Onsite measurements of concrete structures using Impact-echo and Impulse Response

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ABSTRACT: Concrete structures deteriorate, often unnoticed, in worst case the damages are not visible until it is too late for a repair or the repair will be extensive and costly. New structures may have defects from the execution compromising durability and safety. The use of NDT (Non Destructive Testing) can provide valuable information of the condition of a concrete structure and can be a valuable help when planning the maintenance of a structure. NDT can further be used during the construction phase for quality assurance of a structure. Hidden faults can be detected early and can be remedied while access to the structure is still possible without major inconvenience. Special inspections combining a visual survey with NDT techniques can disclose problems at an early state and provides valuable information of the actual condition of the structure. The use of NDT should not be used to evaluate a structure without a thorough calibration of the equipment onsite e.g. by drilling out a limited number of cores.

1 INTRODUCTION

This paper presents some typical testing cases where NDT has been used on bridges and buildings with emphasis on the advantages and limitations of the techniques. The cases shows how flaws and faults on bridges such as poor bonding at interfaces between, asphalt, membranes and concrete on bridge decks or between the original concrete can be discovered as well as the presence of ASR and the extend of ASR. Further quality assurance of injected cable ducts can be conducted.

2 TEST EQUIMENTS

Two test methods has been used on different structures and for different types of faults. The test systems are the Impact-Echo (IE) and the Impulse Response (IR). Both systems are used extensively for quality assurance on new and existing structures by Ramboll Denmark.

2.1 *Impact-Echo (IE)*

The Impact Echo System (IE) used, comprises a mechanical spherical impactor source - normally in the range from 3-12 mm diameter - and a displacement transducer placed approximately 5 cm adjacent to the impact point. The impactor generates a Pressure wave (P-wave), which travels into the media and is being reflected from the back of the column/wall or an internal anomaly as e.g. an air void back to the surface. This P-wave is being reflected several times and the reflected P-waves are being detected by the displacement transducer on the surface. The time-displacement response is being converted to a frequency response using a Fast Fourier Transform (FFT) algorithm.

In Figure 1 a sketch is shown of the setup of the IE system while testing is performed.

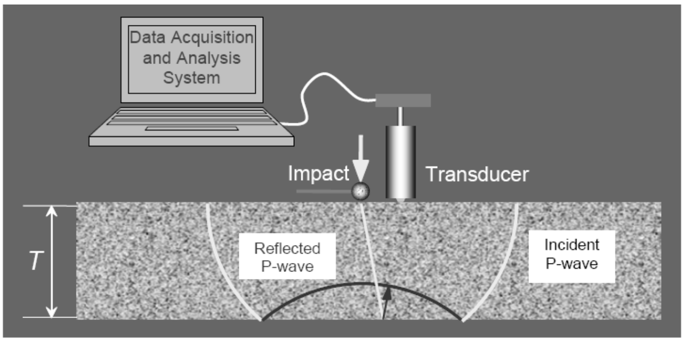


Figure 1. A sketch of the IE system showing the impactor (Steel sphere), displacement transducer and laptop.

The IE systems measures the thickness of the concrete or depth to the defect below the impact-point and the transducer. The time, Δt, taken for the reflected P-wave to reach the transducer is depending on the P-wave velocity, C_p, and the thickness, T, of the concrete is given by equation (1):

$$\Delta t = \frac{2 \cdot T}{C_P} \quad (1)$$

By using the FFT-algorithm the plate thickness, T, or depth to an anomaly can be determined more accurately from the displacement frequency measured, *f*, shown in equation (2):

$$T = \frac{C_P}{2 \cdot f} \quad (2)$$

Where, *T* is the thickness and is either measured directly on the structure or is know from the structural drawings; and C_p is the P-wave velocity, which can be obtained by calibration on a structure of known thickness or by calibration directly on the surface by using two transducers with a well-defined distance and measure the Rayleigh wave running on the surface.

2.2 *Impulse Response (IR) for bridges*

The Impulse Response-method (IR) is used for a fast screening of larger areas with the purpose to determine local areas with possible flaws for a later detailed analysis or coring for visual calibration to the test results. On bridges the IR-method is able to locate delaminations and voids in the bridge deck or wearing layer and honeycombing and delaminations in concrete in general.

A sledgehammer with a built-in load cell in the hammerhead is impacted against the surface. The impact is approximately 100 times the force that of the Impact-Echo. This greater stress input means that the plate responds to the IR hammer impact in a bending mode over a much lower frequency range (0-800 Hz for plate like structures), as opposed to the reflective mode of the Impact-Echo (normally 2-50 kHz). This low strain impact sends stress waves through the tested element (bridge deck). The movement or velocity of the surface dynamic bending movement is recorded with a velocity transducer (geophone). The maximum compressive stress at the impact with the hammer and the velocity of the surface is stored in the laptop. In Figure 2 testing in progress is shown.

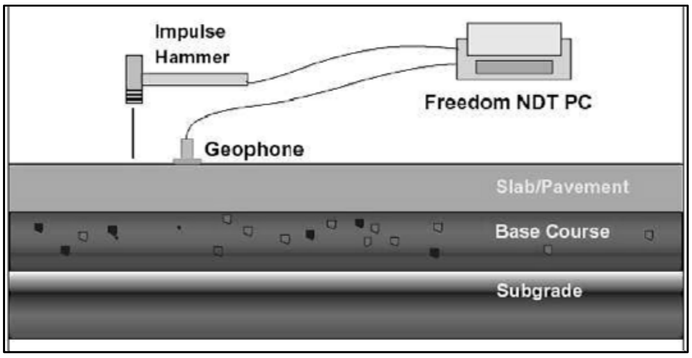


Figure 2. A sketch of the IR system showing the geophone, Impulse hammer and laptop used on a highway.

In the following a brief introduction is given to the theory behind the IR technique and how to interpretate the data. For more elaboration on the subject refer to the literature list at the end of this paper.

An IR examination cannot be used alone to evaluate a structure. The Method is primarily considered as a relative method used for screening of larger surfaces. The method shall always be supplemented and calibrated with other examinations. These calibrations can be done by means of drilling cores, breaking up and/or the use of endoscopy. Screening with the IR gives the possibility to identify potentially damaged areas.

With a FFT-algorithm (Fast Fourier Transformation) of the hammer impact and the velocity of the surface mobility plot is computed by dividing the velocity spectrum (signal from geophone) with the force spectrum (signal from hammer stroke). An example of the mobility-plot is shown in Figure 3.

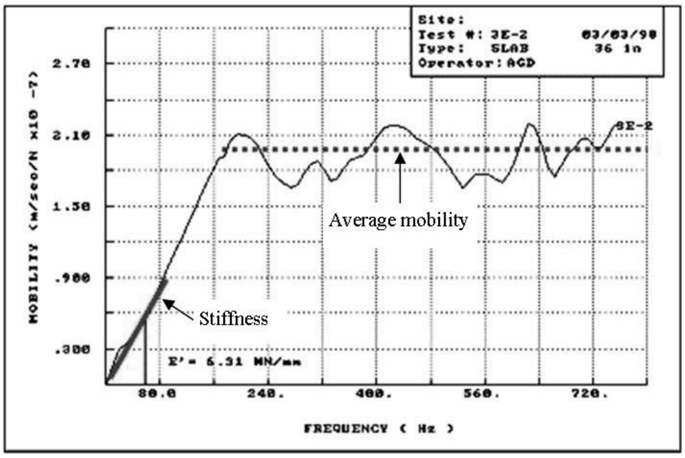


Figure 3. Example of a mobility plot from one testing point from an IR examination.

For analyzing the IR data the parameters mentioned in section 2.2.1 - 2.2.4 are plotted in a spreadsheet as contour plots and used for evaluation of the data.

2.2.1 *Average mobility*

The average mobility is calculated by the software and is shown as the dotted line in Figure 3.

Interpretation: The mobility between 100 and 800 Hz is directly related to the density, support and thickness of the structures tested. A *reduction of the thickness of the plate* results in an *increment in the average mobility*. If the top layer of a road surface is completely or partly delaminated from deeper layers the mobility increases as the average mobility measured corresponds to the upper delaminated layer. A high value compared with other measurements in an apparently homogeneous area is therefore indicating a delamination.

2.2.2 *Stiffness*

The stiffness is the inverse of the slope under 80 Hz on the mobility plot (shown as the thick line on

Figure 3). The slope of the mobility plot is the flexibility (compliance) of the structure.

Interpretation: Indicate the stiffness of the structures around the test point and is a function of the quality, thickness and support of the structures. The value is preliminarily used to evaluate differences in the structures when the other values are compared.

2.2.3 *Mobility slope*

If honeycombs are present in the structures the attenuation of the signal is reduced and with it the stability of the mobility-plot of the examined frequency spectrum (50 Hz to 1 kHz). This leads to an increasing/non stable mobility plot, see Figure 5.

Interpretation: A higher slope or non stable mobility plot indicates a higher probability for honeycombs in the structure.

2.2.4 *Voids index*

The relation between the initial mobility limit and the average mobility.

Interpretation: If delaminations are present or lacking support of the structure the mobility limit below 100 Hz (the first limit) is much higher than the average mobility. If the value in the Voids Index is larger than 2-4 it's an indication of an area with a potentially poor structure.

Typical signals of flaws compared with sound signals are shown in Figure 4 and Figure 5.

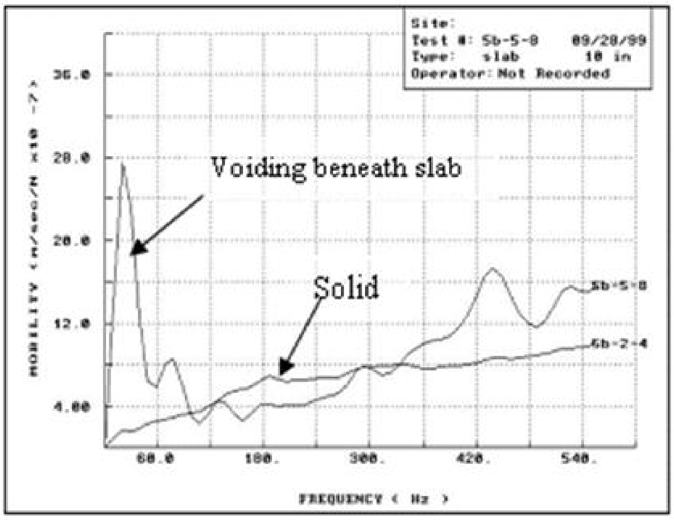


Figure 4. If a void or a delamination is present under a structure a high mobility limit at low frequencies are visible.

The method does not give any specific depth indications to the flaws. It is however possible to distinct between shallow or deeper flaws. But in general only a relative value can be evaluated with other values for the structure in question giving an indication between good and bad areas.

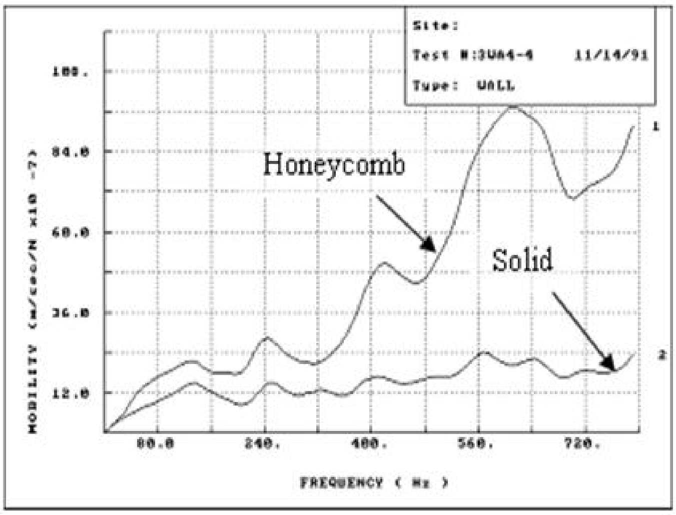


Figure 5. If honeycombs are present an increasing slope in the mobility plot is seen.

2.3 *Impulse Response for examination of piles*

The Impulse Response equipment is also used to determine the length and depth to defects, cracks and bulbs in piles. The principle of testing is shown in Figure 6.

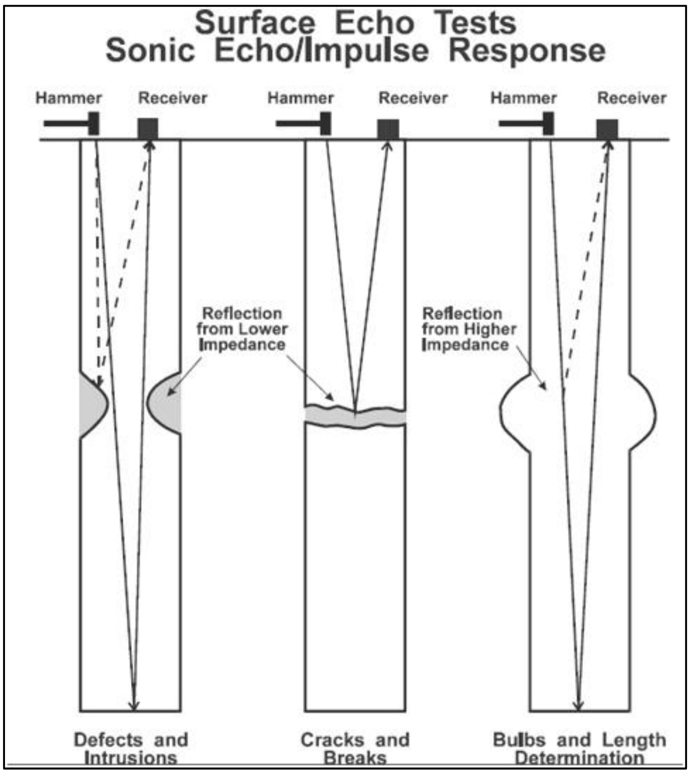


Figure 6. Sketch of the principle of IR testing on piles.

In addition, the IR data provides information about the dynamic stiffness of the foundation. This value can be used to predict foundation behavior under working loads or correlated with the results of load tests to more accurately predict foundation settlement.

3 SELECTED CASES

In the following, four projects will be reviewed, where the two described NDT equipment were used. The problem in each project is briefly described as well as how the project is carried out, interpretation of data and typical results.

3.1 *IE – injection quality of cable ducts*

A few days after a period with cold weather and temperatures below 0˚C in January 2008, cracks and spalling started to appear suddenly on columns in a new 8-story office building, which was still under construction. A visual inspection revealed the presence of cracks and spalling in 29 out of 489 columns distributed on 6 floors with 13 of the damaged columns on Level 4. The cracks were mainly visible at the tops of the columns and always directly in front of one of the four the cable ducts in each column. Figure 7 shows a column with spalling and the sectional view of a column shows one of the cable ducts highlighted with a solid circle.

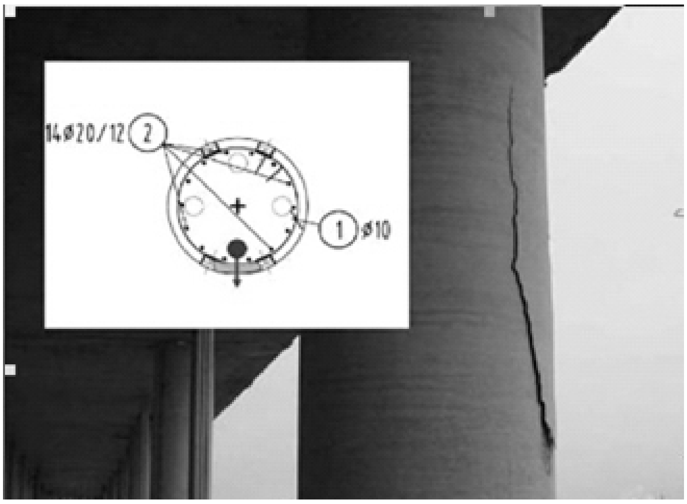


Figure 7. Photo of a column with spalling and a sectional view of the column.

Each column has 4 cable ducts, 80 mm in diameter with a concrete cover of approximately 80 mm. For distribution of the shear forces between the floors of the building a 25 mm diameter reinforcing rebar is embedded in each duct reaching 1 m into the duct above and below the floor.

To investigate the cause of the cracking, holes were drilled with a 25 mm diameter drill bit into the cable duct at 10 cm and 45 cm below the ceiling. The purpose of this preliminary investigation was to investigate if:

1. The ducts were fully grouted or empty.
2. The grout had “no strength”.

The preliminary investigation disclosed the presence of:

1. Empty, fully grouted, and partly grouted ducts.
2. Water was present in some ducts.
3. Grout with no strength – and which appeared to be segregated.

A not expected discovery was the presence of larger aggregates in the “mortar”. Breaking up the ducts revealed the presence of aggregates with a diameter up to 32 mm. The “grout” in the ducts was the same concrete as has been used for casting each floor and not the prescribed mortar mixture. With a 25 mm reinforcing rebar in the centre of an 80 mm duct, the chance of having a blocking due to the large aggregates is high and explain the presence of voids and partly filled ducts. See the photo in Figure 8.

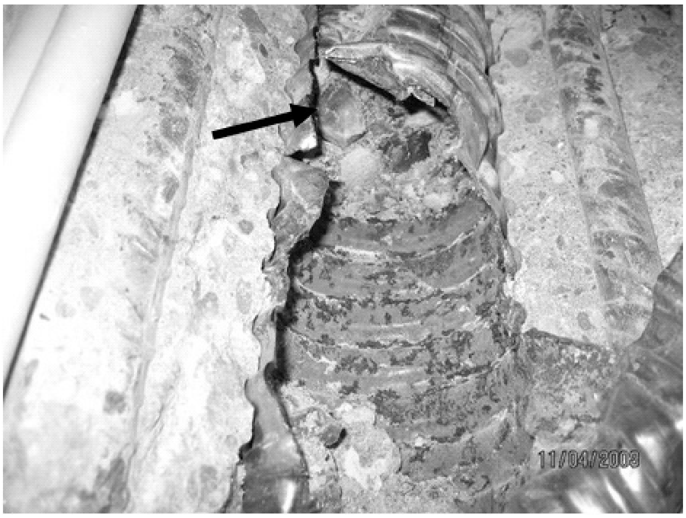


Figure 8. The presence of large aggregates and air voids were revealed during breakup of a duct.

The cracking and spalling can be explained by the presence of water in the ducts, which froze during the few days with temperatures below 0˚C and hence expanded. Construction photos from casting of the floors showed the drainage of the formwork let the water directly to some of the columns.

3.1.1 *Preparing the test*

Three sizes of columns were investigated. The diameters were 450 mm, 560 mm and 650 mm. Each column had 4 embedded cable ducts from level -2 (deepest basement) to level 4. From level 4 and up to level 8, only 2 cable ducts were embedded in the columns. Adjacent to two of the ducts – perpendicular to each other – plastic tubes were embedded for electrical wiring. The top and bottom of these plastic tubes were visible and were used as guidelines to locate the ducts. See Figure 9.

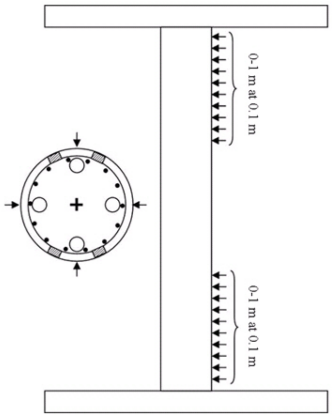


Figure 9. Elevated and sectional view of a column and the location of IE test points are marked with arrows.

Using the IE system on plate-like structure is normally relatively easy and a test gives ideally only one clear frequency peak corresponding to the thickness or depth to an anomaly. Testing round columns requires knowledge of modal frequencies of the cross section to avoid misinterpretation of the data. Modal frequencies occur as the stress waves that are sent into the columns are reflected from the entire boundary of the column and not just the back side. If the diameter and the P-wave velocity are known, these frequencies can be calculated.

Verification tests on the columns have shown that the P-wave velocity is approximately 3800 m/s. The depth to the ducts is 80 mm ±10 mm. With knowledge of the diameter, location of ducts and P-wave speed in the concrete, it is possible to calculate the expected frequencies for a “solid” signal (back side of column), the different modal frequencies and expected frequencies for voids in the ducts. The results are shown in Figure 10, and the most interesting frequencies used for evaluating the data are highlighted.

	Column 450 mm	**Column 560 mm**	**Column 650 mm**
"Solid" frequency	**4.22 kHz**	**3.45 kHz**	**2.92 kHz**
1. mode	6.3 kHz	5.2 kHz	4.4 kHz
2. mode	8.4 kHz	6.9 kHz	5.9 kHz
3. mode	10.1 kHz	8.3 kHz	7.0 kHz
4. mode	12.2 kHz	10.0 kHz	8.5 kHz
5. mode	13.9 kHz	11.4 kHz	9.7 kHz
Void at 80 mm (3.15″) depth	**23.8 kHz**		
Void at 160 mm (6.3″) depth	11.9 kHz		

Figure 10. Overview of expected frequencies for the columns with fully grouted ducts and if voids are present in the ducts.

3.1.2 *Testing*

Initial testing was performed on selected columns on two floors. For verification of the impact-echo data, 50 cores were drilled into the ducts. 39 of the cores were in accordance with the data interpretation. 8 cores showed an empty duct and the interpretation of the impact-echo data was “empty or possible lose aggregates”. These 8 test results were also accepted. The last 3 cores showed an empty duct and the impact-echo data had evaluated the data as “solid”. Some typical IE results are shown in Figure 11 and Figure 12.

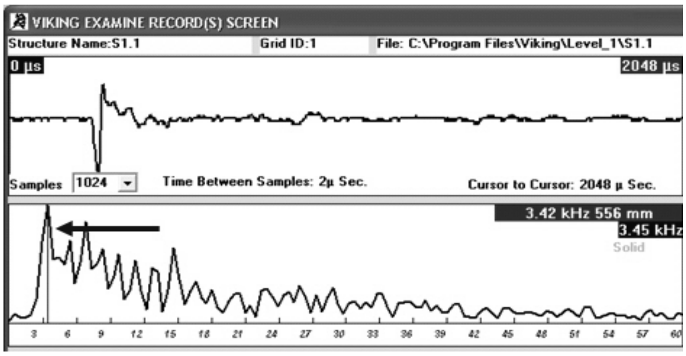

VIKING EXAMINE RECORD(S) SCREEN
Structure Name:S1.1
Grid ID:1
File: C:\Program Files\Viking\Level_1\S1.1
Samples 1024
Time Between Samples: 2µ Sec.
Cursor to Cursor: 2048 µ Sec.
3.42 kHz 556 mm
3.45 kHz
Solid

Figure 11. Frequency peak (arrow), which corresponds to the thickness of the column.

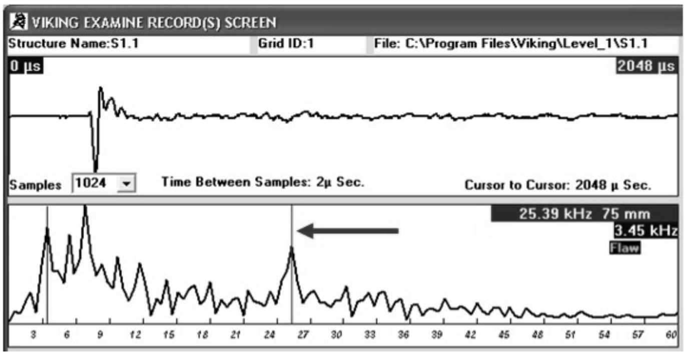

VIKING EXAMINE RECORD(S) SCREEN
Structure Name:S1.1
Grid ID:1
File: C:\Program Files\Viking\Level_1\S1.1
Samples 1024
Time Between Samples: 2µ Sec.
Cursor to Cursor: 2048 µ Sec.
25.39 kHz 75 mm
3.45 kHz
Flaw

Figure 12. Frequency peak (arrow) due to the presence of air in the duct at a depth of 75 mm.

The investigations showed that almost 10 % of the ducts at the bottom of the columns and 33 % at the top of the columns were empty. 4 % of the tests were classified as “uncertain” and could be both lose gravel/aggregates or an empty duct.

The use of the impact-echo method gave the contractor a good overview of the actual condition of the ducts in the columns and saved the repair of many holes if drilling would have been used to investigate the ducts.

3.2 *IE – locating ASR in a bridge deck*

In connection with the forthcoming construction of a tunnel between Denmark and Germany, the existing infrastructure had to be inspected and serviced. One major railway bridge is from the 1930s and it had to be ensured that it does not need any major repair for a period of 20 years after the new tunnel is opened.

A special inspection of the bridge, revealed the presence of alkali silica reactions (ASR) in the bridge deck. Many cores from the upper side showed signs of ASR to various depths and thus a concrete, which consists of many fine, partially closed cracks.

Alkali silica reaction (ASR) is a concrete durability problem whereby certain forms of silica in aggregates react in high alkaline pore solutions in concrete to form a reaction product that expands in the presence of moisture and results in deleterious cracking of concrete. An example of a concrete core with ASR is shown in Figure 13.

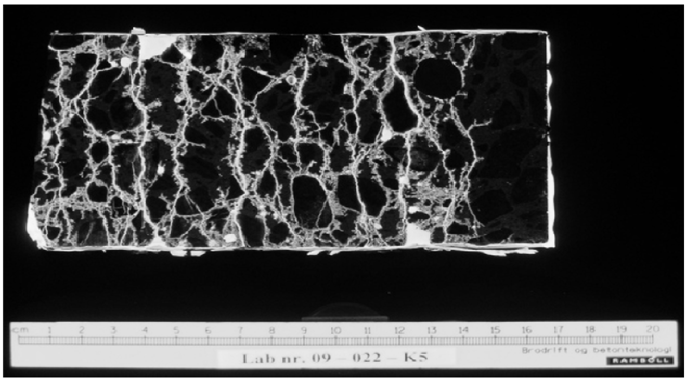


Figure 13. 100 mm core, vacuum impregnated with epoxy and exposed to UV-light.

The extend of ASR, which can be seen from the underside, was most evident adjacent to the joints – but also in other local areas - where there were signs of cracks and moisture permeation. See example in Figure 14.

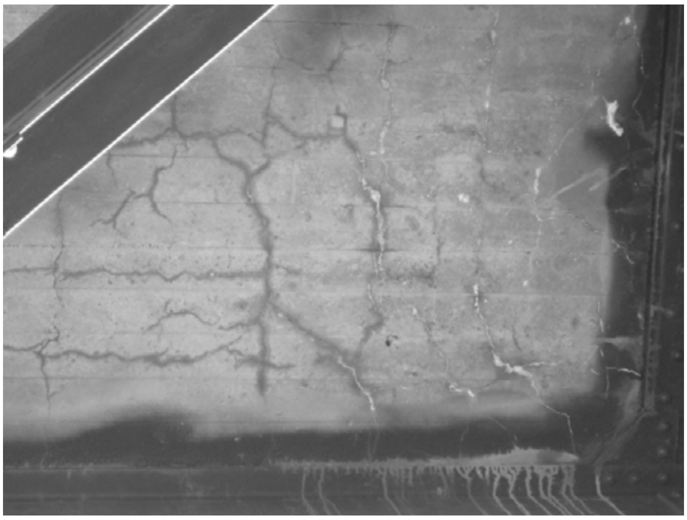
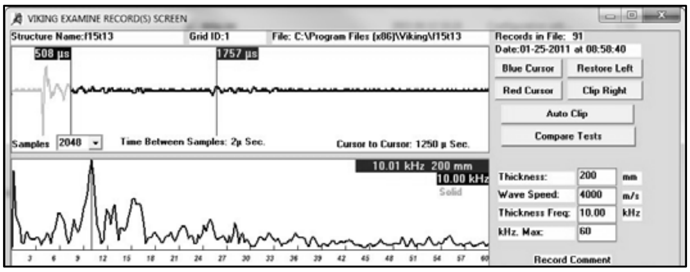


Figure 14. Close-up of the underside of the bridge deck. Moist cracks and white precipitations are visible.

If there are signs of ASR on the underside of the bridge deck the concrete is damage throughout the cross section of the bridge deck as ASR starts on the upper surface and penetrates down through the concrete as long as moisture is available. ASR will stop as soon as the influx of water stops.

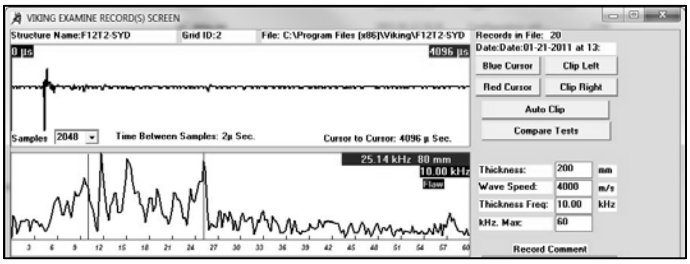
IE measurements on a solid concrete gives a very distinct signal. All the cracks caused by ASR gives a lot of small reflections and thus some "noise" in the IE signal. Using Impact-Echo from the underside of the bridge deck can thus give an indication of how far down the damages from of ASR has reached. Typical signals are shown in Figure 15 and Figure 16.



VIKING EXAMINE RECORD(S) SCREEN

Structure Name:f15t13
Grid ID:1
File: C:\Program Files (x86)\Viking\f15t13
Records in File: 91
Date:01-25-2011 at 08:58:40
Samples 2048
Time Between Samples: 2µ Sec.
Cursor to Cursor: 1250 µ Sec.
Thickness: 200 mm
Wave Speed: 4000 m/s
Thickness Freq: 10.00 kHz
kHz. Max: 60

Figure 15. IE - solid signal with measured thickness of 200 mm.



VIKING EXAMINE RECORD(S) SCREEN

Structure Name:F12T2-SYD
Grid ID:2
File: C:\Program Files (x86)\Viking\F12T2-SYD
Records in File: 20
Date:Date:01-21-2011 at 13:
Samples 2048
Time Between Samples: 2µ Sec.
Cursor to Cursor: 4096 µ Sec.
Thickness: 200 mm
Wave Speed: 4000 m/s
Thickness Freq: 10.00 kHz
kHz. Max: 60

Figure 16. IE - ASR-signal with measured thickness of 80 mm (from the bottom of the bridge deck and upwards).

3.2.1 *Testing*

Testing was performed in a grid of 25 cm x 25 cm – approx. 6 m^2. The results indicate some local areas with reflections from a depth of 125 mm between column 6-8 in row B and D and a large area between columns 10-12 from row A-G with reflections between 75-125 mm. Se Figure 17.

Three cores were drilled out for calibration, Core A, B and C. Core A showed signs of cracks 80 mm from the underside of the bridge deck. B and C were solid.

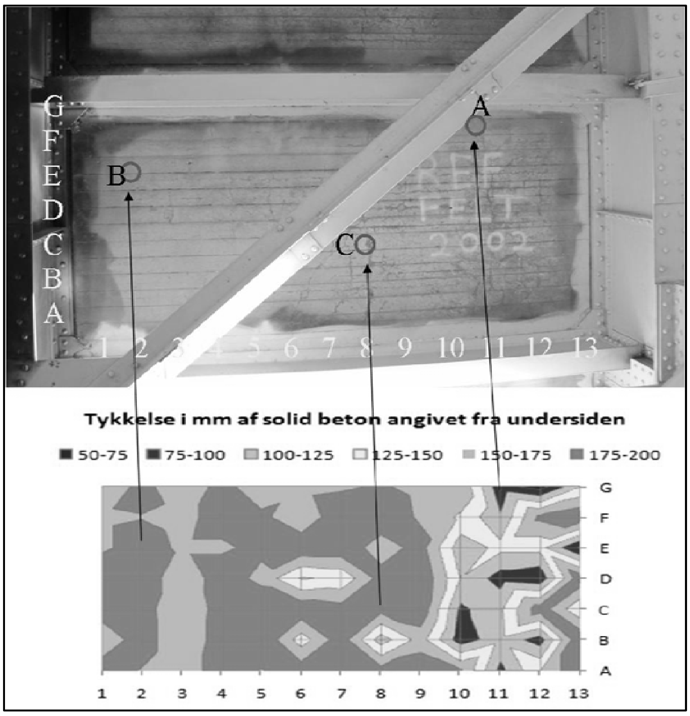


Figure 17. Photo of tested area with data presented as a contour plot below. Dark colors indicate shallow reflections from cracks.

3.3 *IR – locating defects in bridge deck*

On a bridge from the 1930s (The old Lillebælt Bridge, DK) a special inspection of the bridge plate was carried out in the summer of 2010. The purpose of the study has primarily been to locate areas of damages in the top concrete pavement, poor adhesion between concrete and membrane or damage in the structural concrete. The pavement consists of a 10 cm thick concrete, which has been applied in 1965.

The road on the bridge is so narrow that traffic regulations only can be carried out at certain hours during daytime.

3.3.1 *Testing*

Five test areas were selected on the bridge. These areas were tested with IR in a grid with a distance of 1 m along the bridge (up to 20 m long) and 0.5 m across (up to 2 m across). See an example in Figure 18.

The IR equipment was ideal for this kind of testing. The test areas were all tested within 20 minutes with the IR equipment including marking of the test points. The data was analyzed just after the testing followed by drilling of 2-3 cores in each test area for calibration. Within 1 hour each of the five areas had been tested with the IR and data had been calibrated with cores.

Figure 18. Photo of The old Lillebælt Bridge with one test area in between the cars.

The test showed that the 10 cm thick pavement was intact in all the test areas. The problem was either poor adhesion of the membrane and concrete or cracks in the concrete below the membrane (ASR). With the IR it was possible to distinct between shallow defects or deeper defects.

A photo of a core after drilling and after it has been vacuum impregnated with epoxy is shown in Figure 19. The top of the core faces left. The ASR cracks are clearly visible on the lower photo.

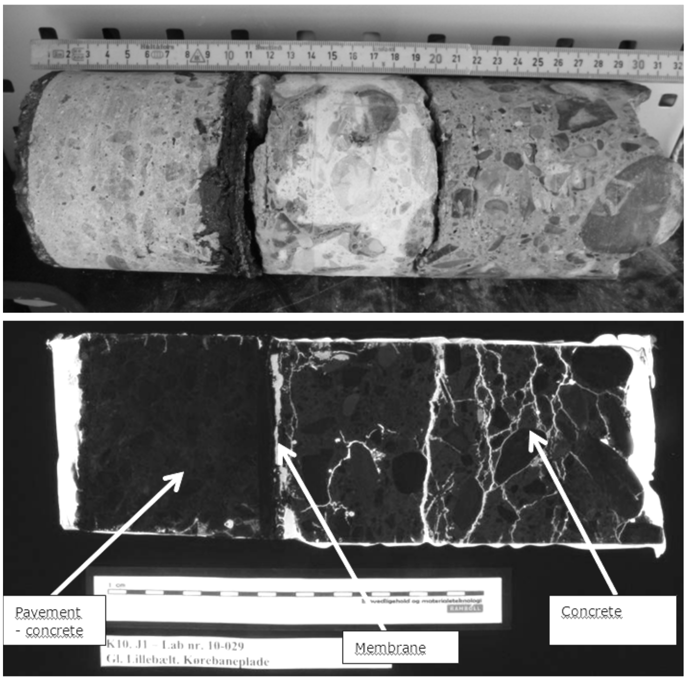


Figure 19. Photo of core after is has been drilled out and after vacuum impregnation with epoxy and exposed to UV light.

3.4 *IR – Pile integrity testing*

In connection with the extension of a Danish harbor it was decided to use driven precast concrete piles to reinforce the foundation. The piles were coupled in various combinations by piles with lengths of 11, 12 and 13 m to a total length of 24 m. The piles have a cross section of 0.35 m x 0.35 m and are reinforced with T12 rebars longitudinally.

After some time it was discovered that the top of several piles - within a restricted area - between row 30-34 and module lines A-E, had moved up to 0.7 m horizontally. Consequently the piles were suspected to be broken.

In Figure 20 is a photo showing how the piles are shifted to one side. The white lines indicate the lines C, D and E. It is evident that the piles furthest away from the photo have moved most towards left.

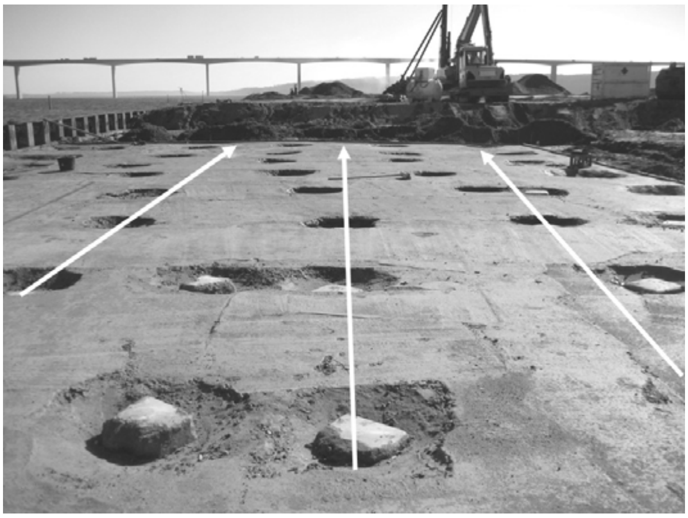
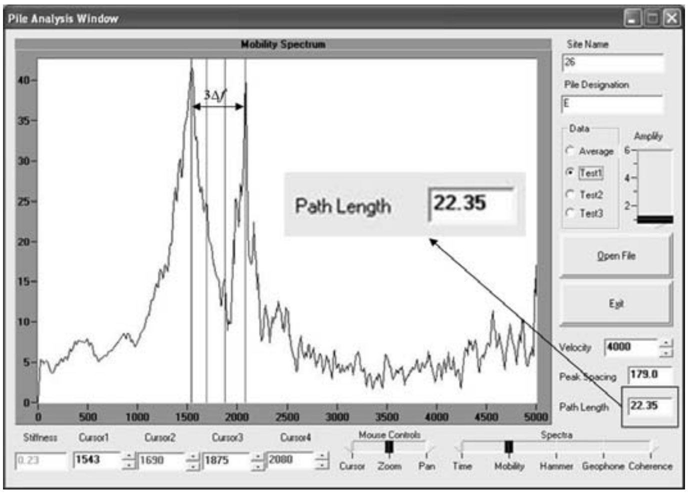


Figure 20. Photo of piles, which are moved up to 0.7 m towards left. The arrows indicate the original location of the piles.

The purpose of the inspections is to make an assessment of whether the piles are intact or if there are indications of damages.

3.4.1 *Testing*

Measurements were performed on 68 precast piles with cross section dimensions of 0.35 m x 0.35 m and a variable length of 11, 12 and 13 m. The length of each of the piles is known. Data are presented in a "mobility diagram”, which is used to analyze the results. From this diagram parameters are calculated such as the stiffness, the speed of the generated stress wave and frequency between the standing waves in piles used to determine the length of the pile or depth to a flaw.



Site Name 26
Pile Designation E
Data
○ Average
● Test1
○ Test2
○ Test3
Path Length 22.35
Velocity 4000
Peak Spacing 179.0
Path Length 22.35
Stiffness 0.23
Cursor1 1543
Cursor2 1690
Cursor3 1875
Cursor4 2080

Figure 21. Mobility diagram from testing an 11 m long pile.

The Mobility diagram can be used for interpretation when, in a range between 1 and about 2500 Hz, an increasing mobility can be seen. The maximum peak value in this part of the diagram is selected by the operator and is used as a starting point. Select the three next peaks with the same peak spacing indicated with the parameter $3\Delta f$ in Figure 21. The software uses the peak spacing to determine the pile length or depth to an anomaly of the tested pile.

At the bottom of the figure the total length that the waves travel down to the end of the pile and back again is indicated as the "Path length". Figure 21 shows in this case a "Path Length" of 22.35 m, which means that the measured length of the pile is approx. 11.17 m. The true length of this pile is 11 m. The pile length is determined by equation (3):

$$L = \frac{C_P}{2 \cdot \Delta f} \tag{3}$$

where:
L = pile length,
C_p = stress wave velocity in concrete [m/s].

IR tests on piles are accurate to within 5% in the determination of the depth of the foundation provided an independent measurement of the wave velocity used in the depth calculation is made. In case the wave velocity is assumed based on the material type, IR tests are normally accurate to within 10%.

The wave velocity was set to 4,000 m/s and was not measured directly on the piles. A total of 68 piles were checked within a few hours. 15 of the piles, which should be 11 m long, had indications of flaws at depths between 7.6 - 10.6 m from the top.

4 CONCLUSION

The four examples show clearly that the use of NDT for evaluation of concrete structures is a powerful tool, which provides valuable information about the current condition of the structure. An experienced operator can quickly achieve a good overview of the structure and locate any hidden faults.

In contrast to the use of destructive testing, which is often time consuming and may not reveal the real extent of the damage NDT can be used to screen larger areas.

IF NDT is used during the construction phase of new buildings errors can already be localized at an early stage and can often be limited to a local area and repaired fast. Experience from these errors can be used constructively and minimize the risk that they will happen again. If errors are detected early in the construction phase the repairs are cheaper than if they are not discovered until late in the construction phase.

By applying NDT it is essential to have data calibrated directly on the structure short after the initial tests are made. The interpretation of data must also be continuous and measurements should always be performed by an experienced operator.

It is further recommend to perform measurements in-house with technicians being trained in the use of the equipment before on-site testing take.

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