

NDE for Concrete Decks: GPR, Half-Cell and Impact-Echo

Concrete bridge decks deteriorate faster than most other bridge components, and much of that deterioration happens below the surface where visual inspection cannot see it. This course explains the nondestructive testing (NDT) methods used to evaluate concrete decks, with emphasis on ground-penetrating radar, half-cell potential and impact echo, and covers chain dragging and hammer sounding, infrared thermography, electrical resistivity, galvanostatic pulse, ultrasonic surface waves, ultrasonic pulse echo and impulse response. It is built on the findings of SHRP 2 Renewal Project R06A, which graded these technologies in laboratory and field validation testing, and it stresses method selection, interpretation and limits.

Learning objectives

- Select NDE methods for decks
- Interpret half-cell potentials
- Use GPR and impact-echo
- Know method limits

Why decks need nondestructive testing

SHRP 2 Report S2-R06A-RR-1, *Nondestructive Testing to Identify Concrete Bridge Deck Deterioration* (Gucunski et al., 2013), opens with a blunt observation: the extensive number of concrete bridge decks in poor structural condition is one of the biggest problems affecting U.S. bridges. Agencies need to evaluate deck condition to optimize the timing, scope and approach for preventive maintenance, repair and replacement. The difficulty is that deck deterioration often takes place below the surface, where it cannot be evaluated by visual means.

The report notes that bridge decks deteriorate faster than other bridge components, and that their inspection and rehabilitation require traffic interruption. Rapid and accurate condition assessment, the authors argue, leads to more effective decision making, better allocation of money to renew and rehabilitate decks, and reduced frequency and duration of traffic interruption caused by slow and ineffective inspection.

Nondestructive testing and nondestructive evaluation (the report uses NDT and NDE broadly) give owners the ability to rapidly inspect and monitor aging decks. Data from deck NDT can complement other information in understanding life-cycle costs and deterioration mechanisms, can evaluate the effectiveness of preservation treatments at various stages of aging, and, most importantly in the report's words, can prevent premature and unexpected failure of bridge decks.

The R06A project was conducted under the second Strategic Highway Research Program, sponsored by FHWA in cooperation with AASHTO and administered by the Transportation Research Board. The research was performed by Rutgers University's Center for Advanced Infrastructure and Transportation, the University of Texas at El Paso, the German Federal Institute for Materials Research and Testing (BAM) and Radar Systems International. Its objectives were to identify and characterize NDT technologies for rapid condition assessment of concrete decks; to validate their strengths and limitations in terms of accuracy, precision, ease of use, speed and cost; to recommend test procedures and protocols; and to build an electronic repository for practitioners, which became the web-based NDToolbox.

The literature search retrieved more than 1,000 reference documents. Its central conclusion, repeated throughout the report and confirmed by validation testing, is the single most important idea in this course: **no single technology can detect or**

provide information about all the deterioration processes and defects of interest. The technologies also differ significantly in ease of use, cost, level of expertise needed for data collection and interpretation, speed and accuracy.

That conclusion shapes how an engineer should approach a deck investigation. The question is never "which NDT method is best?" but "which deterioration am I trying to find, at what level of decision, and which combination of methods answers that question with acceptable speed, cost and confidence?"

This course works through that question. It first reviews the deterioration types the methods are trying to find. It then describes each method's physical principle, applications and limitations as summarized in the R06A report, with the most attention on the three methods named in the course title. It closes with the R06A validation findings, method selection, planning and reporting of a deck survey, and the limits engineers must respect when acting on NDT results. Deterioration mechanisms themselves are covered more fully in BR-C01, deck inspection in BR-I06, and deck preservation treatments in BR-DP02.

What the methods are looking for: four deterioration types

The R06A report lists the most frequent deterioration phenomena in reinforced concrete identified by Bien et al. (2007): corrosion, carbonation, alkali-silica reaction, crystallization, leaching, oil and fat influence, salt and acid actions, creep, fatigue, influence of high temperature, modification of founding conditions, overloading, shrinkage and water penetration. From these, the project focused on four deterioration types of highest concern to bridge engineers: rebar corrosion, deck delamination, vertical cracking and concrete degradation. Of those four, delamination and corrosion were given higher priority.

The report gives a useful rationale for using categories of consequence rather than cause: although there are different causes of deterioration, in most cases NDT cannot determine the cause, only the consequence. Corrosion and shrinkage cracking both produce material degradation that may show up as reduced wave velocity or modulus.

Rebar corrosion. Reinforcing steel is naturally protected by the high alkalinity of concrete, which forms a passive oxide film, and by adequate cover. The report summarizes ACI 222R: once the film is destroyed, an electrochemical cell forms along a bar or between bars, with anodic areas where iron goes into solution and cathodic areas where hydroxide ions form. Chloride diffusion, primarily from deicing salts, is a major contributor. The two most common processes are chloride-induced pitting and carbonation; the report notes that pitting tends to leave blackish rust marks while carbonation-based corrosion leaves red or brown stains. Corrosion rate depends on humidity, temperature, pH and exposure; wet-dry cycles accelerate it, and the report cites studies showing rates highest in spring and lowest in winter, varying by a factor of about four or five during the year. That seasonal variation matters for interpreting any electrochemical survey.

Delamination. Reinforcing steel expands as it corrodes. That expansion can create a crack or subsurface fracture plane in the concrete at or just above the reinforcement. The report emphasizes that delamination may be localized or widespread, especially where cover is thin; that it can occur on different planes in the same area; and that it is not visible on the surface. If not repaired in time, it progresses to open spalls and eventually affects the structural integrity of the deck.

Vertical cracking. Besides corrosion, cracking results from plastic shrinkage, heat of hydration, ambient temperature, restraint as the deck cures, traffic load and freeze-thaw cycles. Corrosion can widen these cracks, and the cracks give chlorides and water a direct path to the steel.

Concrete degradation. The report treats reduction in concrete strength or modulus as degradation, caused by microcracking and macrocracking from alkali-silica reaction (a swelling silica gel), delayed ettringite formation (an internal sulfate attack

associated with improper heat curing), plastic shrinkage and freeze-thaw damage. Freeze-thaw ruptures concrete when hydraulic pressure exceeds tensile strength, eventually causing cracking, scaling or crumbling.

Overlay debonding. Many older decks carry asphalt or portland cement concrete overlays. The report notes overlays can debond, letting moisture and chlorides into the debonded region and eventually producing spalls. Overlays also complicate the analysis of NDT data and can impede the effectiveness of several methods, a theme that recurs in the limitations of almost every technique below.

With these targets in mind, the R06A report grouped technologies by their physical principle: acoustic or seismic (stress wave), electromagnetic, electrochemical and thermal, plus the traditional methods of visual inspection, chain dragging, hammer sounding and chloride sampling.

Chain dragging and hammer sounding: the baseline

Any discussion of deck NDT has to begin with the methods it is trying to improve on. The R06A report states that chain dragging and hammer sounding are the most common inspection methods used by state DOTs and other owners for detecting delamination in concrete decks.

How they work. The objective of dragging a chain or striking the deck with a hammer is to find regions where the sound changes from a clear ring (sound deck) to a muted, hollow sound (delaminated deck). The report categorizes both as elastic wave tests. The hollow sound results from flexural oscillation of the delaminated portion of the deck, a drum-like effect, typically in a 1 to 3 kHz range that falls within human hearing. A delamination changes the frequency of oscillation and therefore what the operator hears.

Chain versus hammer. Chain dragging is relatively fast for finding the approximate location of a delamination, and its speed varies with how deteriorated the deck is. Hammer sounding is much slower and is used to define delamination boundaries accurately; it is also more appropriate for small areas. Chain dragging is limited to horizontal surfaces, while hammer sounding can be used on a wider range of elements, such as soffits, pier caps and walls.

Rotary percussion. The report describes a related device, the rotary percussion system, consisting of gear-shaped wheels on the end of a pole that are rolled over the surface. Some systems add a microphone and headphones to amplify the sound and block ambient noise. The report notes that it was accepted as a standard procedure by ASTM D4580 for measuring delaminations in concrete bridge decks. (ASTM D4580 itself was not reviewed for this course.)

Limitations. The R06A report lists three:

- Both methods depend on the operator's skill and hearing, which makes them subjective.
- Initial or incipient delamination often produces oscillations outside the audible range, so it is not detected. Sounding mainly finds the late stages of delamination.
- Both methods are generally ineffective on decks with overlays.

Traffic noise, wind and fatigue of the inspector add practical difficulty that every field inspector will recognize.

How it performed. In the R06A field validation on a bridge in Haymarket, Virginia, chain dragging and hammer sounding indicated delaminations at the correct locations on the deck. In the final ranking, the report lists chain dragging and hammer sounding among the four technologies with a fair-to-good ability to detect and characterize delamination, alongside impact echo, infrared thermography and GPR.

This is an important point for engineers who might assume that newer technology always outperforms older practice. Sounding is cheap, needs little equipment and, in experienced hands, finds advanced delamination reliably. Its weaknesses are subjectivity, inability to find early-stage delamination, poor performance through overlays, slow speed for hammer work, and the need for lane closures. The R06A report's encouraging finding was that several NDT technologies can generate data at a production rate comparable to chain dragging and hammer sounding, which removes the main argument against using them.

Practical role. In most deck investigations, sounding remains useful as a check on instrument results, for marking boundaries on bare decks before repair, and for verifying a small number of locations flagged by a faster screening method. Treat the sounding map as a measurement with known limits, not as ground truth; it cannot see early delamination that impact echo may detect.

Impact echo: principle and interpretation

What it is. The R06A report describes impact echo (IE) as a seismic or stress wave method used to detect defects in concrete, primarily delaminations, citing Sansalone and Carino (1989). The objective is to detect and characterize wave reflectors, or resonators, in a deck or other element by striking the surface and measuring the response at a nearby location. Devices range from simple handheld units to automated steppers and deck scanners.

Physical principle. The surface is struck by wire-mounted steel balls, automated projectiles or solenoid impactors, and the response is measured by a nearby contact or air-coupled sensor. The position of reflectors is obtained from the frequency spectrum of the response; more rigorously, the report notes, the response is related to the first symmetrical Lamb wave mode in the deck. The frequency of the reflection, the "return frequency," is identified in the spectrum, and the depth of the reflector is obtained from that frequency and the measured or estimated compression-wave velocity of the concrete.

Strong reflections occur wherever there is a contrast in acoustic impedance, such as a concrete-air interface. In a sound deck, the dominant reflector is the bottom of the deck. A delamination is another concrete-air interface, so delaminated areas are recognized as shallow reflectors. Other reflectors include voids, tendons and supporting members.

Grading delamination severity. The report explains one interpretation scheme used in the study:

- *Intact:* the dominant return frequency corresponds to the full deck thickness.
- *Initial or incipient delamination:* return frequencies from both the bottom of the deck and the delamination are present, reflecting partial separation within the slab.
- *Progressed delamination:* a single peak at a frequency corresponding to the depth of the delamination. A delaminated point shows a shift toward higher frequencies because reflections come from a shallower depth.
- *Wide or shallow delamination:* the dominant response is a low-frequency flexural oscillation of the delaminated upper layer. This response is almost always in the audible range, which is why sounding finds it, whereas incipient delamination may show only in higher frequency ranges that the ear cannot hear.

This severity scheme is the main reason impact echo adds value beyond sounding: it can identify early-stage delamination before it becomes audible, and it can estimate the depth of the separation plane.

Frequency range. The report contrasts IE with impulse response: IE relies on wave propagation modes within the deck, typically in a range of about 3 to 40 kHz, while impulse response uses structural response at 0 to 1 kHz.

Applications. The report groups IE applications into four categories: condition assessment for delamination; characterization of surface-opening (vertical) cracks; detection of ducts, voids in ducts and rebars; and material characterization. Rebar and

duct detection requires a scanning approach, more expertise and a bar diameter to cover ratio above roughly one-third; even then, cover depth is hard to define accurately. IE has also been used to evaluate modulus and estimate compressive strength, to check grouting in tendon ducts (see BR-P03), and to detect overlay debonding.

Illustrative relationship. Because the reflector depth is obtained from the compression-wave velocity and the return frequency, depth and frequency are inversely related: for the same concrete, a shallower reflector returns a higher frequency. As a purely illustrative example, a delamination plane at roughly one-third of the deck thickness would return a frequency roughly three times that of the deck bottom. The exact relationship, including any shape factor, and the wave velocity must come from the governing standard and calibration on the actual deck; these numbers only show the direction of the shift.

Impact echo: limits and field performance

Limitations in the report. The R06A report lists the following limitations of impact echo:

- IE can detect delaminations on decks with portland cement concrete overlays. On asphalt overlays, detection is possible only when the asphalt is cold enough that it is not highly viscous, or when the overlay is intimately bonded to the deck.
- Data must be collected on a very dense grid to define delamination boundaries accurately.
- Near deck edges, boundary reflections interfere with the signal sought. The report notes the boundary problem is more common on elements of limited size such as girders, piers and pier caps than on decks.

The report also cautions that different authors interpret delamination severity from IE in various ways. An owner commissioning IE work should therefore specify, or at least require disclosure of, the interpretation criteria so results from different consultants or years can be compared.

Field validation. In the R06A field test on the Route 15 bridge over I-66 in Haymarket, Virginia, a two-span concrete deck on steel girders about 8 inches thick, five participants performed impact echo. All five identified five sections of the deck with predominant delamination. Despite using different impact sources and different analysis parameters (frequency, amplitude, thickness), the resulting contour maps were generally in good agreement in defining the main delaminated areas, and comparison with cores confirmed the capability of IE to detect major delaminated areas.

The laboratory validation at UTEP used a newly built slab 20 feet long, 8 feet wide and about 8.5 inches thick, with two mats of uncoated No. 5 bars, nine artificially delaminated areas at different sizes and depths, vertical cracks and a corroded section, plus a 9-foot by 14-foot section salvaged from a distressed I-10 bridge with a 4-inch asphalt overlay. The fabricated slab test grid was at 1-foot spacing; the salvaged section at 1.5 feet. Ten teams participated in validation testing: five from industry, four from academia and one from an agency.

Overall ranking. In its conclusions, the report lists impact echo among the four technologies with fair-to-good ability to detect and characterize delamination, among the three with capability for concrete deterioration detection (with ultrasonic surface waves and GPR), and first in its list of top technologies by overall value. The executive summary similarly places GPR, impact echo and ultrasonic surface waves at the top for overall value.

Practical considerations. Point-by-point IE with a handheld device is slow, so on a production deck survey it is typically used either with automated multi-sensor equipment or on a grid concentrated in areas flagged by a faster screening tool. Air-coupled sensors, which several participants used, remove the need to press a transducer to the surface and speed up data collection. The method needs no electrical connection to the steel, works through concrete overlays, and is not affected by deck moisture in the way GPR and electrochemical methods are.

The engineer reviewing an IE report should look for: the grid spacing and whether it is dense enough for the delaminated area sizes that matter for repair quantities; the assumed or measured wave velocity; whether near-edge and joint data were excluded or flagged; how incipient versus progressed delamination was distinguished; and whether any cores or sounding were used to confirm the interpretation. IE results expressed as "percent of deck area delaminated" depend directly on those choices.

Ground-penetrating radar: principle

What it is. The R06A report describes GPR as a rapid NDT method that uses electromagnetic waves to locate objects buried in a structure and produce contour maps of subsurface features such as reinforcement, wire mesh and interfaces. Antennas of different frequencies give different combinations of detail and penetration depth. Ground-coupled antennas are pushed on carts in contact with the surface; air-coupled systems are used for faster deck screening, often mounted on a vehicle.

Physical principle. A GPR antenna transmits high-frequency electromagnetic waves into the deck. Part of the energy reflects back from any reflector, such as a rebar, and is received by the antenna; the rest continues to penetrate and is reflected from deeper interfaces until it is diminished. GPR responds to variations in two electrical properties of the materials: electrical conductivity (the inverse of resistivity), which governs how well energy penetrates, and relative dielectric permittivity (dielectric constant), which governs wave speed. The dielectric contrast between adjacent materials causes part of the wave to reflect.

The report's table of dielectric constants illustrates the contrasts: air 1, fresh water 81, ice 4, asphalt 4 to 8, concrete 8 to 10, sand 4 to 6, gravel 4 to 7, clay 25 to 40, silt 16 to 30, silty sand 7 to 10, crushed base 6 to 8 and insulation board 2 to 2.5. The large difference between water and dry concrete is why moisture so strongly affects GPR.

How deck condition is assessed. The key point, the report explains, is that electromagnetic waves cannot penetrate metal. Rebars are therefore excellent reflectors and appear on a scan as a series of hyperbolas. Most construction materials are fair-to-good host materials, but concrete that is moist and high in free chloride ions can significantly attenuate the signal. Attenuation is more pronounced where the deck is cracked or delaminated and the cracks are filled with moisture, chlorides and other conductive materials.

Condition assessment is therefore based on **attenuation of the reflection at the top rebar level**. In most cases, the amplitude of the reflection at every rebar is corrected for rebar depth and plotted to create an attenuation map. Zones of high attenuation are related to zones of likely deterioration. On the report's example scan, most rebar reflections are strong, while one rebar appears fuzzy, indicating strong attenuation at that location.

This is the most important conceptual point about deck GPR: *GPR does not see delaminations directly*. It sees the electrical environment around the top mat. High attenuation indicates moist, chloride-laden, likely corrosive concrete, which correlates with deterioration but is not the same as a measured delamination.

Applications. The report lists typical GPR deck applications as evaluation of deck thickness, measurement of concrete cover and rebar configuration, characterization of delamination potential, characterization of concrete deterioration, description of concrete as a corrosive environment and estimation of concrete properties. Outside decks, GPR is used for tunnel linings, pavement layer thickness at project and network levels, voids under pavements and other subsurface work.

Cover and rebar layout measurements are often the most immediately useful GPR products for a design engineer. A cover map identifies areas of thin cover that are likely to corrode early, informs the depth of hydrodemolition or milling for an overlay, and confirms the bar spacing assumed in a load rating or repair design. Converting travel time to depth requires a wave

velocity, which depends on the concrete's dielectric constant; field calibration at a known depth, such as a core or exposed bar, improves the result.

The course reference list includes ASTM D6087, the standard test method for evaluating asphalt-covered concrete decks using GPR, but that standard was not obtained for this course; consult it directly for the procedure.

Ground-penetrating radar: limits and field performance

Limitations in the report. The R06A report is direct about GPR's limits:

- GPR cannot directly image or detect delamination in decks unless the delaminations are epoxy-impregnated or filled with water.
- Extremely cold conditions affect the data; completely frozen moisture is no longer detected.
- Deicing salts applied in winter affect the dielectric constant and therefore the results.
- GPR provides layer structure and the location and layout of reinforcing, but no information about mechanical properties such as strength or modulus.
- GPR cannot provide definitive information about the presence of corrosion, corrosion rate or section loss, even though it is sensitive to a corrosive environment and can map the probable severity of deterioration.
- GPR results generally must be correlated or validated by other NDE methods or limited destructive sampling, such as cores and chloride testing.
- GPR may be less cost-effective than other methods on small or individual structures.
- FCC regulations controlling transmit power and pulse repetition rate limit the design of newer, larger-area array systems.

Field validation. Five participants ran GPR on the Haymarket bridge. All maps were based on attenuation at the top rebar level, with delamination detected indirectly from high-attenuation areas. Despite discrepancies in boundaries and intensity, the maps were generally in good agreement, and all five participants identified the five predominantly delaminated sections as deteriorated. These areas matched those found by impact echo "to some extent," in the report's words.

Overall ranking. GPR appears in the report's final list of four technologies with fair-to-good ability for delamination, among four with fair-to-good capability for corrosion detection or characterization of a corrosive environment, and among three with capability for concrete deterioration. The executive summary lists GPR among the top technologies by overall value. Its strength is breadth and speed rather than precision on any single deterioration type.

Interpreting a GPR deliverable. A deck GPR map typically shows color-coded attenuation, often binned into condition categories. Questions to ask:

- Was the amplitude corrected for rebar depth, as the report describes? Without correction, deeper bars look worse simply because they are deeper.
- How were the category thresholds chosen? Attenuation thresholds are usually relative to the population of readings on that deck, so "poor" on one deck is not necessarily comparable to "poor" on another.
- When was the survey done? The report's warnings about frozen moisture and winter salt mean that season and recent weather matter. A survey soon after salting or during a hard freeze should be read with caution.
- What ground truth was used? Cores, chloride samples or a limited sounding survey on the same deck turn a relative map into something an engineer can quantify.

- Is there an overlay? The report notes overlays complicate analysis of most methods; GPR is commonly used on asphalt-covered decks because sounding and IE struggle there, but the overlay interface adds reflections that must be handled in processing.

Where GPR fits. Because air-coupled GPR can collect data at traffic speed and ground-coupled GPR at walking speed with high detail, GPR is well suited to network-level screening, to deciding which decks warrant project-level investigation, and to producing cover and thickness information for design. For repair quantity estimates, its attenuation maps are most useful when combined with a direct delamination method (IE or sounding) and with electrochemical data that indicate where corrosion is active.

Half-cell potential: principle and mapping

What it is. The R06A report describes half-cell potential (HCP) as a well-established and widely used electrochemical technique for evaluating active corrosion in reinforced and prestressed concrete. Using empirical comparisons, results can be linked to the probability of active corrosion. HCP was the only method in the course title that measures corrosion activity rather than a physical consequence of it.

Measurement. The potential difference between the reinforcement and a standard portable half-cell, typically a copper/copper sulfate (Cu/CuSO_4) reference electrode, is measured with the electrode placed on the concrete surface. Moving the electrode along a line or grid maps the spatial distribution of corrosion potential. The measurement requires an electrical connection to the reinforcing steel and a high-impedance voltmeter.

Physical principle. The report explains that when a metal is placed in an electrolyte, positive metal ions dissolve, leaving a surplus of electrons and a net negative charge on the metal surface. Ions accumulate at the interface to form a charged double layer, the "half-cell." A potential difference develops that depends on the metal and the ions in solution (in concrete, chloride and sulfate). When two half-cells with different potentials are electrically connected, a galvanic element forms; the less noble metal dissolves as the anode and the more noble remains stable as the cathode. In concrete, actively corroding areas of steel behave as anodes with more negative potentials than passive steel, so a contour map of potential points to likely areas of corrosion activity.

Conditions of use. The report, citing Elsener (2003), states that HCP can be used at any time in a structure's life and in any climate provided the temperature is above 2°C . Measurements should be made on a free concrete surface; insulating layers such as asphalt, coatings or paint can make measurements erroneous or impossible. This is a major practical limit: on asphalt-overlaid decks, HCP generally requires removal of the overlay or testing through openings.

Interpretation bands. The HCP condition maps in the R06A report are binned into three ranges with boundaries at about -200 mV and -350 mV : readings more positive than about -200 mV are labeled "90% probability of no corrosion activity," readings more negative than about -350 mV are labeled "90% probability of corrosion activity," and readings between are labeled "transition." The catalog references ASTM C876 as the standard test method for corrosion potentials of uncoated reinforcing steel in concrete, but ASTM C876 was not reviewed for this course; confirm the current standard's criteria and reference electrode corrections before applying them.

Illustrative reading of a map. Suppose, purely for illustration, a grid survey shows most of a deck between -150 and -250 mV , with two patches near a leaking joint below -400 mV . The bands above would place most of the deck in the no-corrosion or transition range and flag the joint patches as likely active corrosion. The engineer would then compare those patches with

GPR attenuation and IE delamination maps, take chloride samples at cover depth, and perhaps expose a bar. The potential map alone does not give a corrosion rate or section loss.

HCP surveys are typically plotted as equipotential contour maps, and the gradient between adjacent readings is often as informative as the absolute value, because steep gradients mark the boundary between anodic and cathodic regions.

Half-cell potential: limits, and other corrosion methods

HCP limitations. The R06A report notes that although many bridge engineers have used HCP for years almost as a standard tool, the influence of cover depth has not been thoroughly researched, so correcting data for depth is not straightforward, and neither is correction for moisture or salt content, which influence concrete resistivity. Combined with the temperature limit, the need for a bare surface and the seasonal variation in corrosion rate noted earlier, HCP results should be interpreted as a probability map tied to the conditions on the test day, not a fixed property of the deck.

The report's discussion of galvanostatic pulse measurement adds another limit: estimating corrosion rate from HCP is often unreliable when concrete is wet, dense or polymer-modified, where access to oxygen is limited.

Field validation. In the R06A conclusions, half-cell potential could recognize some corrosion activity on the test decks, and HCP is listed among the four technologies with fair-to-good capability for corrosion detection (with electrical resistivity, galvanostatic pulse and GPR). The report's final list of top technologies by overall value names HCP second, after impact echo. It notes that electrical resistivity describes the corrosive environment, which in some cases correlates with corrosion rate, while HCP yields the probability of active corrosion.

Electrical resistivity (ER). The report describes ER as often used for moisture detection, which can be linked to cracks. Water and chlorides are important parameters in the corrosion state; damaged and cracked areas are preferential paths for fluid and ion flow. The higher the resistivity, the lower the current that can pass between anodic and cathodic areas. The most common setup is the four-probe Wenner array: current is applied between the outer electrodes and potential measured between the inner two, with resistivity calculated as 2π times electrode spacing times voltage divided by current. The report reproduces a correlation (after Gowers and Millard, 1999) between resistivity and normally observed corrosion rate: below 5 k Ω ·cm very high; 5 to 10 high; 10 to 20 moderate to low; above 20 low. It notes saturated concrete is on the order of 100 to 1,000 Ω ·m, while oven-dried concrete acts as an insulator.

ER limitations, per the report: interpretation is challenging because resistivity depends on moisture, salt content, porosity and other properties whose contributions are hard to separate; surface drying, carbonation and nearby reinforcement affect field readings; automated road systems were not available at the time; and electrodes need galvanic coupling, so the surface must be prewetted. ER is used with HCP to map corrosion activity.

Galvanostatic pulse measurement (GPM). GPM imposes a short anodic current pulse between a counter electrode on the surface and the reinforcement and measures the resulting potential change. Actively corroding steel has low resistance to current flow and shows a small potential change; passive steel shows a large change. The report presents GPM as providing more realistic corrosion rate estimates where HCP is unreliable. Its limits: high cover resistivity produces unstable readings, so prewetting is essential and the first reading should be taken after a few minutes; and because the area of steel affected differs between passive and active reinforcement, apparent polarization resistance does not directly give corrosion status in both cases.

Putting the corrosion tools together. HCP indicates where corrosion is probably active. ER indicates how corrosive the environment is and how fast corrosion could proceed. GPM estimates rate. GPR maps attenuation that correlates with a

corrosive environment over large areas quickly. None measures section loss; that still requires exposure of the steel. Chloride sampling at bar depth, which the report lists among traditional methods, links all of these to the mechanism.

Other methods: thermography, ultrasonics and impulse response

Infrared thermography (IRT). The report notes IRT has been used since the 1980s to detect cracks, delaminations and disintegration in concrete. Infrared cameras measure thermal radiation at wavelengths of about 0.7 to 14 μm and produce temperature-coded images. When sunlight (passive) or a heater (active) warms the deck, delaminated and voided areas, filled with air or water, heat up and cool down faster than the surrounding concrete and can be 1°C to 3°C warmer when conditions are favorable. Limitations: no information about flaw depth; deep flaws are hard to detect; surface anomalies and boundary conditions affect results; and with sunlight as the source, clouds and wind can draw heat away by convection. In the Haymarket validation, IRT was not as successful in identifying delaminated areas; the report suggests shadows cast by many people testing on the deck at once may have affected the results, so no firm conclusion could be drawn from that test. In the final conclusions, IRT is still among the four methods with fair-to-good delamination capability. Its attraction is coverage: vehicle-mounted or overhead imaging can cover large areas quickly when weather and timing are right.

Ultrasonic surface waves (USW). USW is an offshoot of the spectral analysis of surface waves method, limited to a high-frequency range where the surface wave penetration does not exceed the deck thickness. The surface wave body extends to about one wavelength, so at short wavelengths the measured velocity depends only on concrete modulus. Significant variation in phase velocity indicates delamination or another anomaly. Applications include evaluating damage from ASR, DEF and freeze-thaw, quality control of concrete and asphalt modulus, measuring vertical crack depth, and indirectly detecting delamination. Limitations: unreliable modulus on debonded or delaminated sections, a supplemental role in deterioration detection, need for experience, and complications on layered systems such as asphalt-overlaid decks. In the report's conclusions, USW was the only technology validated as fair for vertical crack characterization and was among the three with capability for concrete deterioration.

Ultrasonic pulse echo (UPE). UPE uses ultrasonic stress waves from piezoelectric transducers; for concrete, low-frequency (about 50 to 200 kHz) dry-coupled transducers overcome scattering. One system described uses an array of 24 probes, 12 pulsers and 12 receivers, with synthetic aperture focusing to produce cross-section images. Applications include thickness measurement with one-sided access, defects, debonding of bars, shallow cracking, delamination and material interfaces such as grouting defects. Limitations: very close test point spacing (time-consuming), dependence on coupling on rough surfaces, masking of very shallow flaws by surface waves, and possible missed defects at lower frequencies.

Impulse response (IR). Also called the transient dynamic or mechanical impedance method, IR was developed in France in the late 1970s for drilled shaft quality control. An instrumented hammer strikes the surface and a nearby geophone or accelerometer measures the response, typically at 0 to 1 kHz; the ratio of response to impact spectra gives a mobility or flexibility spectrum that reflects local stiffness and support. Applications include honeycombing, voids under slabs, delamination and overlay debonding. Limitations: detects gross defects while smaller ones may be missed, depends on test point selection, and lacked automated equipment at the time of the report. In the Haymarket validation, impulse response was not very successful in detecting the delaminated areas.

What R06A validation tells us about selecting methods

The R06A conclusions are the best available evidence base for method selection on concrete decks. They can be summarized in a selection matrix, taken from the report's final chapter:

- **Delamination:** impact echo, chain dragging and hammer sounding, infrared thermography and GPR were identified as having fair-to-good detection and characterization ability.
- **Corrosion or corrosive environment:** half-cell potential, electrical resistivity, galvanostatic pulse measurement and GPR.
- **Vertical cracking:** only ultrasonic surface waves was validated as fair.
- **Concrete degradation:** ultrasonic surface waves, impact echo and GPR.

The report lists the top technologies by overall value as impact echo, half-cell potential, ultrasonic surface waves, GPR, chain dragging and hammer sounding, electrical resistivity, infrared thermography and galvanostatic pulse. It cautions that the overall value and ranking were influenced to some extent by the selected performance measures and the weights and significance factors used in grading. Accuracy and precision were given the highest importance, followed by speed, ease of use and cost, each graded from 1 (poor) to 5 (excellent).

Two decision variables drive selection, according to the executive summary: the type of deterioration of highest concern to the agency, and whether the evaluation is for **network-level** condition monitoring or **project-level** maintenance or rehabilitation.

Network level. The goal is to rank decks and find candidates for action. Speed, cost per deck and minimal traffic impact dominate. Vehicle-mounted GPR and imaging methods suit this level because they cover large areas fast. Results are relative and used to prioritize.

Project level. The goal is to decide what to do to a particular deck and how much of it. Accuracy and spatial resolution dominate. A typical combination, consistent with the report's matrix, pairs a delamination method (IE, with sounding on bare decks) with a corrosion method (HCP, often with ER) and GPR for cover, thickness and a continuous attenuation map, calibrated by a limited number of cores and chloride samples.

Illustrative selection examples. The following scenarios are illustrative and simplify real decisions:

- *Bare deck, considering a thin polymer overlay:* the concern is whether delamination or active corrosion is too widespread for an overlay. Sounding or IE for delamination, HCP for active corrosion, and GPR for cover would answer the question; cores confirm.
- *Asphalt-overlaid deck of unknown condition:* sounding and HCP are compromised by the overlay. GPR is the usual first tool; IE may work if the asphalt is cold and well bonded. Removing test patches of asphalt allows direct checks.
- *New deck with cracking concerns:* the question is crack depth and concrete quality. USW (fair for vertical cracks) and UPE apply; visual mapping and cores remain essential.

The report's encouraging finding is that several NDT technologies can now collect data at a production rate comparable to chain dragging and hammer sounding, and that cost and speed should continue to improve. That removes much of the historical justification for relying on sounding alone.

Planning, reporting and acting on a deck survey

Define the question first. A deck NDT program should start with a written statement of the decision it supports: rank decks for a program, decide between overlay and replacement, quantify patching, or assess a specific concern such as a leaking joint. That statement drives the methods, grid density, ground truth and deliverables.

Grid and coverage. The R06A field validation used a 2-foot by 2-foot grid on a roughly 1,000 square foot test area, with seven longitudinal survey lines of 43 points each, and required every participant to repeat one survey line to evaluate

repeatability. That is a good template for a project-level point-based survey: a defined grid tied to permanent reference points, complete coverage, and a repeated line to demonstrate precision. The report's IE limitations note that a very dense grid is needed to define delamination boundaries accurately.

Ground truth. The R06A laboratory validation was valuable because cores and autopsies provided ground truth; the field validation could evaluate accuracy only to a lesser extent. In practice, a modest number of cores placed in areas the NDT classifies as sound, marginal and deteriorated lets the engineer check the classification and convert relative maps into repair quantities. Chloride samples at bar depth support the corrosion interpretation.

Conditions. Record temperature, recent precipitation, surface moisture and salting. The report's limits make these relevant: HCP needs temperatures above 2°C; GPR is affected by frozen moisture and deicing salts; IRT needs adequate solar loading and calm conditions; ER and GPM need prewetting; IE on asphalt overlays needs cold asphalt. Corrosion rates also vary seasonally.

Deliverables. Ask for raw or minimally processed data in addition to interpreted maps, the interpretation criteria and thresholds, grid coordinates tied to the plans, and a statement of method limitations as they applied to this deck. The R06A report noted that participants' repeatability results were reported at different levels of analysis, some only as graphics, which made objective comparison difficult; requiring a consistent level of reporting avoids the same problem in your program.

Integrate, then decide. Overlaying maps from different methods on the same grid is the most powerful step. Areas where IE shows delamination, GPR shows high attenuation and HCP shows potentials in the active range are high-confidence repair areas. Disagreement is also informative: high GPR attenuation without IE delamination may indicate a corrosive environment that has not yet cracked the concrete, a candidate for preservation rather than patching. Repair approaches are discussed in BR-C02 and preservation in BR-DP02.

Inspection records. NDT results can inform element-level condition data (see BR-I04) and deck ratings, but they do not replace the inspector's observations, and they should be documented as supplementary investigations with dates and methods so trends can be tracked.

Know the limits. Each method measures a physical property that correlates with deterioration; none measures "deck condition" directly. GPR measures attenuation, not delamination. HCP measures probability of active corrosion, not rate or section loss. IE measures reflector depth, not repair area. Sounding hears late-stage delamination, not early. The R06A report's central conclusion should be repeated in every deck investigation scope: no single technology detects all deterioration types, and complementary use of multiple technologies is required.

Key takeaways

- No single NDT method detects all deck deterioration; SHRP 2 R06A concluded complementary methods are required.
- Impact echo finds delamination, including incipient delamination below the audible range, and estimates its depth.
- GPR maps depth-corrected attenuation at the top rebar level; it indicates a corrosive environment and probable deterioration but cannot directly image dry delaminations.
- Half-cell potential gives the probability of active corrosion; it needs a bare surface, electrical connection and temperatures above 2°C, and gives no rate or section loss.
- Select methods by target deterioration and by network- versus project-level purpose, and calibrate with cores and chloride samples.

References

1. Gucunski, N., et al., Nondestructive Testing to Identify Concrete Bridge Deck Deterioration, SHRP 2 Report S2-R06A-RR-1, Transportation Research Board, Washington, D.C., 2013 (doi:10.17226/22771)

Study text only; the final quiz is taken online. Verify all references against the edition your agency has adopted.