses. Figure 7 shows a plot of mean mobility slope obtained for one of the pier faces, highlighting those areas with suspected poor concrete consolidation. Subsequent intrusive inspection at these locations confirmed this analysis, even though the poorer concrete was not always visible at the surface.

3.4 GENEVA AIRPORT

A new hard stand area was being constructed at Geneva Airport, in Switzerland, to accommodate the new generation of heavy wide-bodied jets. The pavement design called for concrete to be placed in two lifts, with a total thickness of 600-mm (2-ft). The concrete was placed in a series of adjacent, continuously reinforced lines; each divided into square slabs by crack inducers and/or expansion joints. During construction, the first layer, 400 mm (16 in) thick, was consolidated by a vibrating poker. The second layer, 200 mm (8 in) thick, was consolidated and leveled by vibrating beam.

As each line of slabs was completed and the edge form work removed, a horizontal saw cut was made in the exposed side to allow installation of a load-transfer plate along the joint to the next line of slabs to be placed. In one particular area it was noted that some honeycombing was visible at the edge of the slab, and in other areas the saw cutting progressed much more quickly than normal, indicating concrete with a reduced modulus or reduced density.

Investigation of construction records and interviews with contractor's employees revealed that the vibrating poker had broken down several times during the placement of the lower layer of concrete. The particular line of slabs in question also contained numerous box-outs for later installation of taxiway lighting. The formwork for the box-outs had been such that it was necessary to dismantle the vibrating beam used to consolidate the upper layer of concrete, and lift it past the box outs. The engineers decided that the full extent of the anomalous material must be determined.

The size of the paved area and the apparent randomness of the problem made core-sampling an unattractive proposition due to the large number of cores that would be required. The fact that the poorly consolidated material might be in the lower layer of concrete, overlain by a layer of normal quality material, made it unlikely that Ultrasonic Pulse Velocity (UPV) tests would provide enough useful information. An additional factor was that the work area was immediately adjacent to an active taxiway and aircraft parking area, and all work would have to be performed between normal aircraft movements. The authors therefore suggested Impulse Response testing.

The method was applied manually, on a grid pattern typically 1 m on center. Where anomalous results were recorded, additional tests were performed on a smaller grid pattern to map the approximate boundaries of the affected zone. Core samples were subsequently taken from areas identified as anomalous by the Impulse Response test, and laboratory assessment was made of the concrete at those locations.

In two days of site work, approximately 500 m² of pavement were tested. It would have been prohibitively time-consuming and costly to investigate such an area by core sampling and laboratory testing alone.

3.5 FLY ASH STORAGE SILOS

A major southeastern utility company was constructing a set of four reinforced concrete storage silos to hold fly ash from a large coal fired electricity generating station, using the slip-form method. A coal-fired generating station environment is known to be hostile to both concrete and steel because of the acidic nature of the exhaust gas streams, and the owners wanted to take a proactive approach to monitoring and maintenance of the new silos. A key part of the proposed program was accurate documentation of as-built conditions, and establishment of baseline data in a predictive maintenance database. The authors performed a thorough assessment of the new structures, using a battery of nondestructive tests that included Ultra-sonic Pulse Velocity testing, reinforcing steel location and depth measurement, and Impulse Response testing.

The Impulse Response test was performed on a regular grid spacing over the entire exterior of the silos, where UPV testing was impractical due to lack of access to the inner surface. The Impulse Response tests revealed several areas of low density concrete, typically at the transition from slip-formed wall to the cast-in-place roof slab, or at changes in section where the slip form size was changed. None of the areas were visible at the surface, due either to the slip-form process itself, or to deliberate attempts to camouflage the honeycombed material by "bagging" or rubbing the surface. Therefore visual inspection alone would not have found the anomalous areas.

Given the aggressive environment at the plant, there is little doubt that the poorly consolidated concrete would have deteriorated rapidly, leading to significant maintenance costs much earlier than expected or planned. The Impulse Response test program allowed the anomalous areas to be detected and remedial action to be taken before significant deterioration could occur.

3.6 MUNICIPAL WATER TOWER

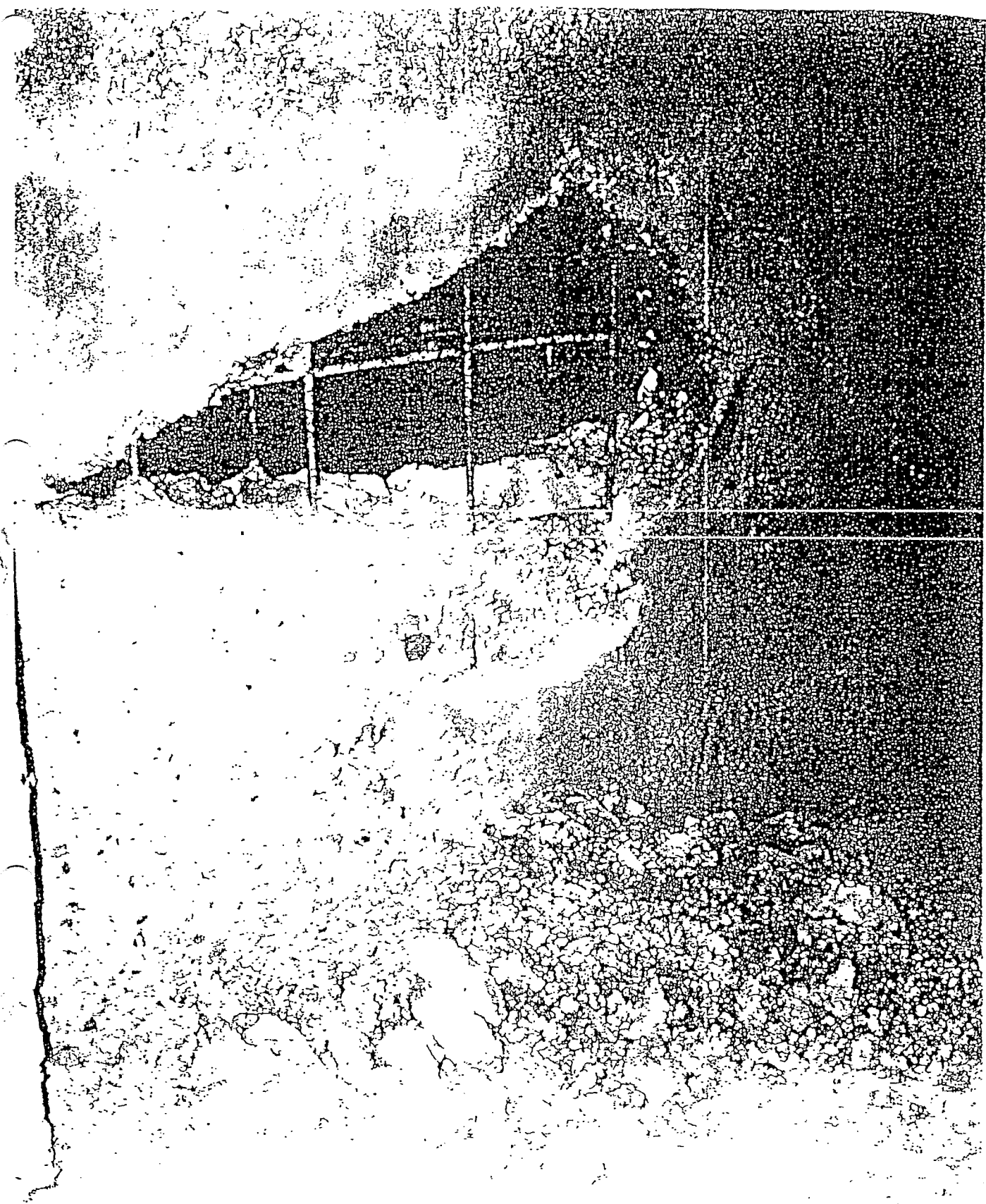
A new water tower was constructed for a city in southern Wisconsin. The tower consisted of a tubular reinforced concrete shaft, or pedestal, with a welded steel tank on top. The top of the slip-formed pedestal was a shallow dome of cast-in-place reinforced concrete. When the formwork for the underside of the dome was removed, voids and pockets of honeycomb concrete were visible. Investigation showed that the visible defects were in the vicinity of planned penetrations, or other areas where extra reinforcing steel created congestion that inhibited the flow of the fresh concrete, such as the peripheral ring beam. The Engineer was concerned that a thin layer of concrete or grout could mask other areas of voided or honeycombed concrete. The authors performed IR testing on the upper surface of the dome at areas selected by the Engineer, based on his knowledge of the reinforcing steel placement. Tests were also performed on areas that were visibly defective on the underside, to verify the interpretation of the test results. The IR tests identified areas of low density that were not visibly apparent on the underside of the dome. Concrete condition at these areas was verified by chipping out the material. The unconsolidated material was found to be so extensive that the contractor elected to completely remove and rebuild the dome portion of the tower.

4. CONCLUSIONS

The IR test has been shown to be useful in the detection and quantification of areas of poorly consolidated concrete in several different structure types. The initial empirical correlation of rising mean mobility on the test plots with poor concrete consolidation now appears to be supported by theoretical modeling, and it is hoped that simulation of structural response in the IR test can be achieved in the near future.

5. REFERENCES

1. Davis, A.G. and Dunn, C.S. (1974), "From Theory to Field Experience with the Nondestructive Vibration Testing of Piles", *Proc. Inst. Civ. Engrs. Part 2*, 59, Dec., 867-875.
2. Davis, A.G. and Hertlein, B.H. (1987), "Nondestructive Testing of Concrete Pavement Slabs and Floors with the Transient Dynamic Response Method", *Proc. Int. Conf. Struct. Faults and Repair*, 2, 429-433, London, England, July 1987.
3. Davis, A.G. and Hertlein, B.H. (1990), "Assessment of Bridge Deck Repairs by a Nondestructive Technique", *Proc. NATO Advanced Research Workshop on Bridge Evaluation, Repair and Rehabilitation*, Baltimore, MD, ed. A. Nowak, NATO ASI Series, 229-234.
4. Davis, A.G. and Hertlein, B.H. (1995), "Nondestructive Testing of Concrete Chimneys and Other Structures", *Conf. Nondestructive Evaluation of Aging Structures and Dams*, SPIE 2457, 129-136, Oakland CA, June 1995.
5. Davis, A.G., Hertlein, B.H., Lim, M.K. and Michols, K.A. (1996), "Impact-Echo and Impulse Response Stress Wave Methods: Advantages and Limitations for the Evaluation of Highway Pavement Concrete Overlays", *Conf. Nondestructive Evaluation of Bridges and Highways*", SPIE 2946, 88-96, Scottsdale AZ, Dec, 1996.
6. Davis, A.G., Evans, J.G. and Hertlein, B.H. (1997), "Nondestructive Evaluation of Concrete Radioactive Waste Tanks", *J. Perf. Of Constr. Fac.*, ASCE, 11(4), 161-167.
7. Davis, A.G. and Kennedy, J. (1998), "Impulse Response Testing to Evaluate the Degree of Alkali-Aggregate Reaction in Concrete Drilled Shaft Foundations under Electricity Transmission Towers", *Conf. Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing*, SPIE 3398, 178-185, San Antonio TX, March-April 1998.
8. Nazarian, S., Baker, M.R. and Crain, K. (1993), "Development and Testing of a Seismic Pavement Analyzer", *Research Report H-375*, Strategic Highway Research Program, National Academy of Sciences, Washington DC, 165 pp.
9. Pederson, C.M. and Senkowski, L.J. (1986), "Slab Stabilization of PCC Pavements, Transportation Research Board Meeting, Washington DC, January 1986.
10. Reddy, S. (1992), "Improved Impulse Response Testing: Theoretical and Practical Validations", M.S. Thesis, Civil Engineering, University of Texas at El Paso, 208 pp.
11. Sansalone, M. (1997), "Impact-Echo: The Complete Story", *ACI Structural Journal*, 94 (6), Nov.-Dec., 777-786.



- *Damping*: The test element's response to the impact-generated elastic wave will be damped by the element's intrinsic rigidity (body damping). Any cracking or honeycombing in the concrete under test will reduce damping and hence the stability of mobility over the frequency range of 50 Hz to 1 kHz.
- *Peak/Mean Mobility Ratio*: When debonding or delamination is present within a structural element, or when there is loss of support below a concrete slab on grade, the behavior of the upper layer controls the IR response. In addition to the increase in N , the dynamic stiffness, K_d is greatly reduced, and the peak value of mobility below ~50 Hz (M_p) becomes appreciably higher than the mean mobility, N . An increasing ratio of M_p/N is an indicator of the presence and degree of either debonding within the element or voiding/loss of support beneath a slab on grade.

A recent approach to the measurement of the impulse response of concrete slab structures (walls, pavements...) has been developed at the University of Texas at El Paso (Reddy, 1992; Nazarian *et al*, 1993). This method uses the flexibility spectrum from the impulse response, which is the displacement/force transfer function. For this approach, the slab is modeled as a flexible slab on an elastic foundation, and the impact is assumed to be a half sine wave. The parameters that affect the flexibility response are:

- slab thickness, h ,
- slab elastic modulus, E ,
- modulus of the support beneath or behind the slab,
- slab dimensions and shape,
- point of impact on the slab.

This modeling has allowed the separation of the stiffness function from the damping function (phase) obtainable from the IR spectrum, and has been useful in understanding the difference in spectral response between sound and poorly consolidated concrete.

3. IR APPLIED TO STRUCTURES WITH POOR CONCRETE CONSOLIDATION

Preliminary trials were run in France at the French National Building Research Station (CEBTP) in 1981 on concrete slabs built with intentional honeycombing. These trials were intended to assess the potential of the method for the location of zones of poor consolidation in the runway for the newly constructed Djakarta airport, Indonesia. When the mobility of a sound slab was compared with that of concrete with honeycomb inclusions, it was noted that the latter showed increasing mobility with increasing frequency over the frequency range 100-800 Hz, whereas the former maintained a relatively constant average mobility over the same frequency range. Typical test results showing this comparison are given in Figure 1.

These three test methods are fully described in the ACI Report 228.2R-98¹, and are reviewed in the chapters below.

IMPULSE RESPONSE TEST METHOD

The IR test method is a nondestructive, stress wave test, used extensively 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 (I-E) test².

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 for evaluating the integrity of concrete drilled shafts, developed in France in the 1960's³. The basic theory of dynamic mobility developed at that time has not changed; however, its range of applications to different structural elements has increased to incorporate the following problems:

- Voiding beneath concrete highway, spillway and floor slabs⁴
- Degree of stress transfer through load transfer systems across joints in concrete slabs⁴
- Delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimney stacks and silos⁵
- Low density concrete (honeycombing) and cracking in concrete elements^{5,6}
- Depth of AAR attack in drilled shafts used as pylon foundations⁷
- Debonding of asphalt and concrete overlays to concrete substrates⁸

The IR method uses a low strain impact to send a stress wave 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 stress levels range from 5 MPa for hard rubber tips to more than 50 MPa for aluminum 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.

When testing plate-like structures, the Impact-Echo method 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 10 and 50 kHz). The IR test uses a compressive stress impact approximately 100 times stronger than 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