In-Place Evaluation Methods

Concrete Technology and Codes

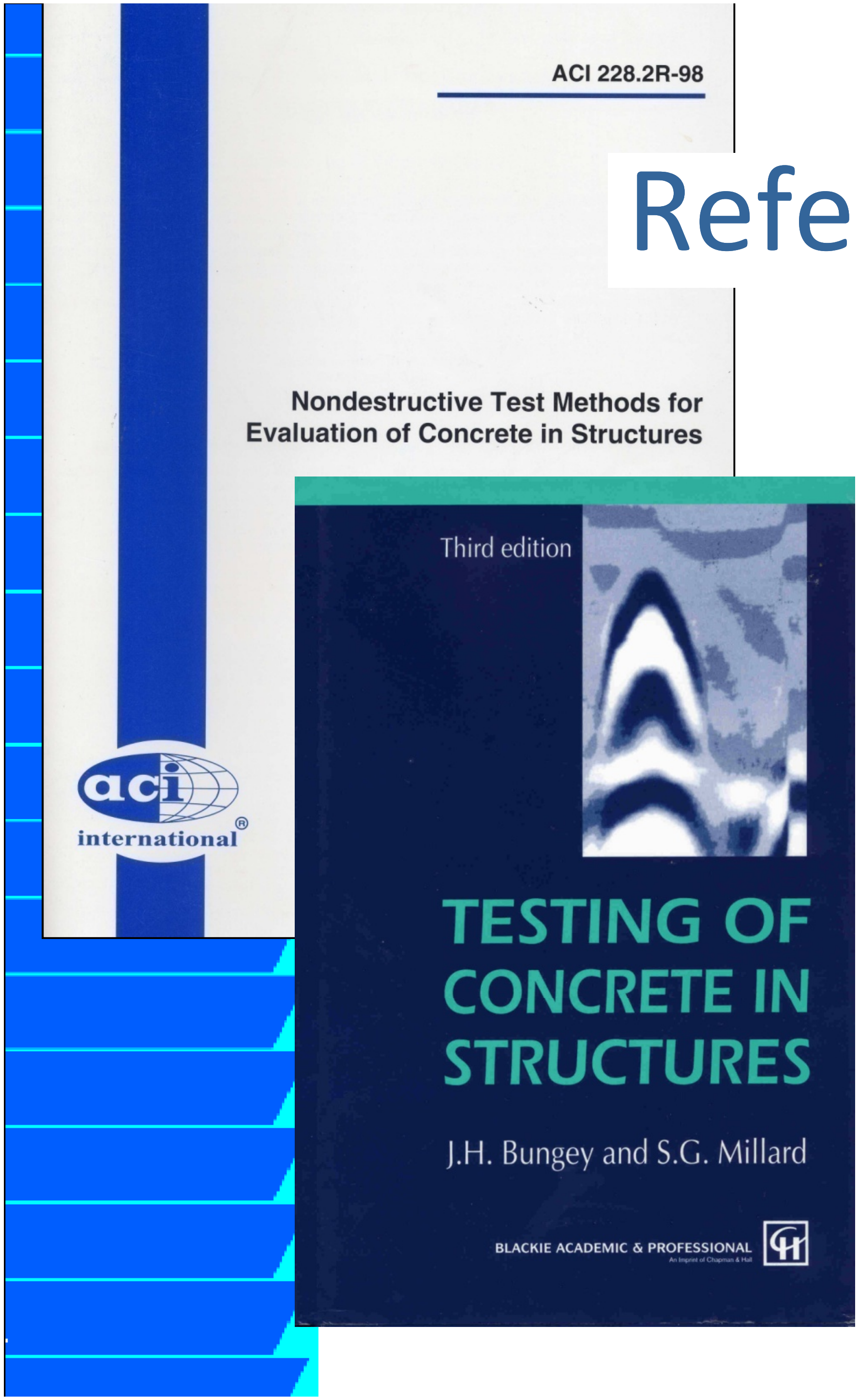
Evaluation of Concrete

- Visible features
  - Cracking, deterioration, deflections
- In-place strength
- Internal conditions
  - Corrosion of reinforcement
  - Voids
  - Honeycombing
  - Voids in tendon ducts
  - Delaminations
  - Member thickness

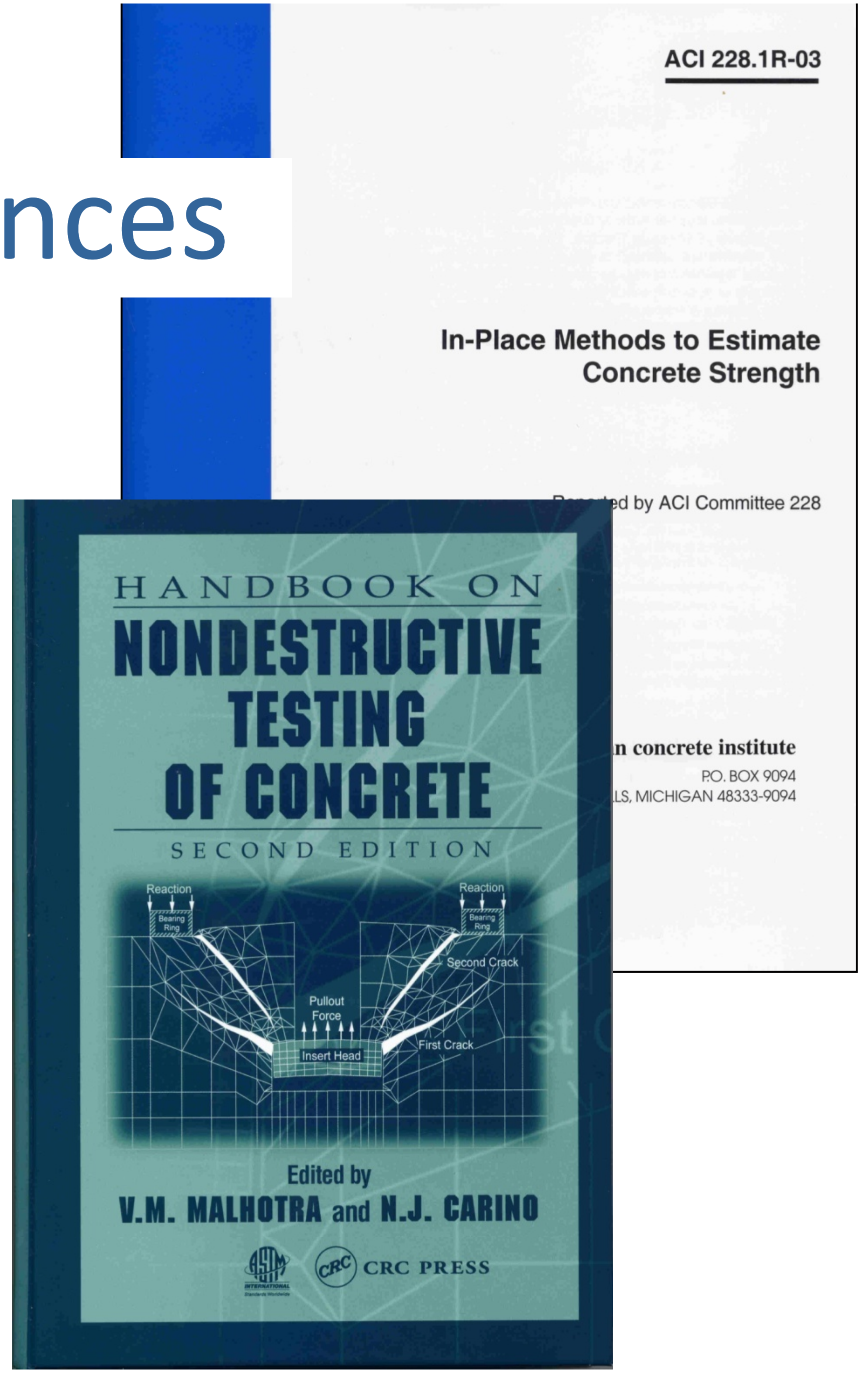
Tools

- Visual inspection
- Removal of samples
  - Core compressive strength
  - Petrographic analysis
- Tests for in-place uniformity
- In-place strength methods
- Stress-wave methods
- Ground penetrating radar
- Corrosion evaluation methods

References



ACI 228.2R-98
Nondestructive Test Methods for
Evaluation of Concrete in Structures
aci
international
Third edition
TESTING OF
CONCRETE IN
STRUCTURES
J.H. Bungey and S.G. Millard
BLACKIE ACADEMIC & PROFESSIONAL



ACI 228.1R-03
In-Place Methods to Estimate
Concrete Strength
P.O. BOX 9094
HANDBOOK ON
NONDESTRUCTIVE
TESTING
OF CONCRETE
SECOND EDITION
Reaction
Reaction
Second Crack
Pullout
Force
Insert Head
First Crack
Edited by
V.M. MALHOTRA and N.J. CARINO
CRC PRESS

ACI 349.3R

ACI 349.3R-02

Evaluation of Existing Nuclear Safety-Related Concrete Structures

Reported by ACI Committee 349

Ronald J. Janowiak*
Chair

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Gunnar A. Harstead	Dragos A. Nuta	

*Members of subcommittee authoring this report.

This report recommends guidelines for the evaluation of existing nuclear safety-related concrete structures. The purpose of this report is to provide the plant owner and engineering staff with an appropriate procedure and background for examining the performance of facility structures and taking appropriate actions based on observed conditions. Methods of examination, including visual inspection and testing techniques, and their recommended applications are cited. Guidance related to acceptance criteria for various forms of degradation is provided.

CONTENTS

ACI 364.1R

ACI 364.1R-07

Guide for Evaluation of Concrete Structures before Rehabilitation

Reported by ACI Committee 364

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Timothy R. W. Gillespie	Keith E. Kesner	K. Nam Shiu	

This guide presents general procedures for evaluation of concrete structures before rehabilitation. Among the subjects covered are: preliminary investigation, detailed investigation, documentation, field observation and condition survey, sampling and material testing, evaluation, and final report. Evaluation to identify seismic deficiencies is beyond the scope of this report.

Keywords: concrete; condition survey, deterioration; distress; evaluation, investigation, rehabilitation; sampling; testing.

Outline

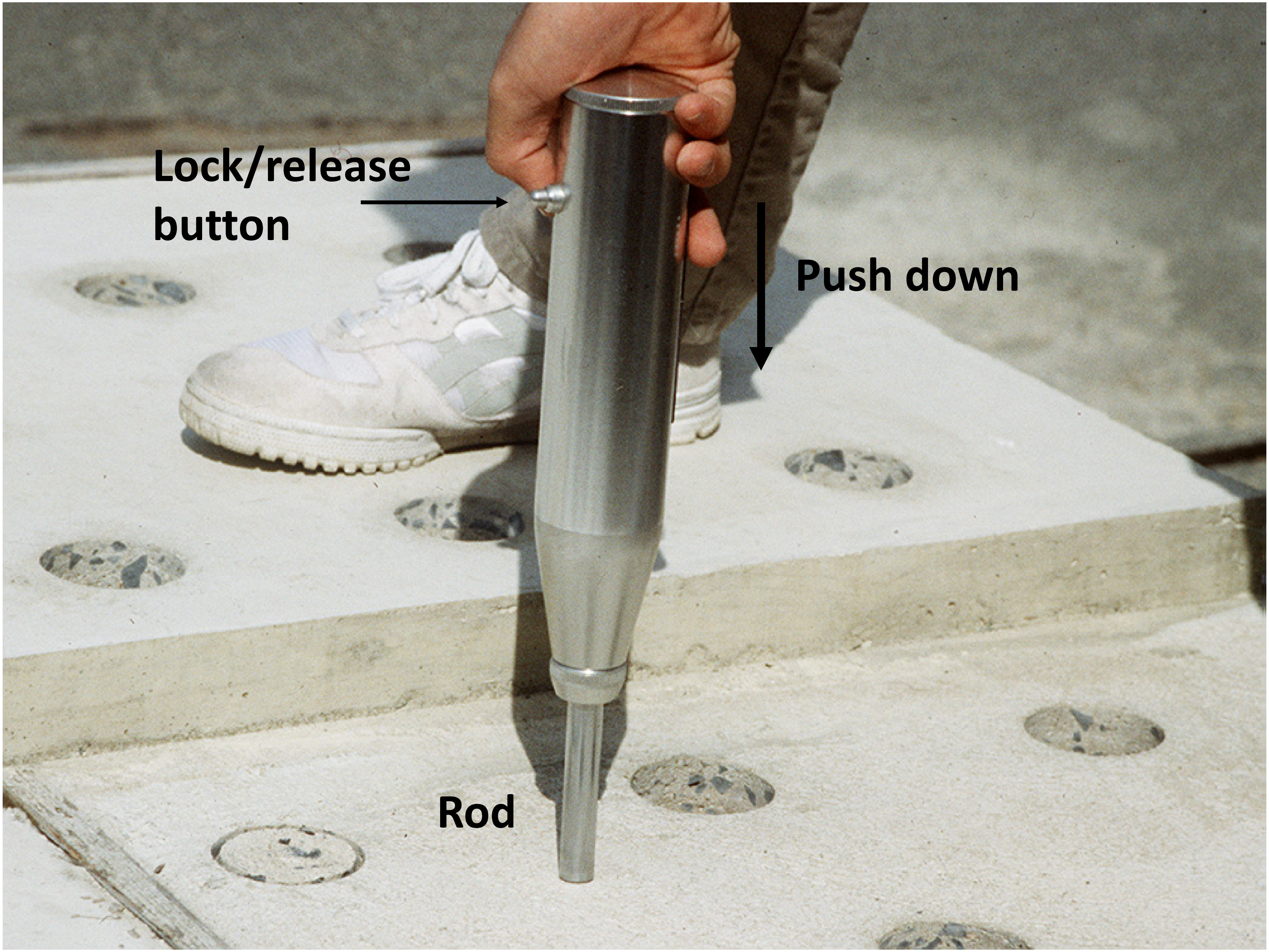
- Tests for uniformity
- Tests for in-place strength
- Methods to locate internal defects
- Evaluation of corrosion

Tests for Uniformity

- Determine which portions of structure are similar
- Identify areas for further investigation by other means
- Methods
  - Rebound number (hammer)—ASTM C805
  - Ultrasonic pulse velocity—ASTM C597

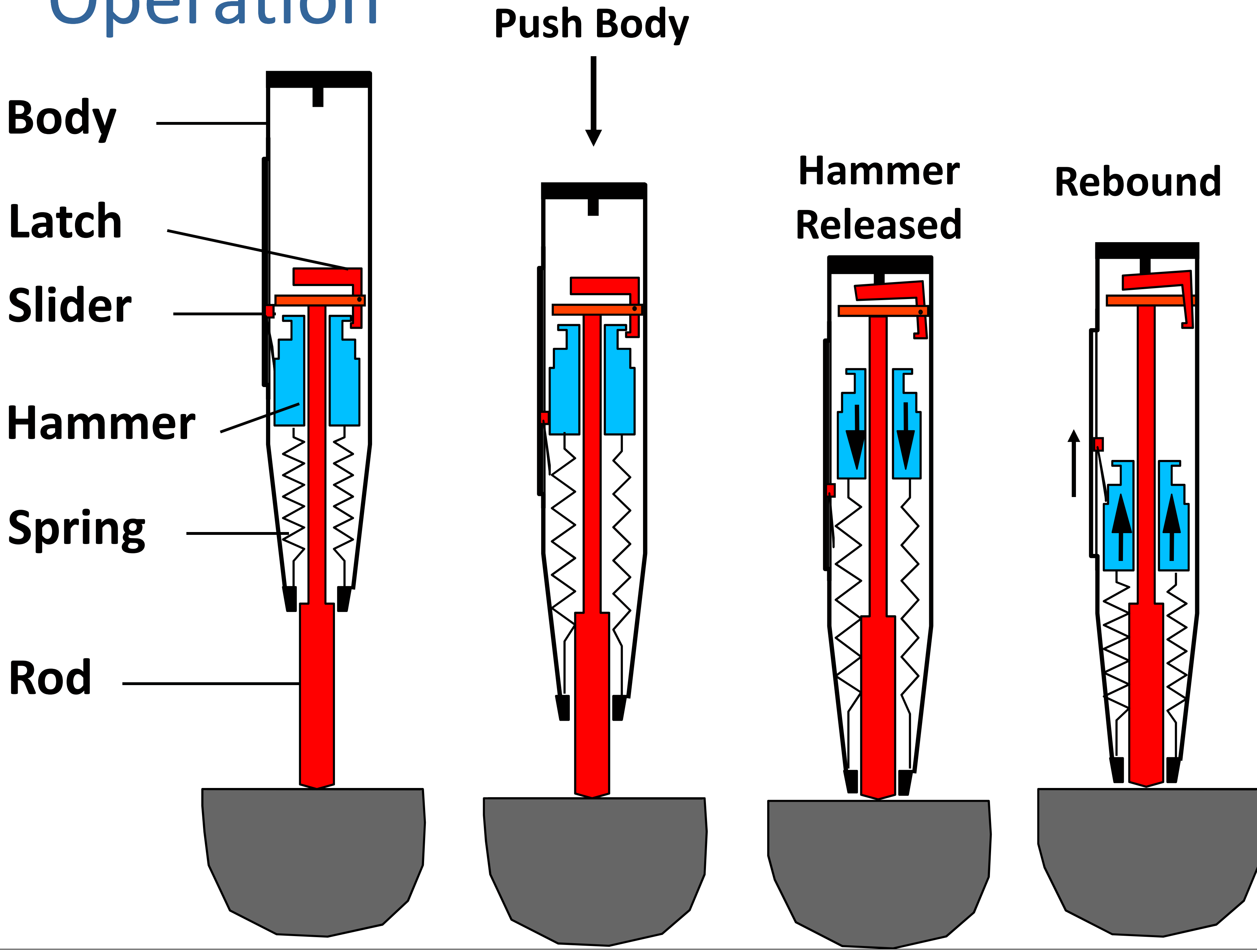
Rebound Number (Hammer) ASTM C805

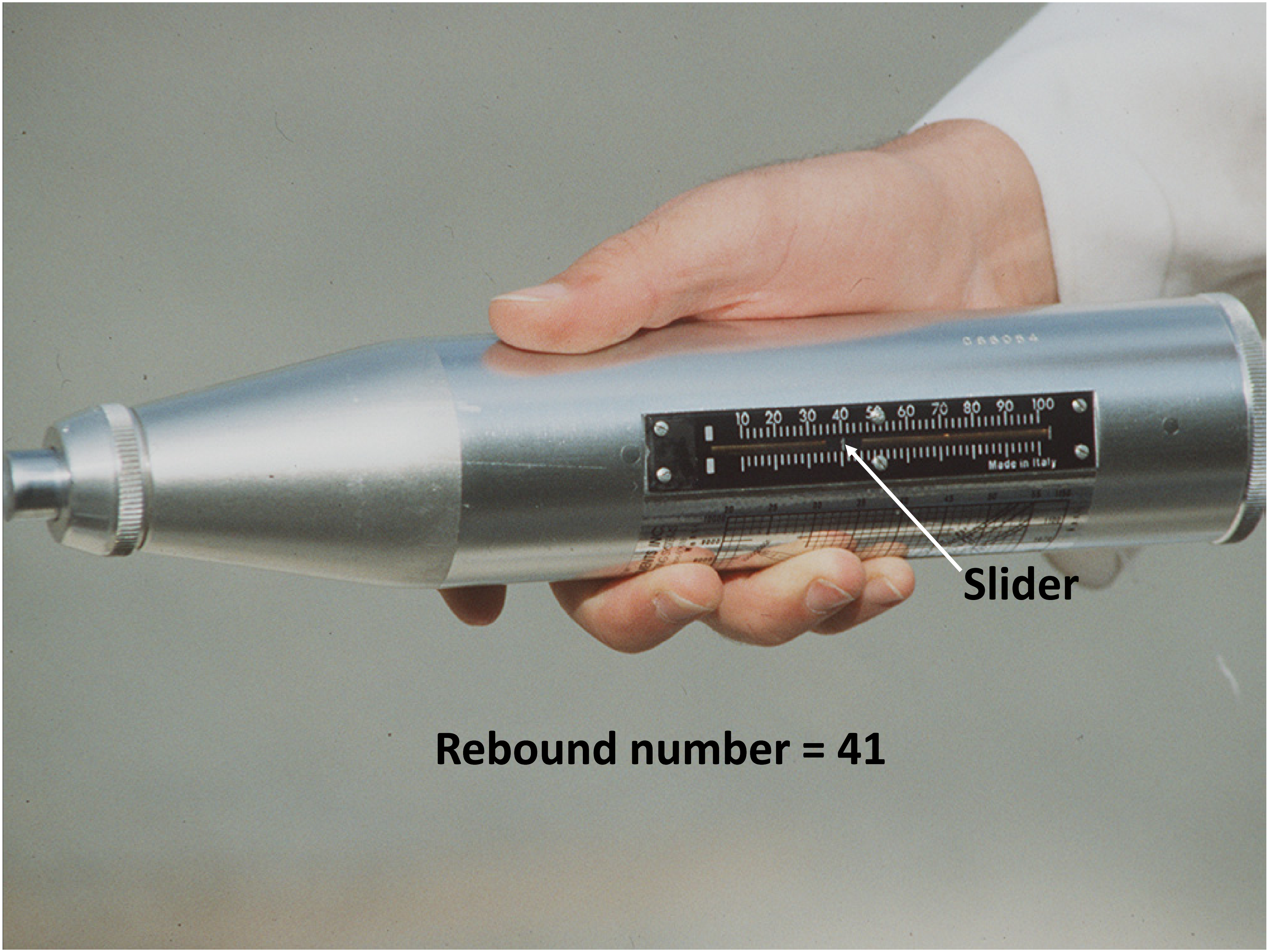
Measure the rebound of spring-driven mass (hammer) after impact with rod in contact with concrete.


Lock/release
button
Push down
Rod

Rebound Hammer

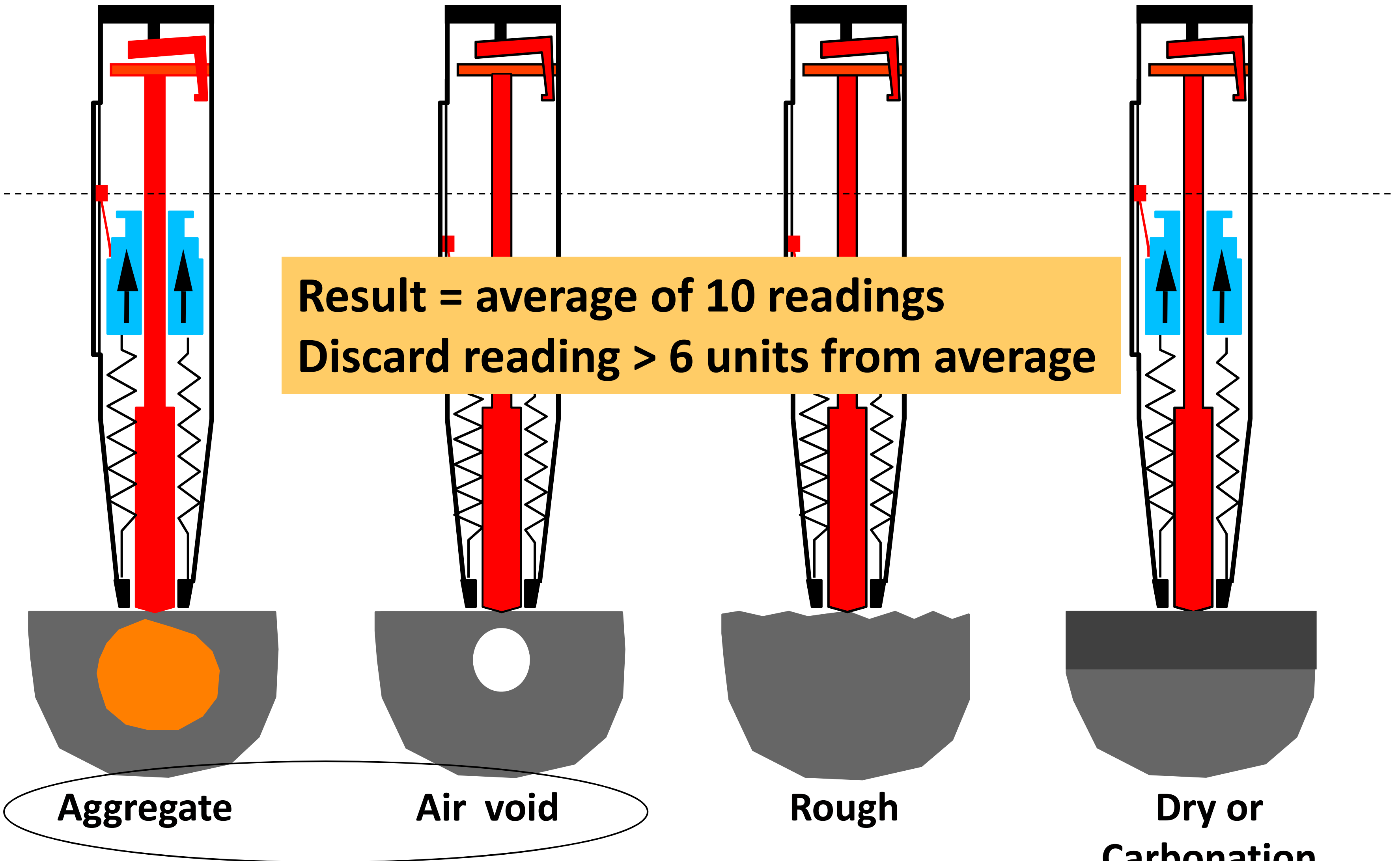
Operation


Body
Latch
Slider
Hammer
Spring
Rod
Push Body
Hammer Released
Rebound



Rebound number = 41

Near-surface Effects



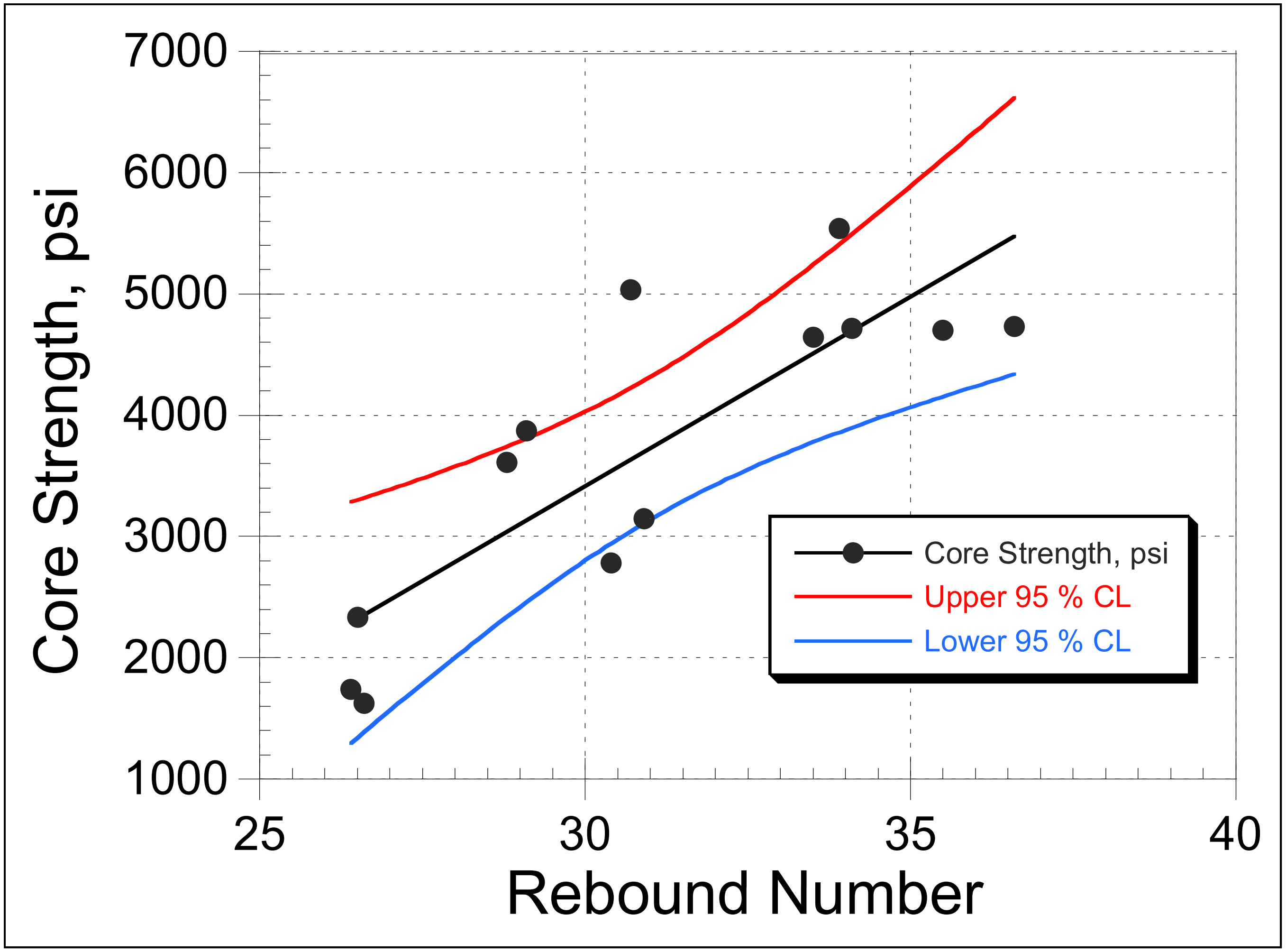
Factors Affecting Rebound Number

- Strength and elastic modulus of near surface concrete
- Layer of carbonation
- Surface texture
- Surface moisture condition

To Estimate Strength

- The only reliable approach is to correlate rebound number with strength of cores
- Need at least 6 strength levels (ACI 228.1R)
- Thus at least 12 cores to establish a correlation

Example



Ward, M.A. and Langan, B.W., *Cement Concrete and Aggregates*, 16(2), Dec. 1994, 181-185

Ultrasonic Pulse Velocity ASTM C597

Measure travel time of ultrasonic pulse (compressional stress wave) over known path length.

Stress Wave

- A disturbance that transfers energy progressively from point to point in a medium

  WebFiles\waves-intro.html

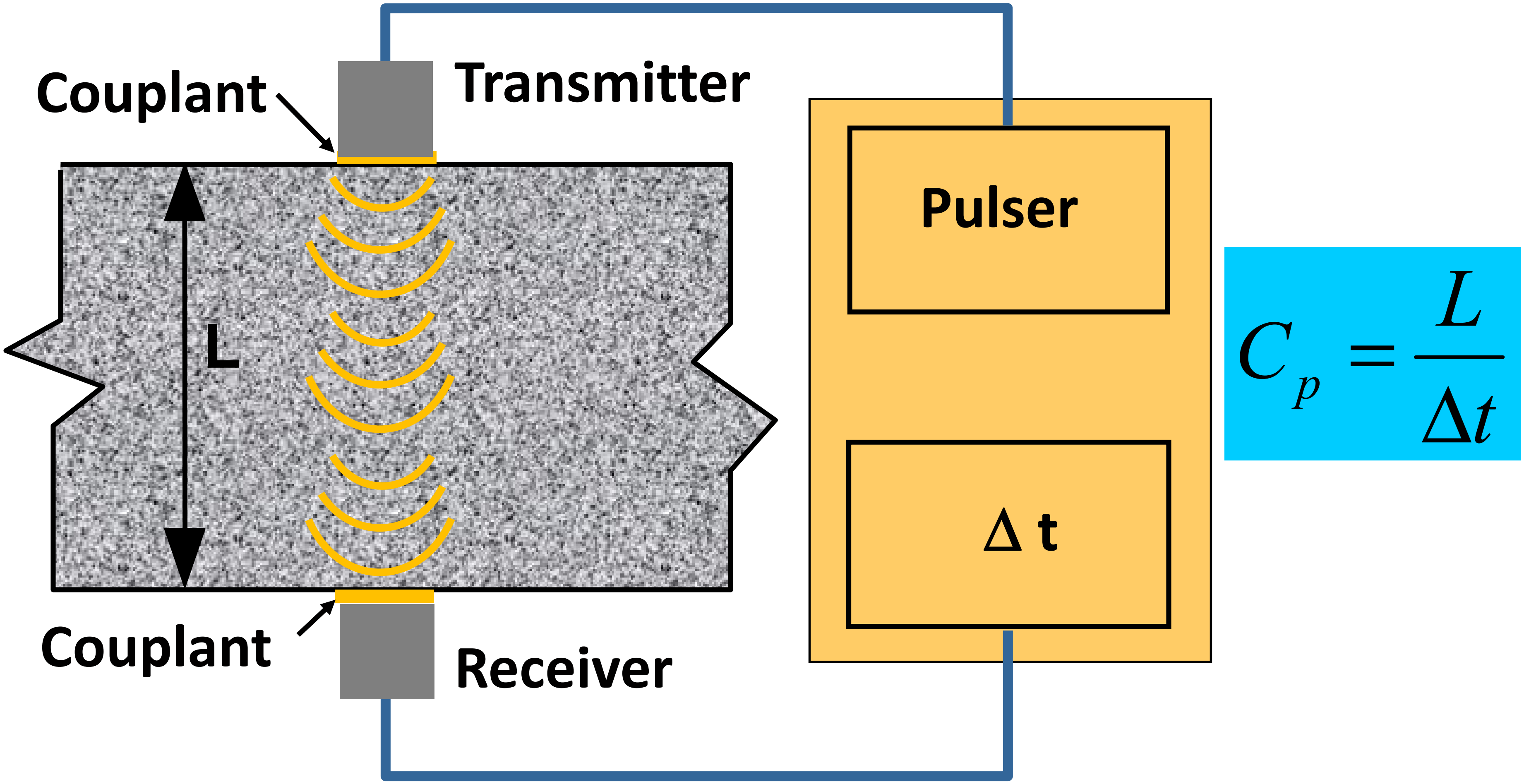
- Speed of compression stress wave in concrete:

$$C_p \approx 1.05\sqrt{\frac{E}{\rho}}$$

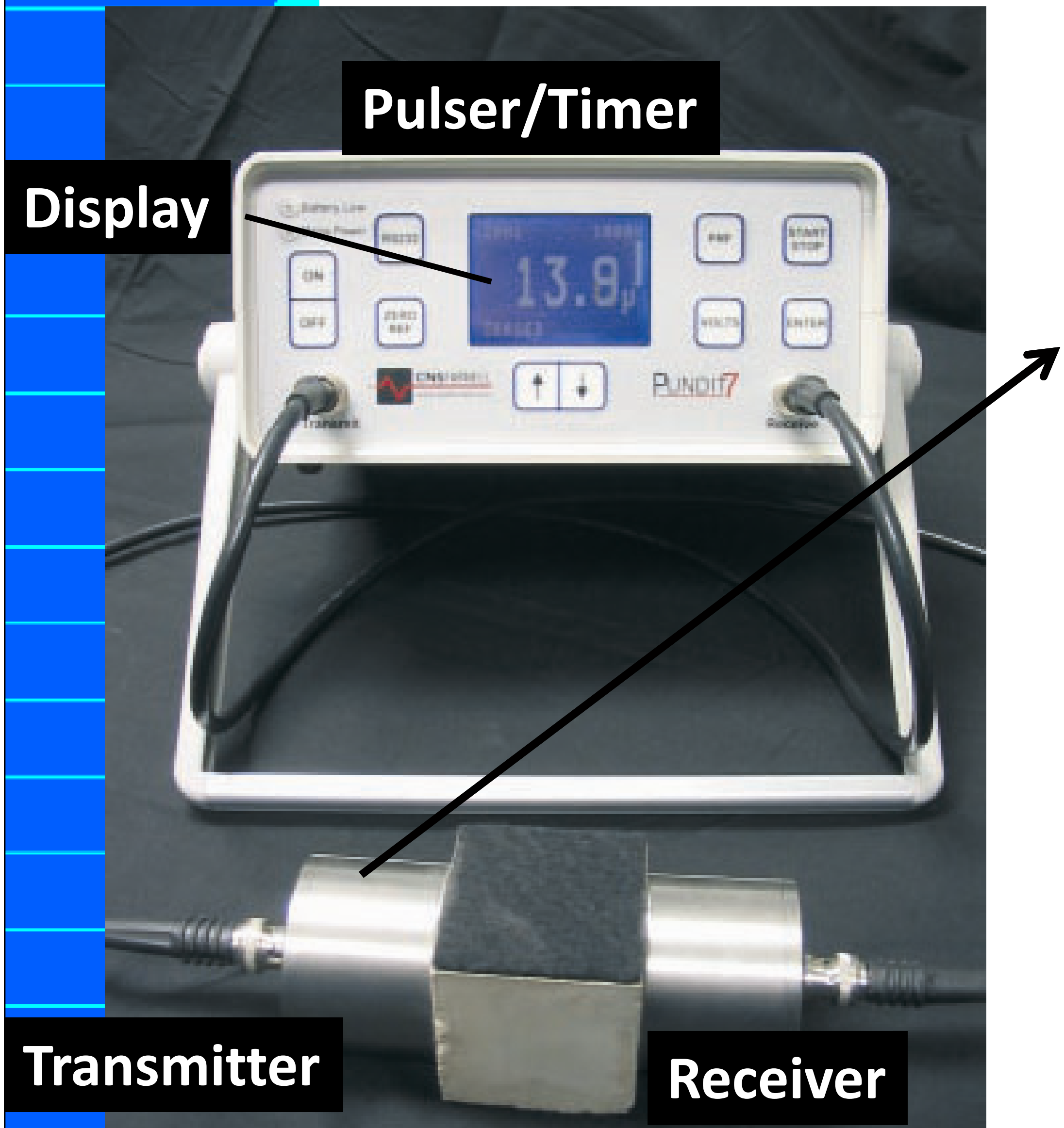
- For "good" concrete: $C_p \approx 4000$ m/s

http://www.kettering.edu/~drussell/Demos/waves-intro/waves-intro.html

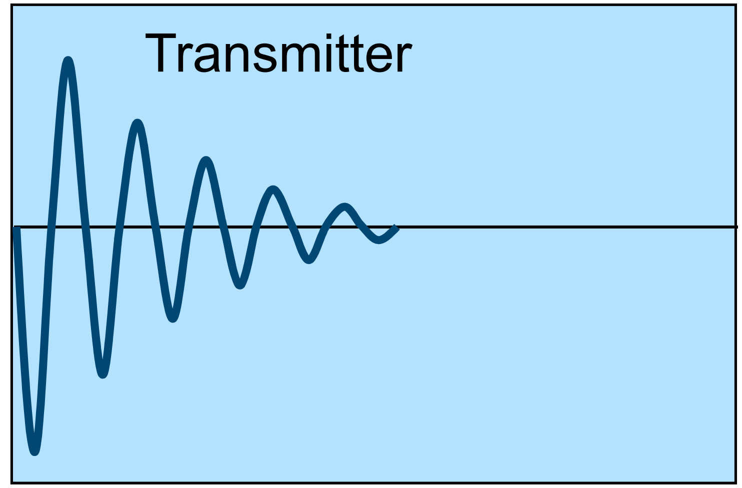
UPV—Principle of Operation

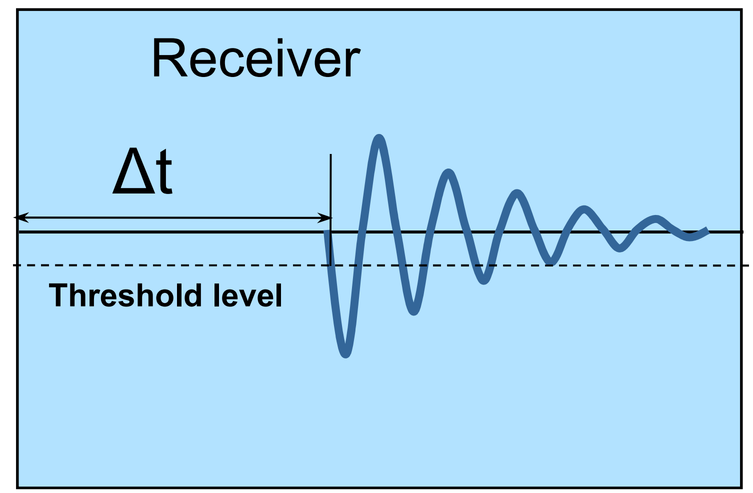


Example



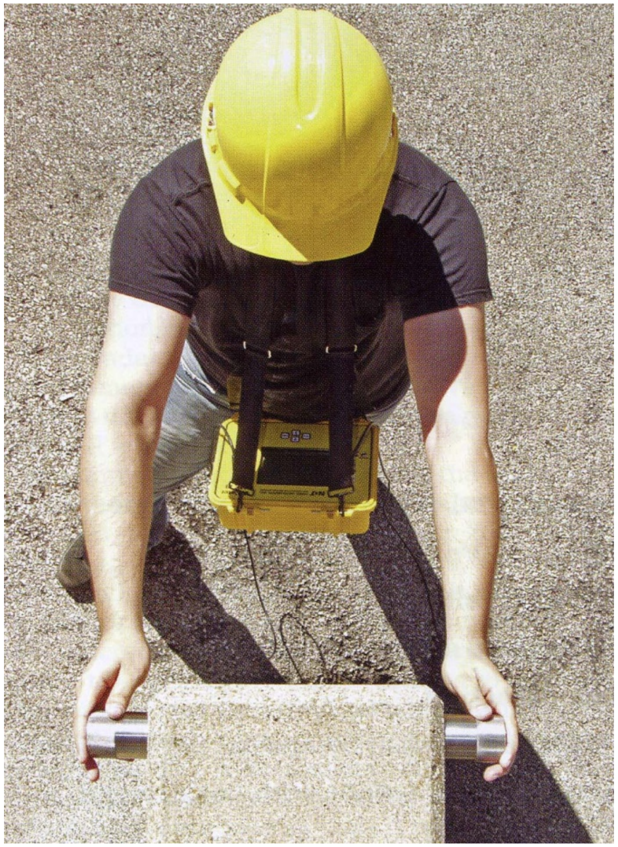
Courtesy of CNS Farnell



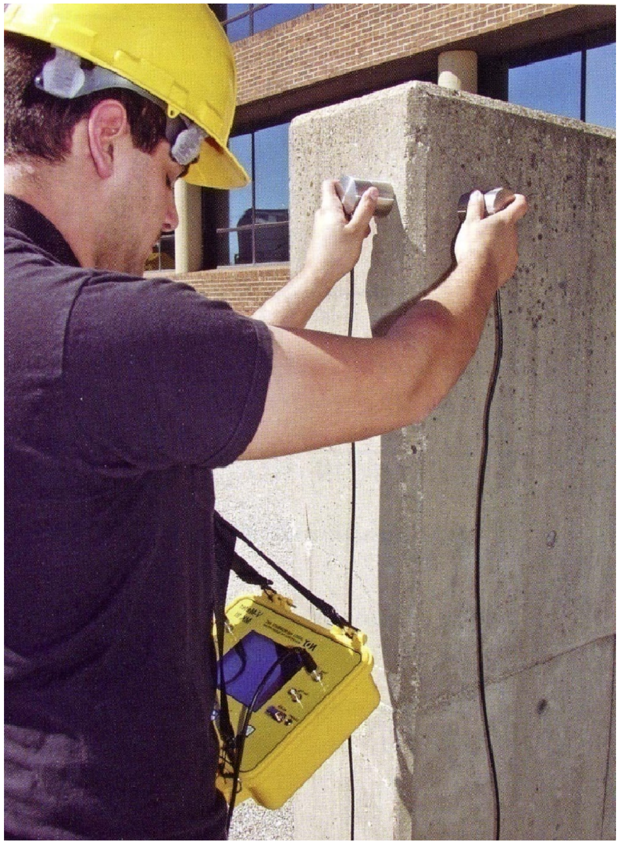


Measurement Paths

Direct path



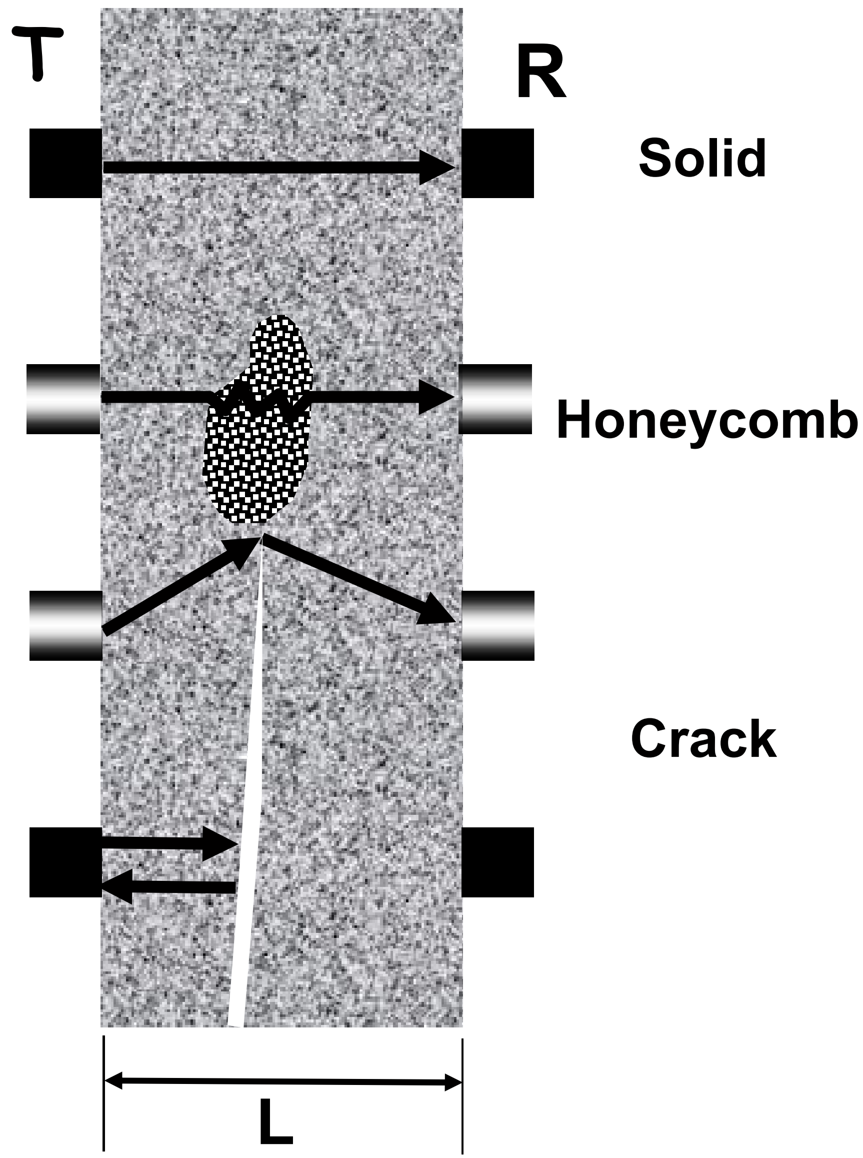
Semi-direct path



Courtesy of James Instruments Inc.

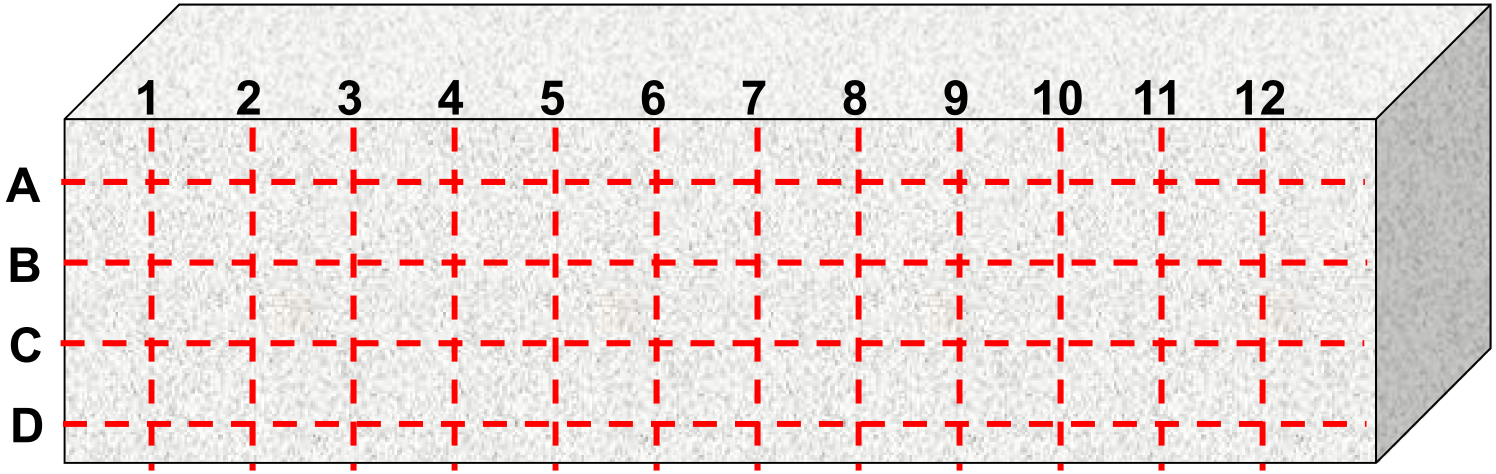
Effects of Internal Defects

Presence of "defects" increases travel time, and results in lower computed speed.



Assessment of Uniformity

- Draw grid on the surface of test object
- Perform tests at grid points
  - Test at same points to assess age related deterioration
- Plot UPV contours



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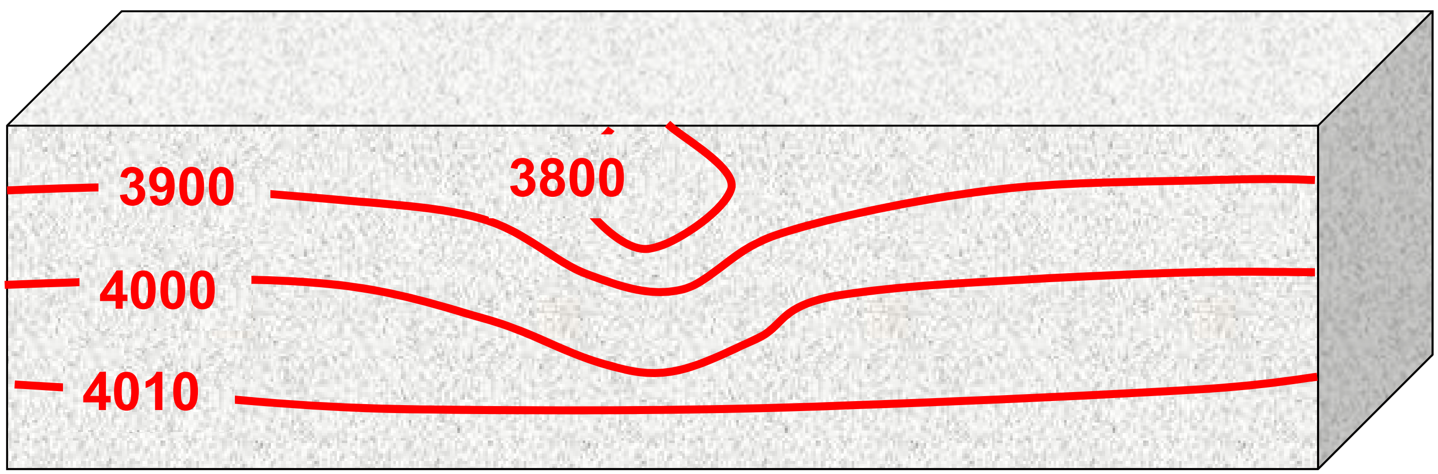
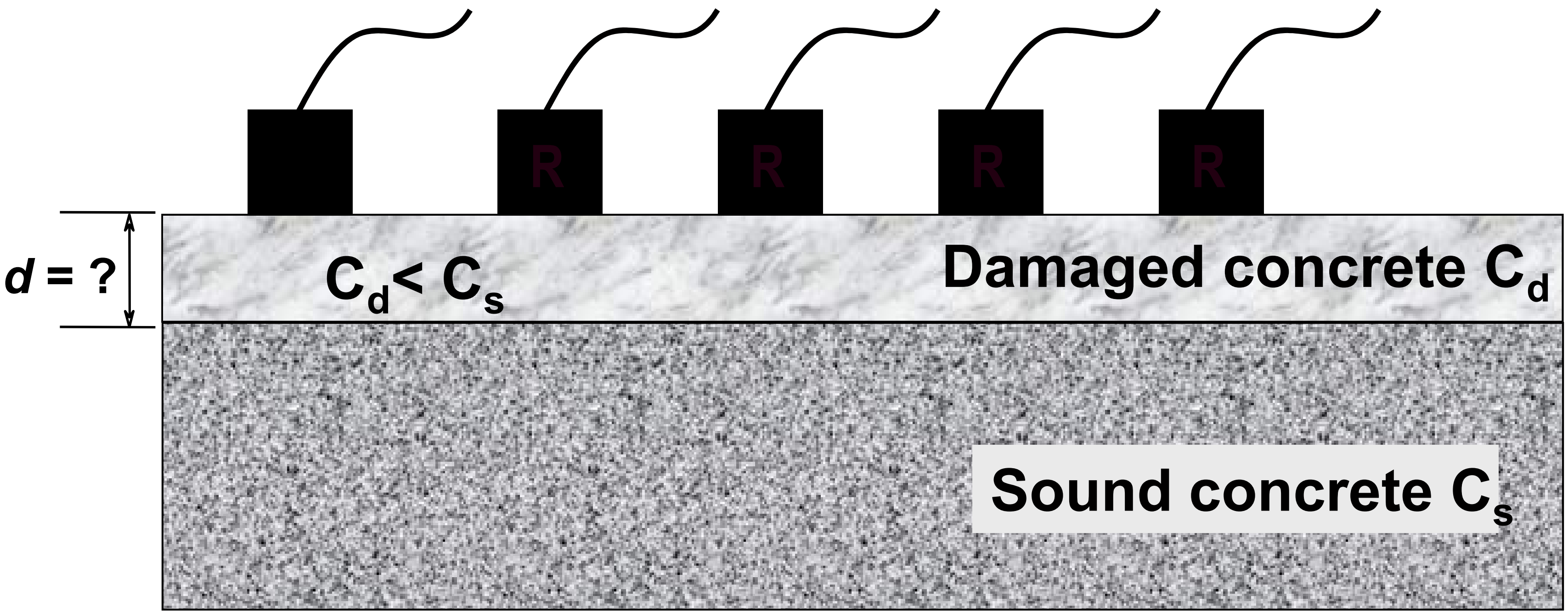


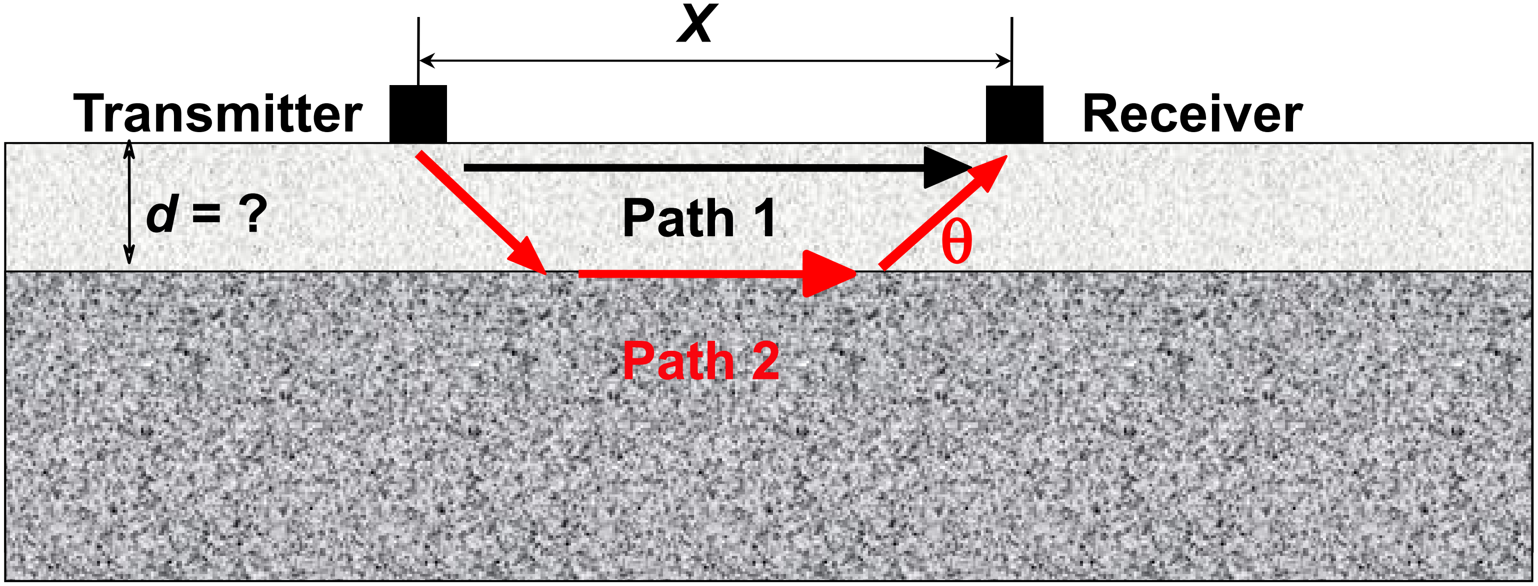
Depth of Surface Damage

- UPV Method can be used to estimate depth of damaged concrete (such as by fire)
  - Requires distinct boundary between sound and damaged concrete
  - Multiple travel time measurements along surface

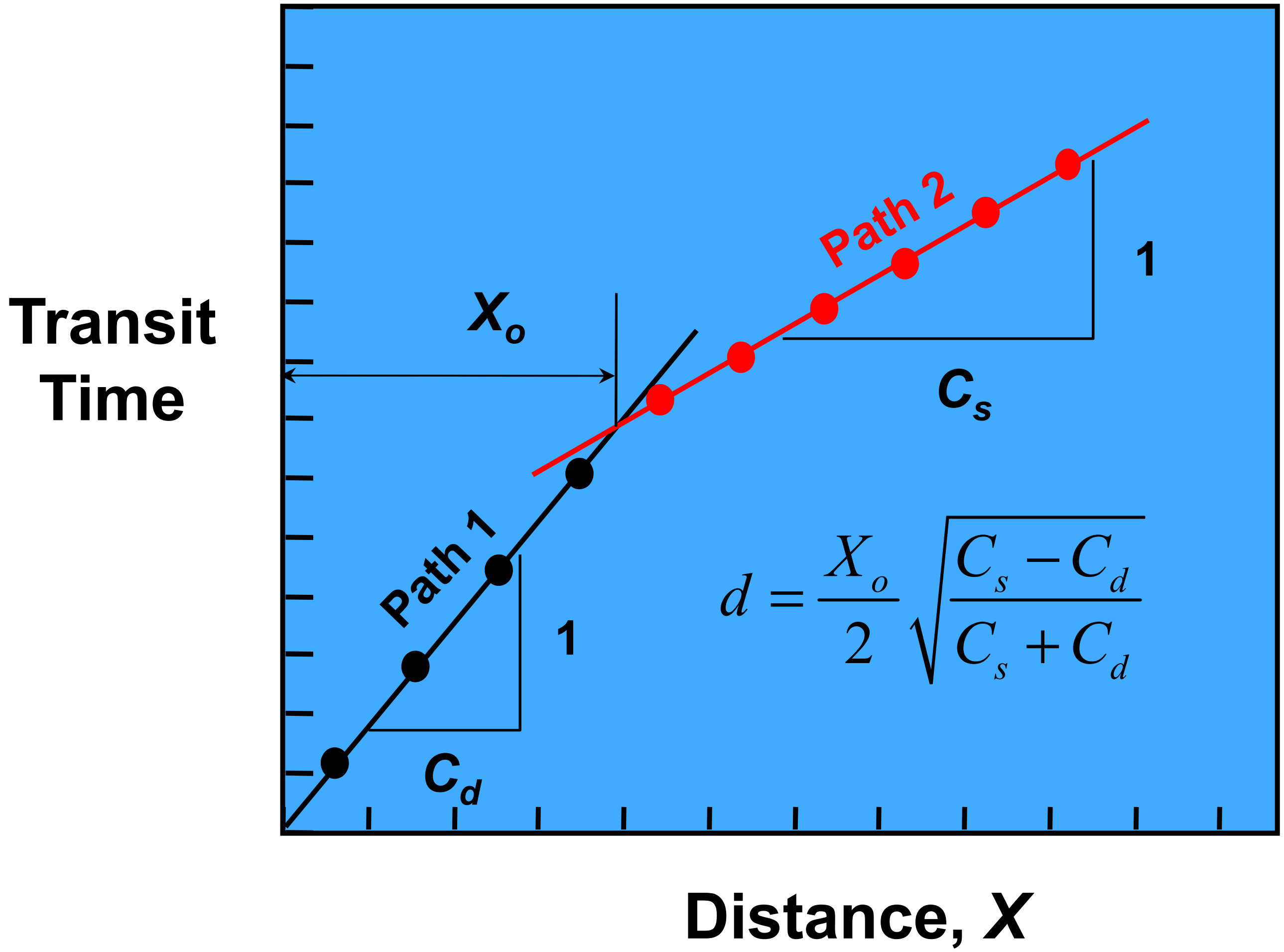


Depth of Surface Damage

- There are two ray paths
  - Path 1: through damage concrete
  - Path 2: through damaged concrete and sound concrete
- For certain separation, X_o, transit times are equal



Determination of *d*



Chung and Law, *Cement Concrete and Aggregates*, 7(2), 1985, 84-88

Tests of Uniformity

- Rebound number
  - Fast and simple to use
  - Assesses surface condition
- Pulse velocity
  - Relatively simple to use
  - Assess concrete between transducers
  - Advanced application—depth of surface damage (fire)

In-Place Strength

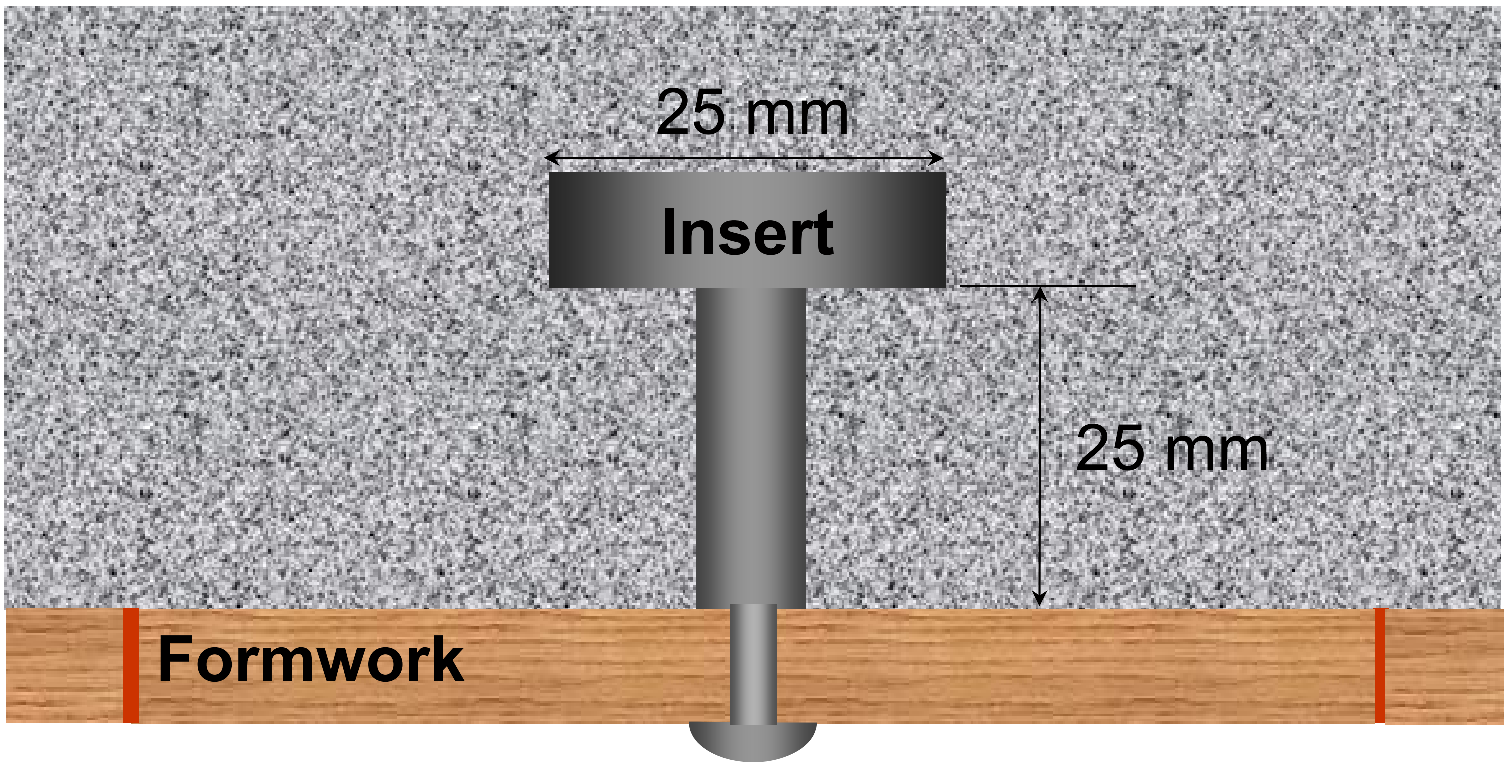
- Common method: drill cores according to ASTM C42/C42M and test according to ASTM C39/C39M
  - Requires at least 3.7 in. diameter and length
  - No reinforcing steel in core
- Post-installed pullout test (CAPO)
  - Estimate compressive strength based on correlation
- Pull-off test
  - Direct tensile strength

Pullout Test
ASTM C900

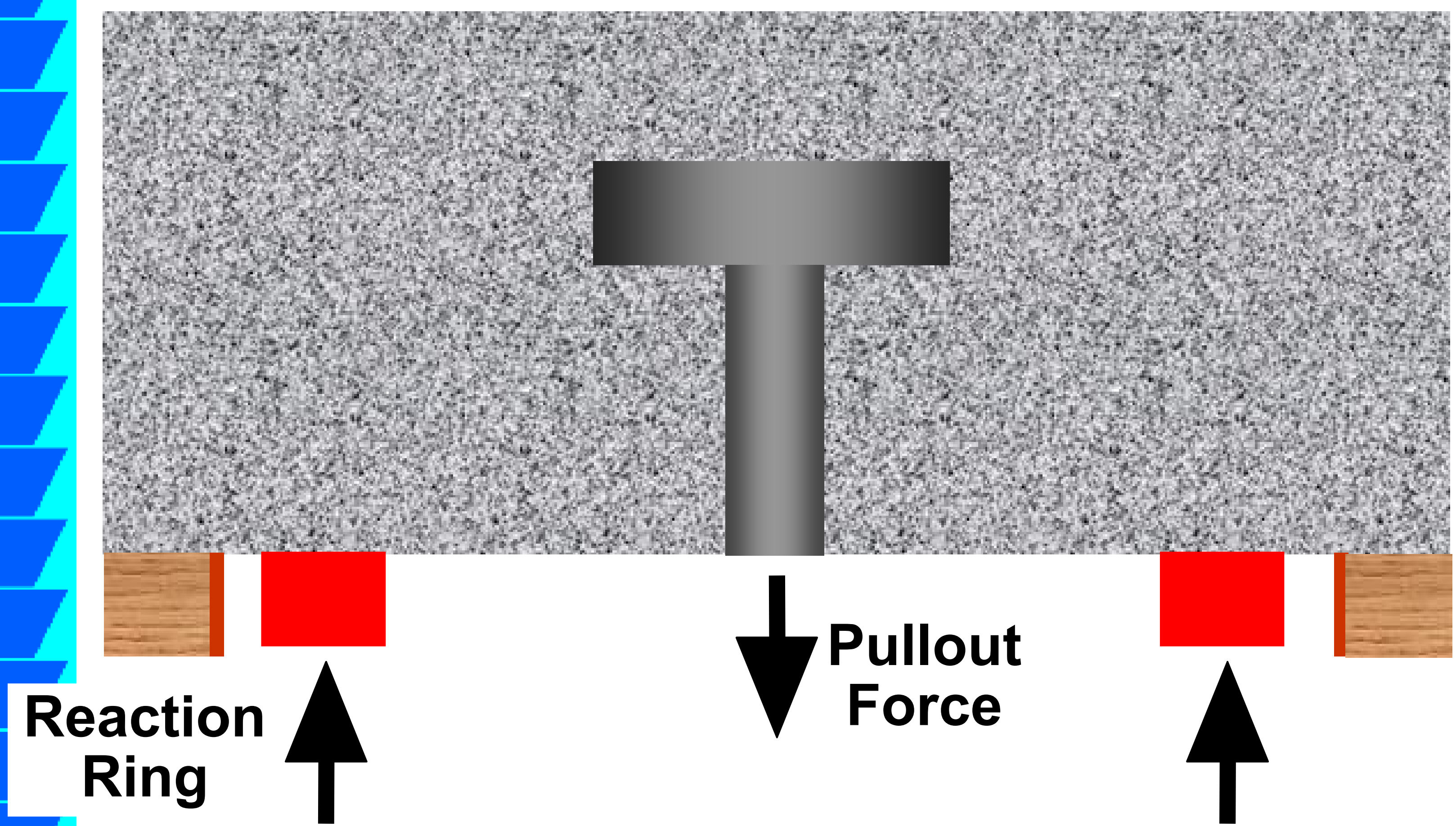
Measure force to pullout an insert anchored in concrete.

- Cast-in-place (CIP): attached to formwork or inserted into top surface of freshly cast slab (during construction)
- Post-installed (PI); placed into drilled hole with undercut slot (existing construction)

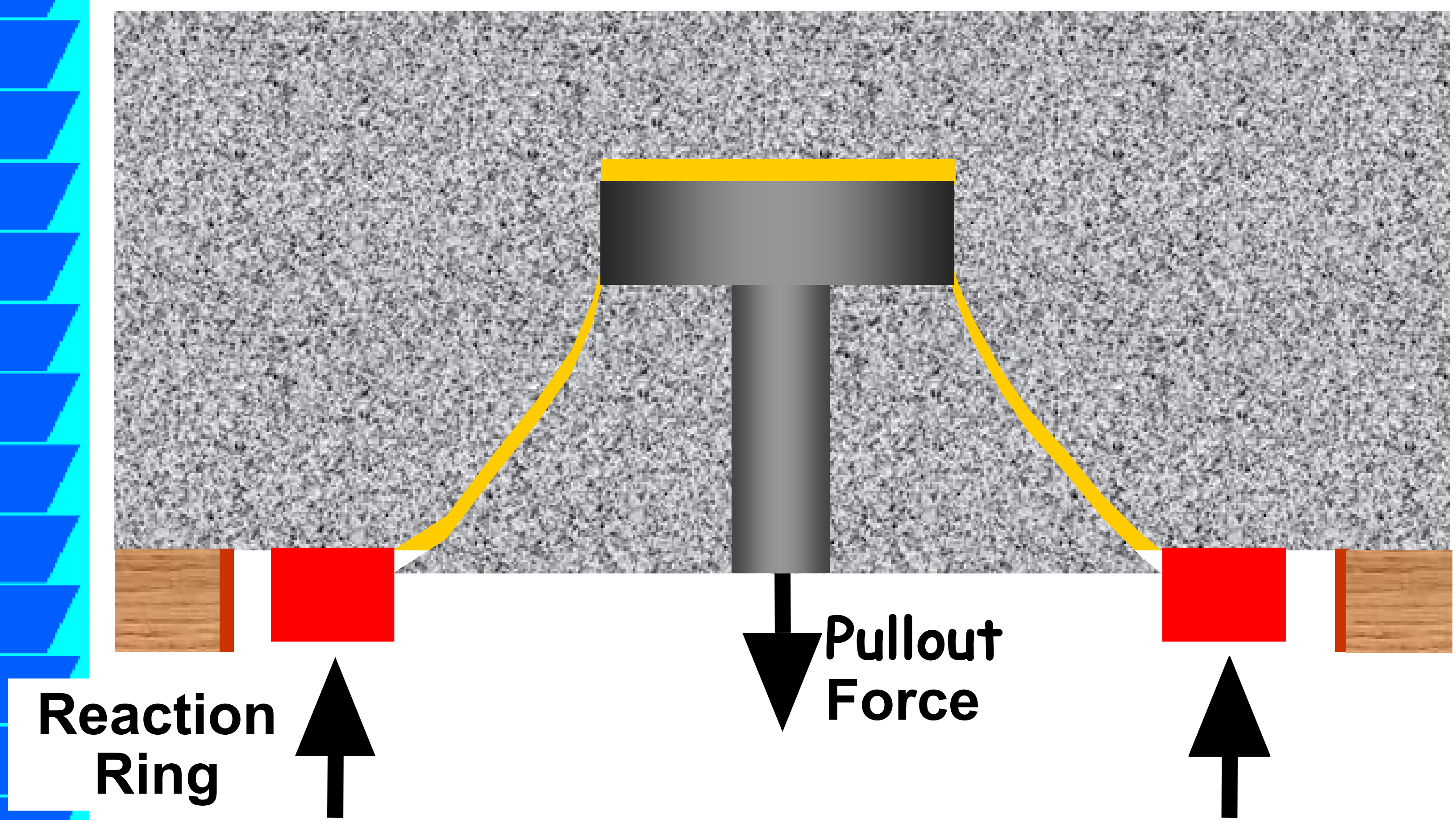
CIP-Pullout Test



CIP-Pullout Test

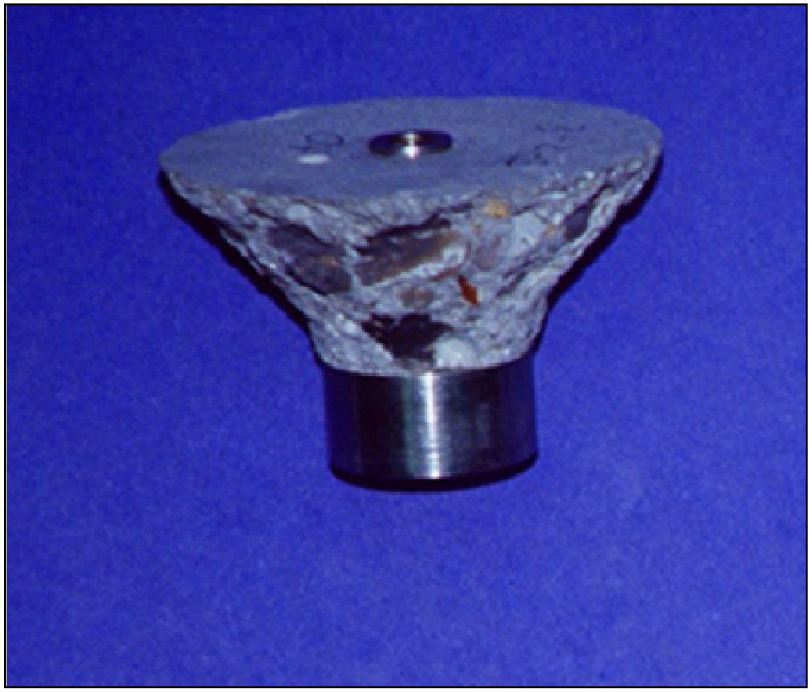


CIP-Pullout Test



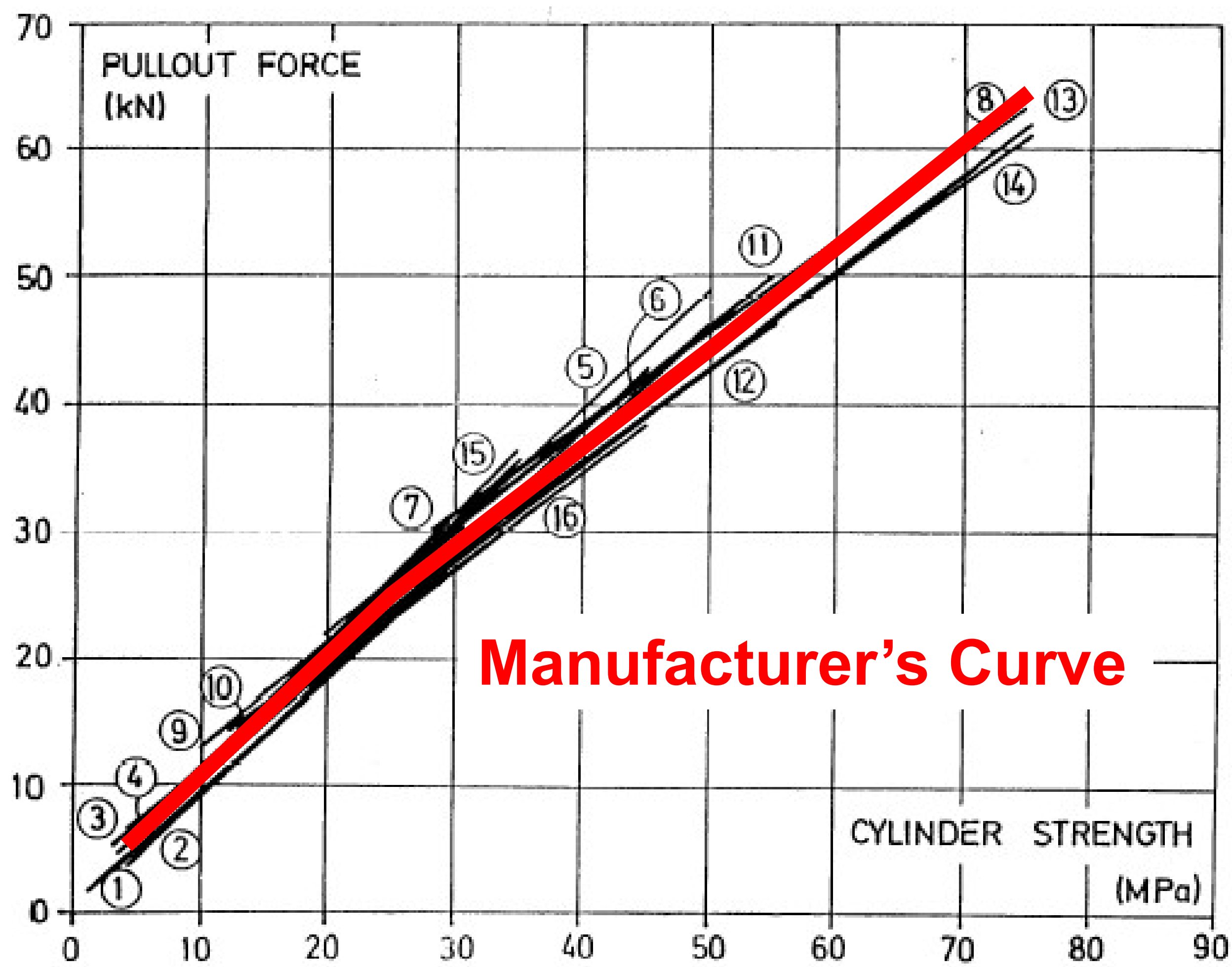
Pullout Test-LOK Test

Pull Machine



Conical Fragment

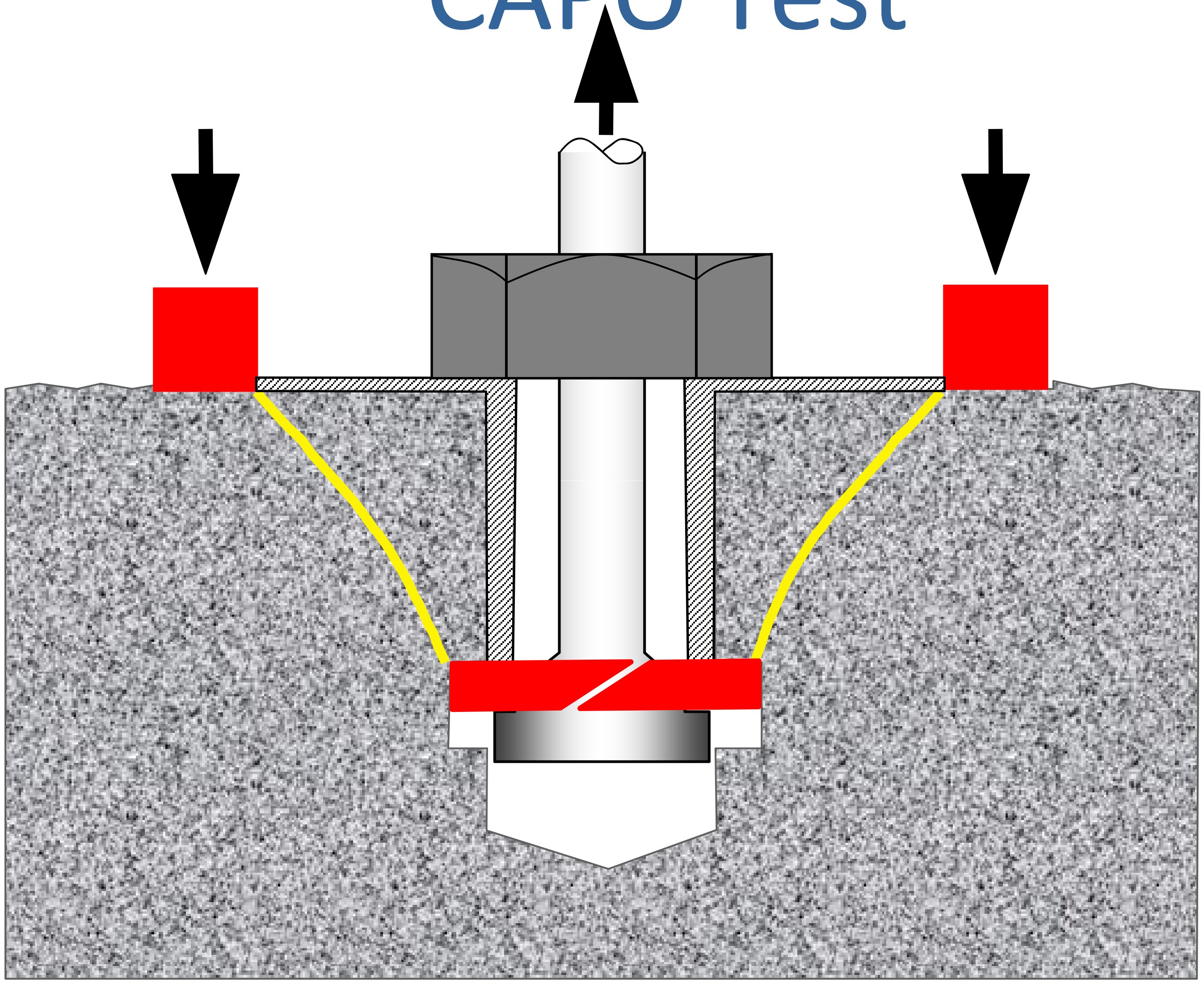
Results of 16 Correlations



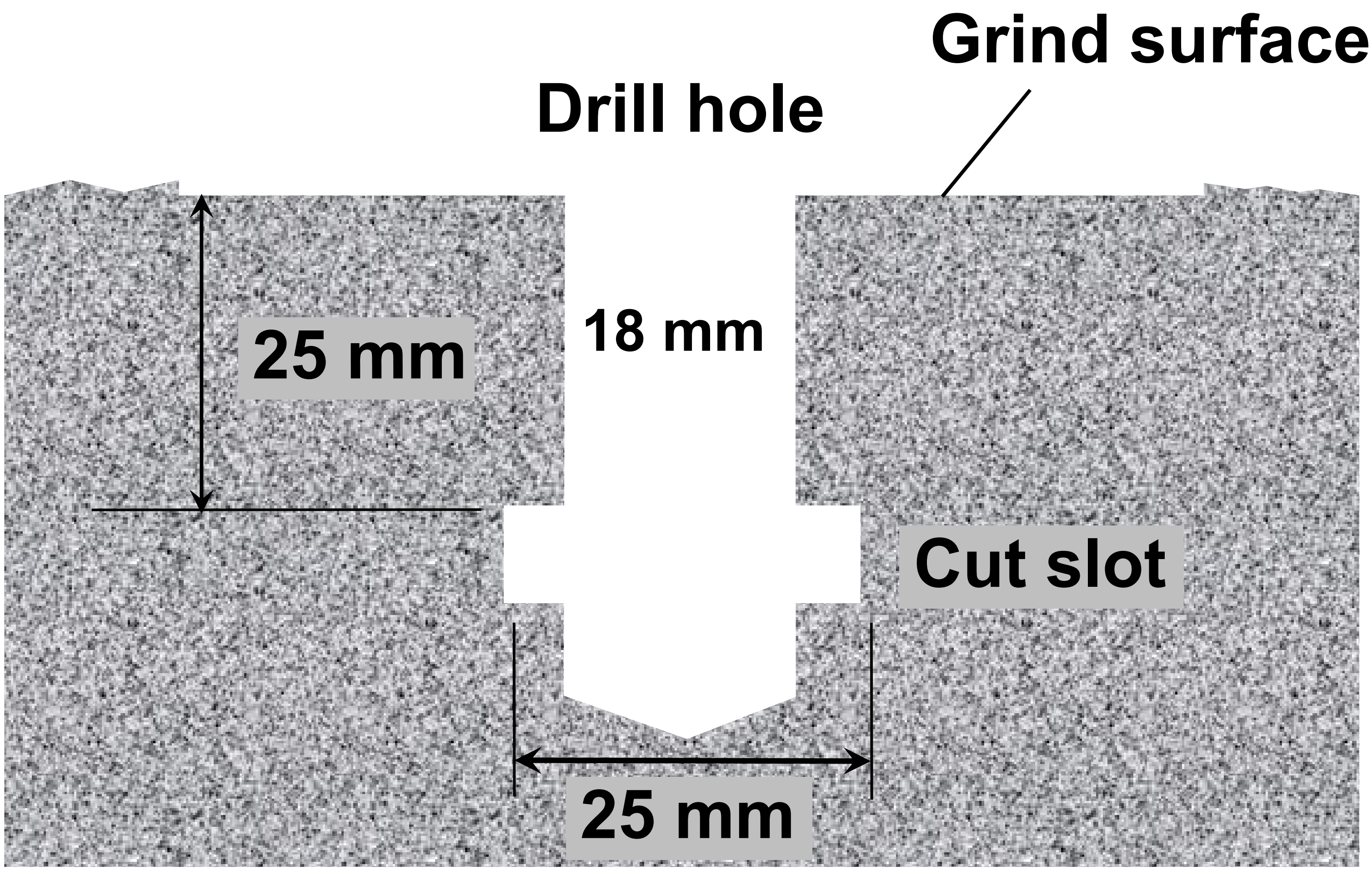
Post-Installed Tests

- Does not require pre-planning test locations
- Can perform test at any accessible location
- Permits testing of existing structures

Post-Installed Pullout Test
CAPO Test



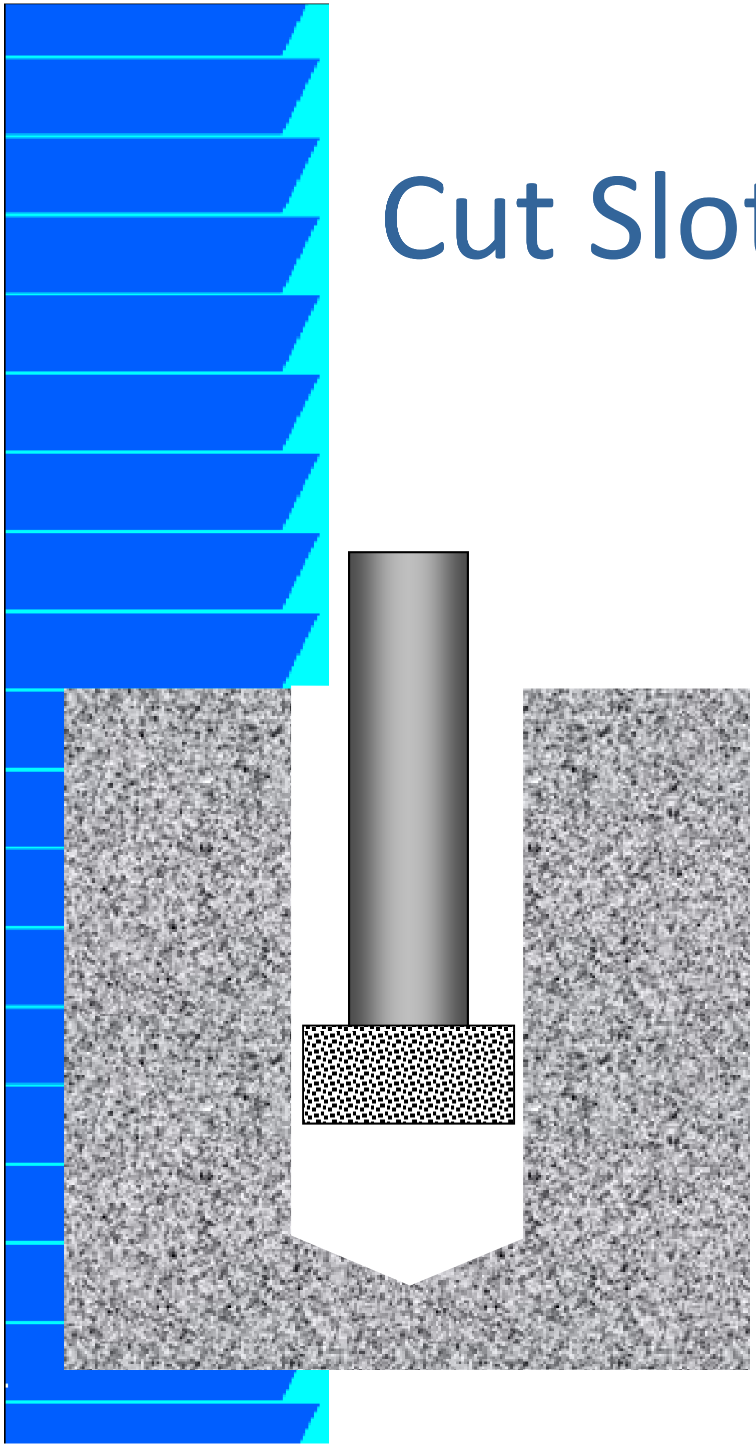
Prepare Concrete



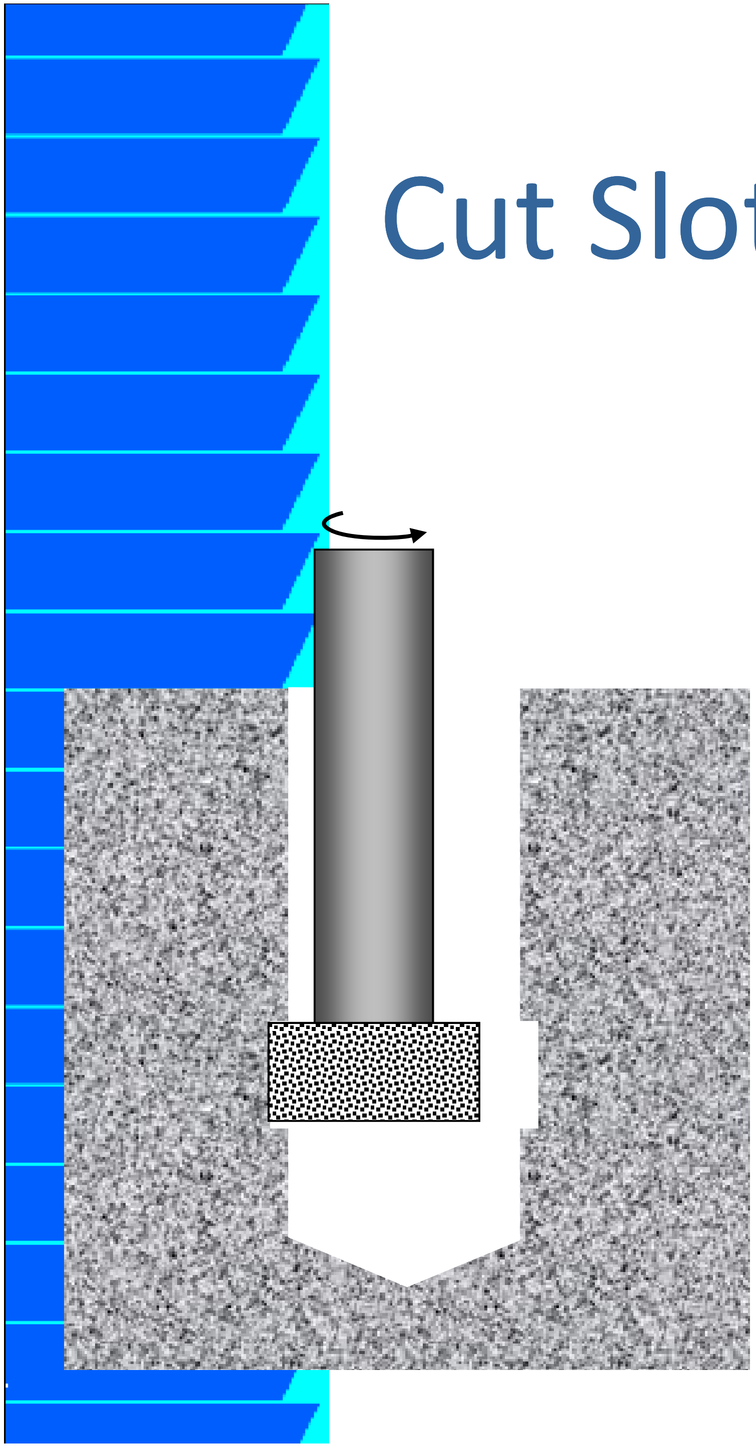
Drill Hole

Surface Planing

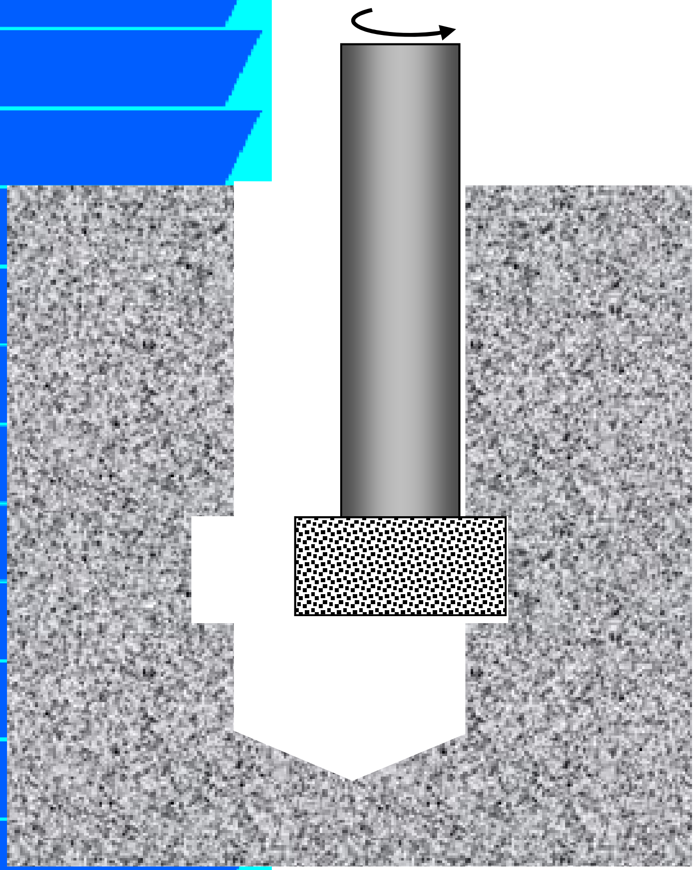
Cut Slot



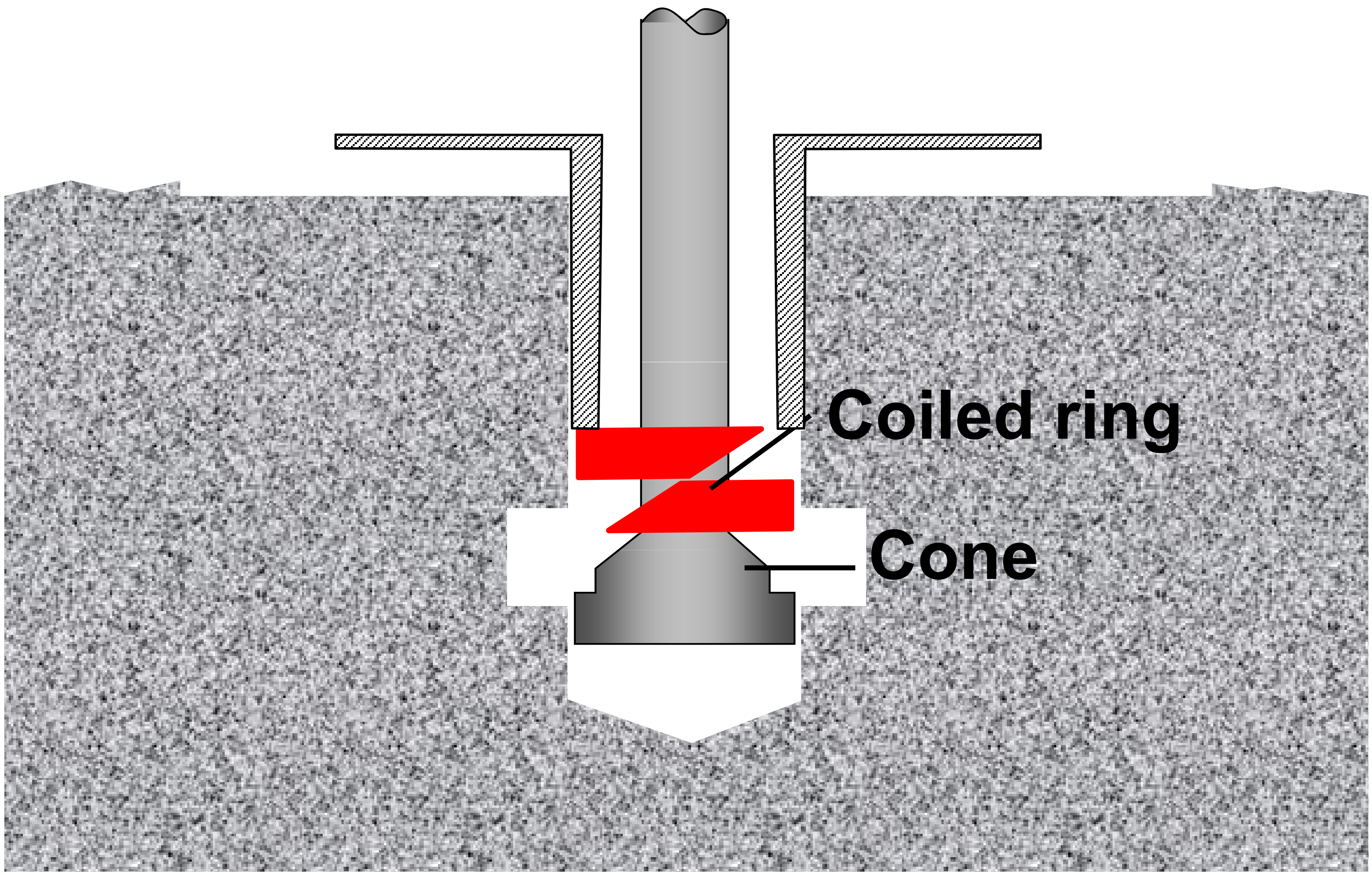
Cut Slot



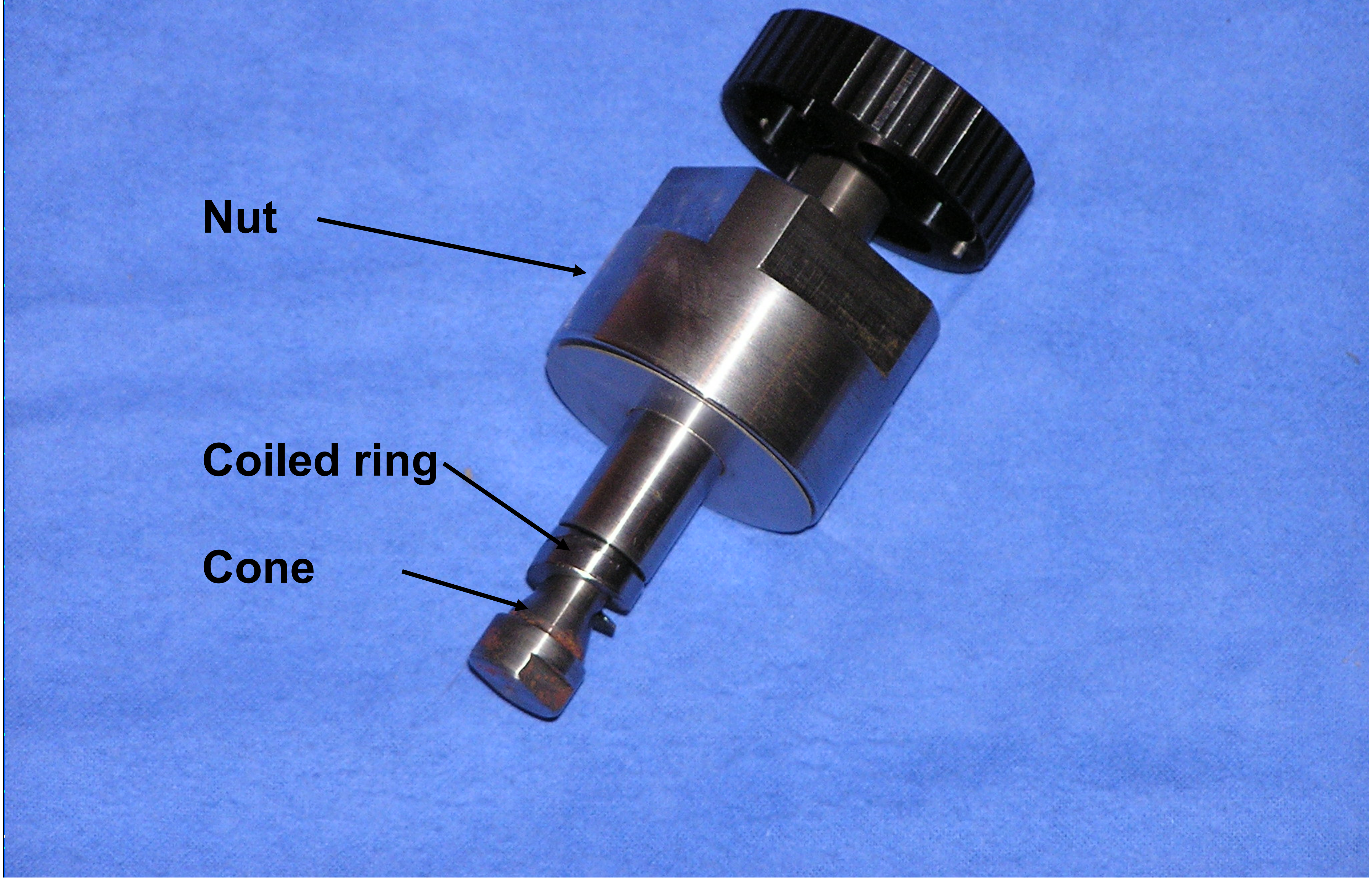
Cut Slot



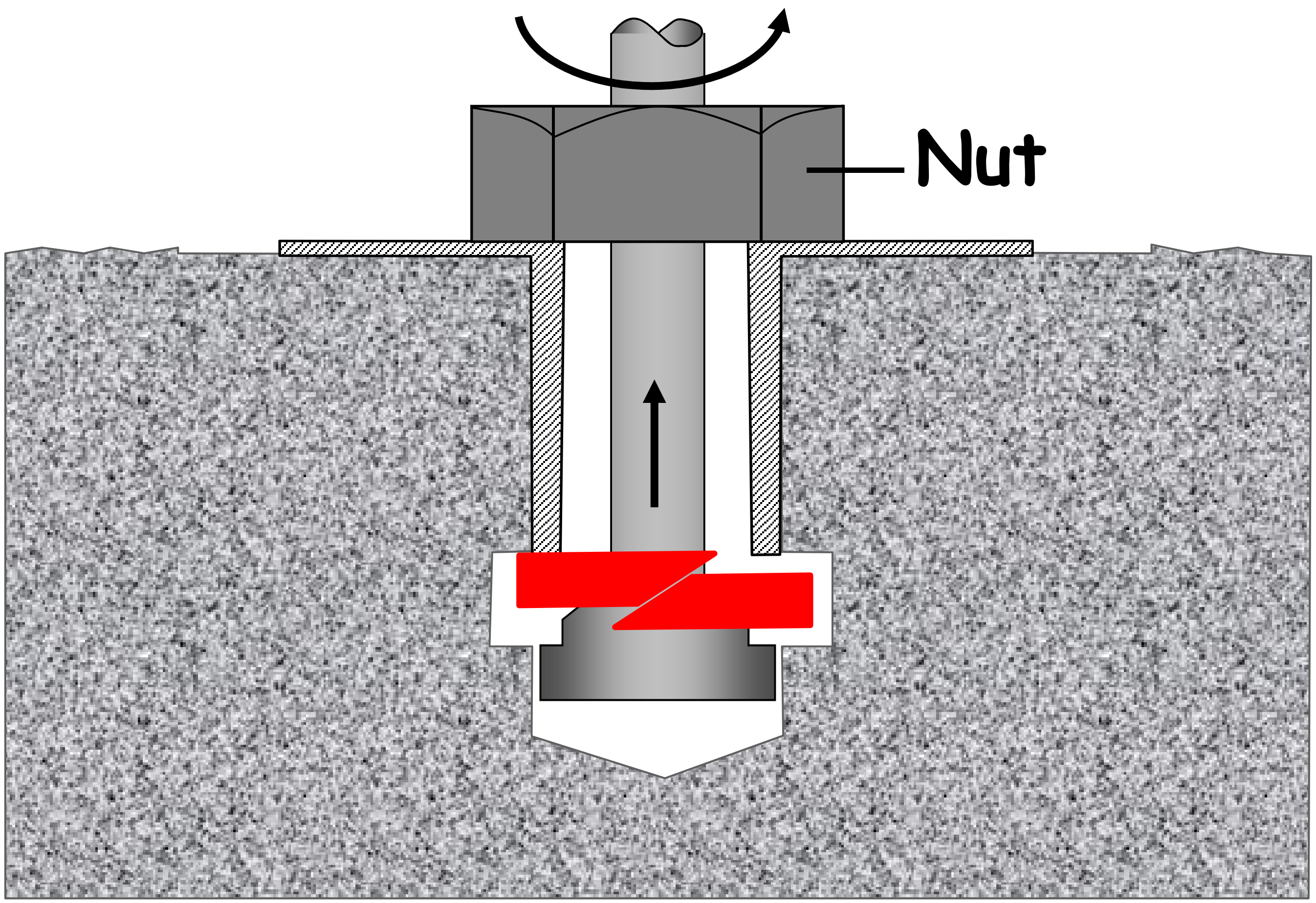
Insert Expansion Cone and Coiled Ring



Ring Expansion Hardware

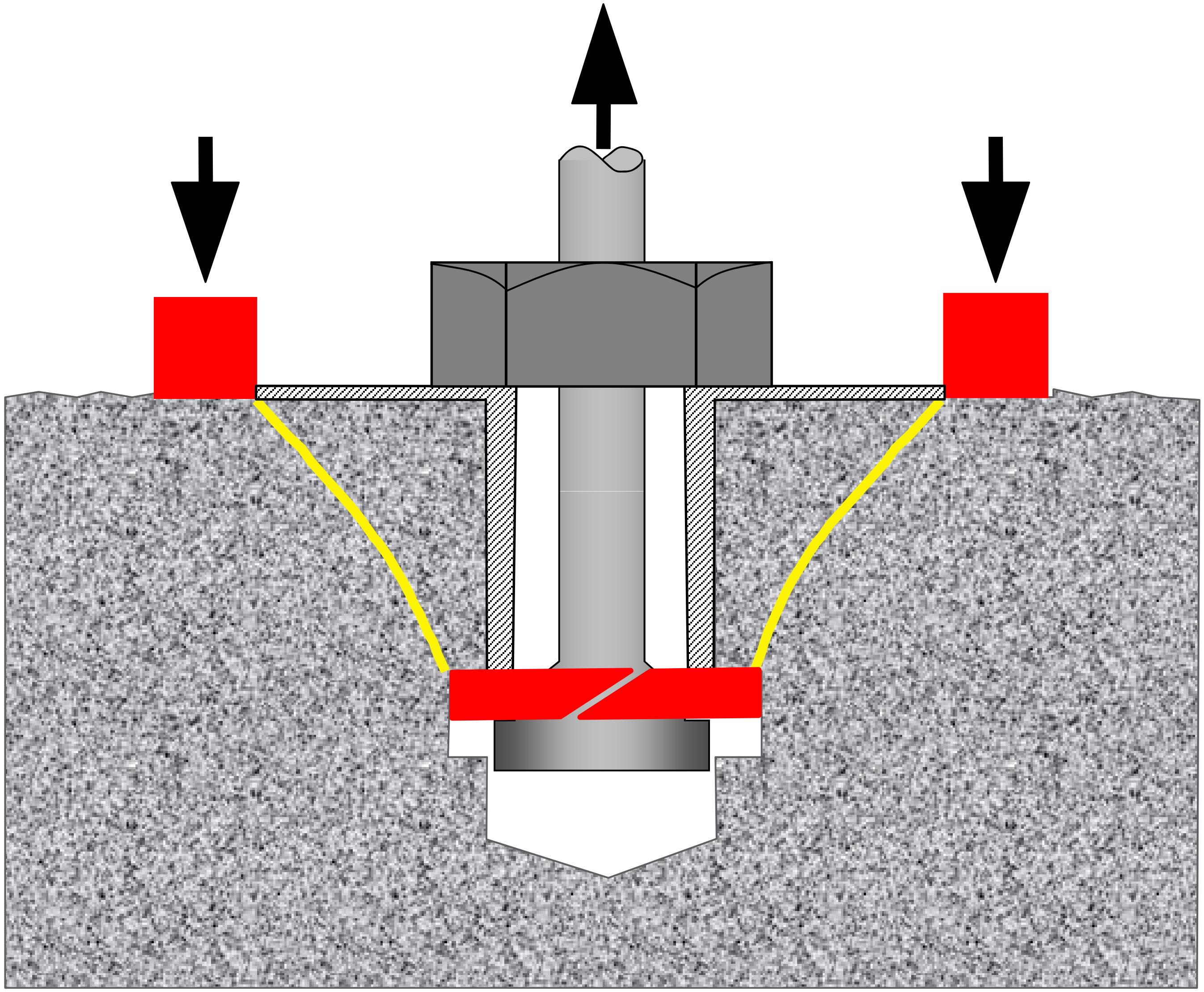


Expand Ring



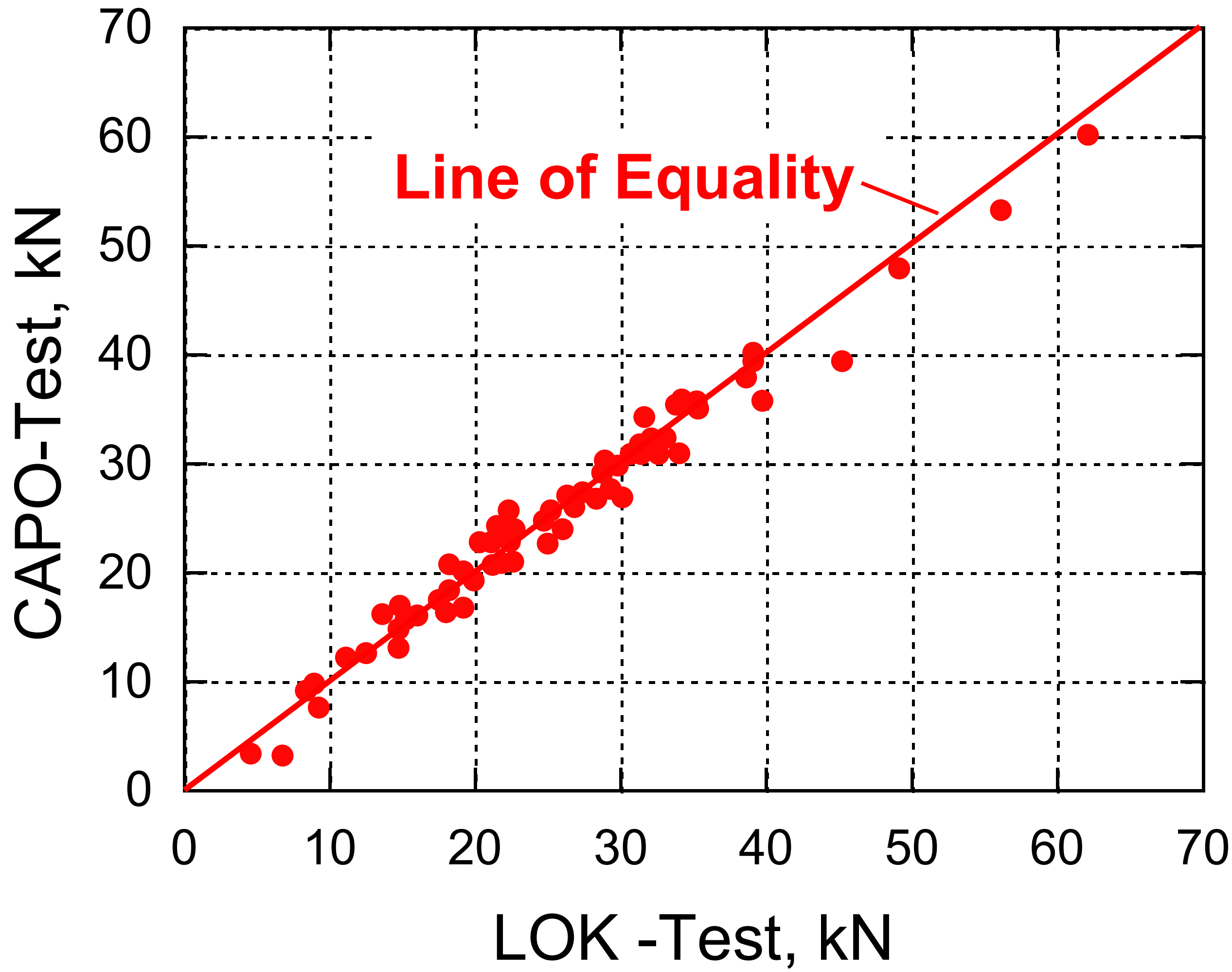
Expand Ring

Pullout the Expanded Ring



Apply Pullout Force

CAPO-Test vs LOK-Test



Pull-off Test
ASTM C1583

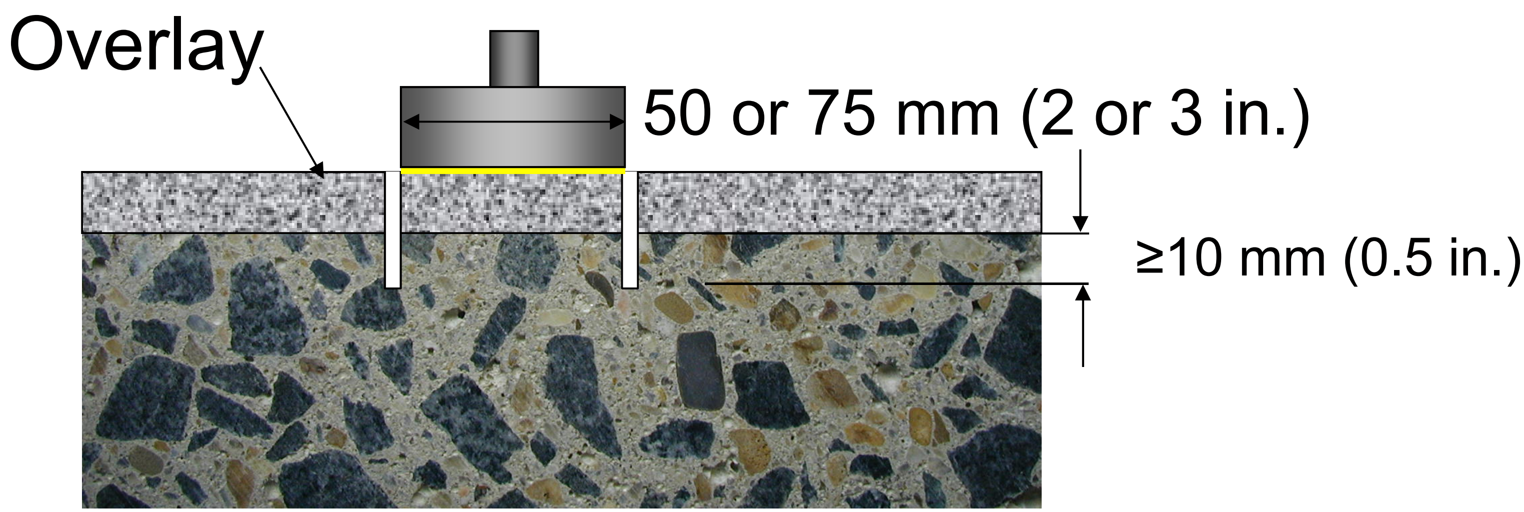
Measure force required to pull off a metal disc bonded to concrete surface.

Pull-off Test

- Direct tensile strength test
- Evaluate condition of concrete surface before application of overlay or repair material
- Measure bond strength of overlay or surface repair materials

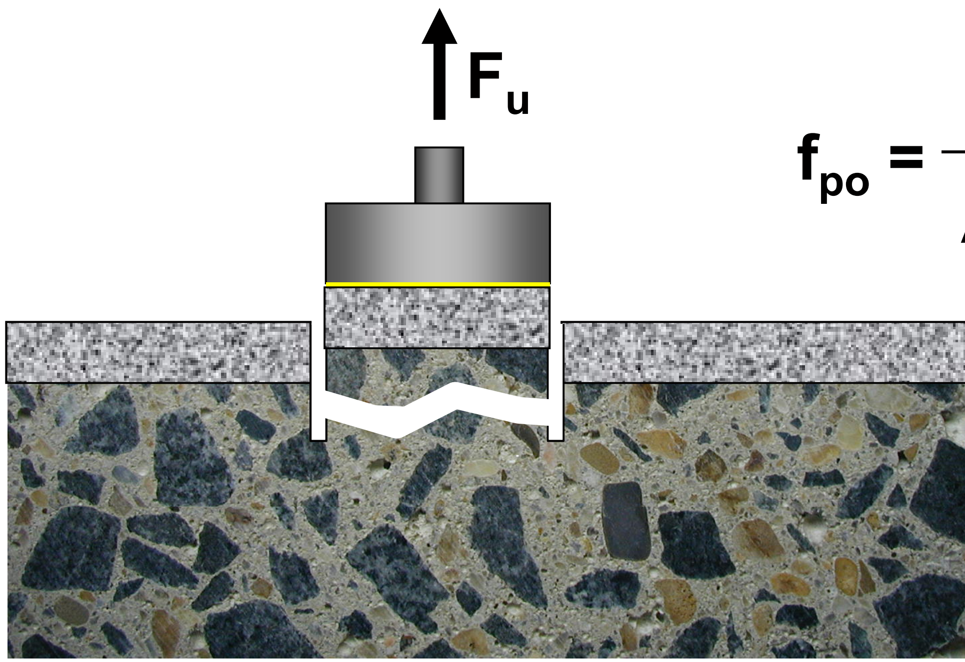
Pull-off Test

- Bond metal disc to surface
- Drill partial core
- Apply tensile force



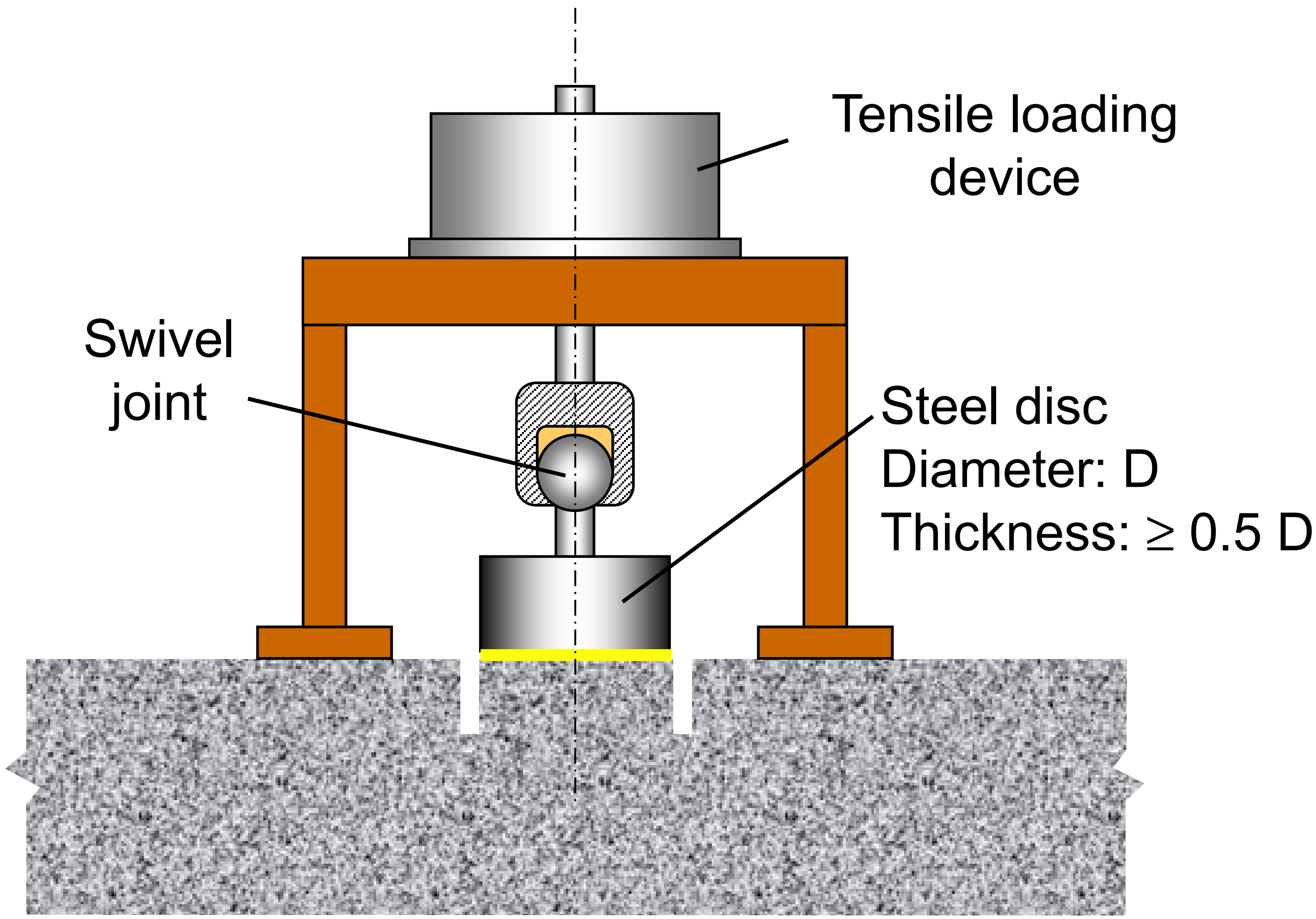
Pull-off Test

- Bond metal disc to surface
- Drill partial core
- Apply tensile force



$$f_{po} = \frac{F_u}{A}$$

Schematic of Apparatus ASTM C1583



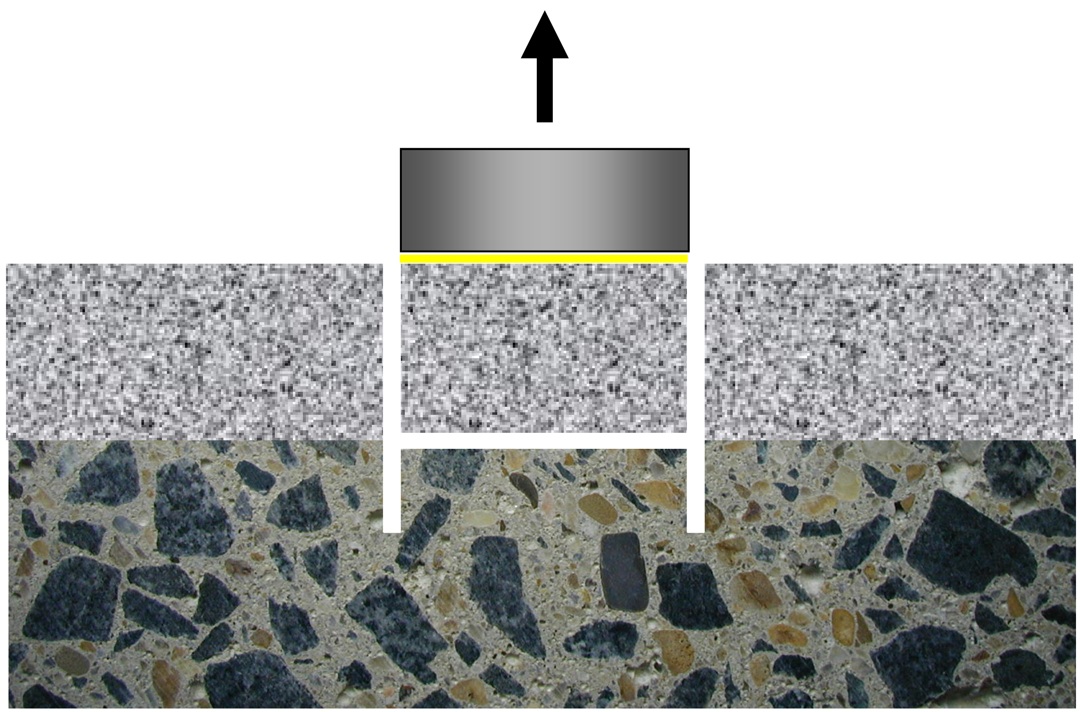
Pull-off Test Apparatus

Proceq

Germann Instruments

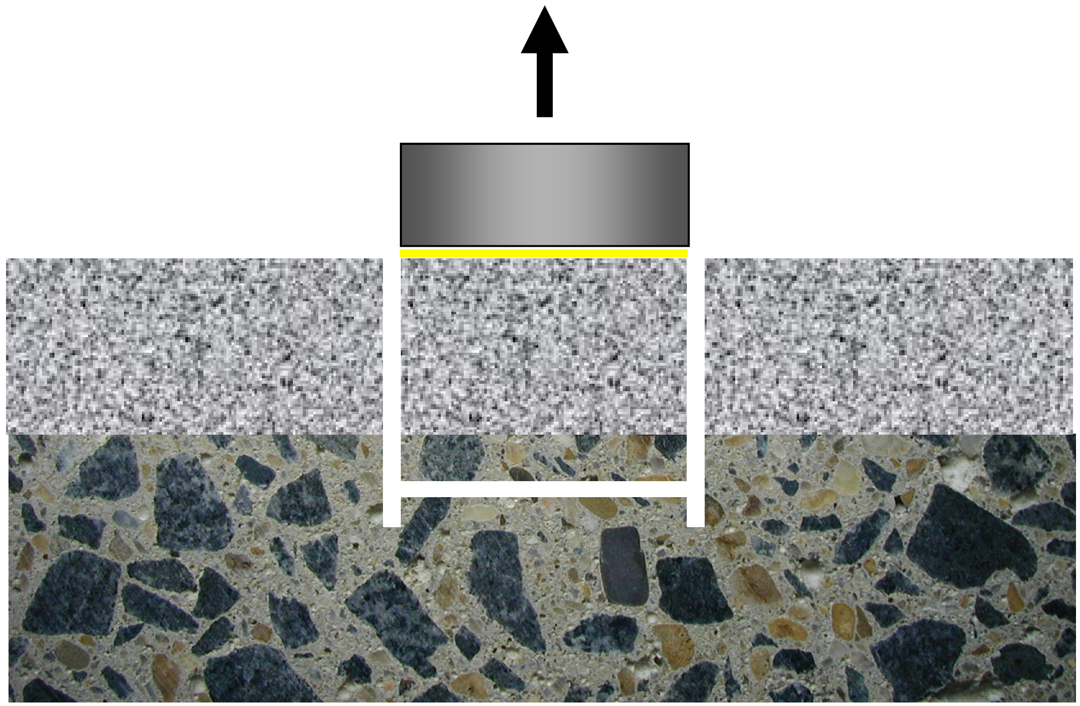
Pull-off Test Failure Locations

- Interfacial bond failure (bond strength)



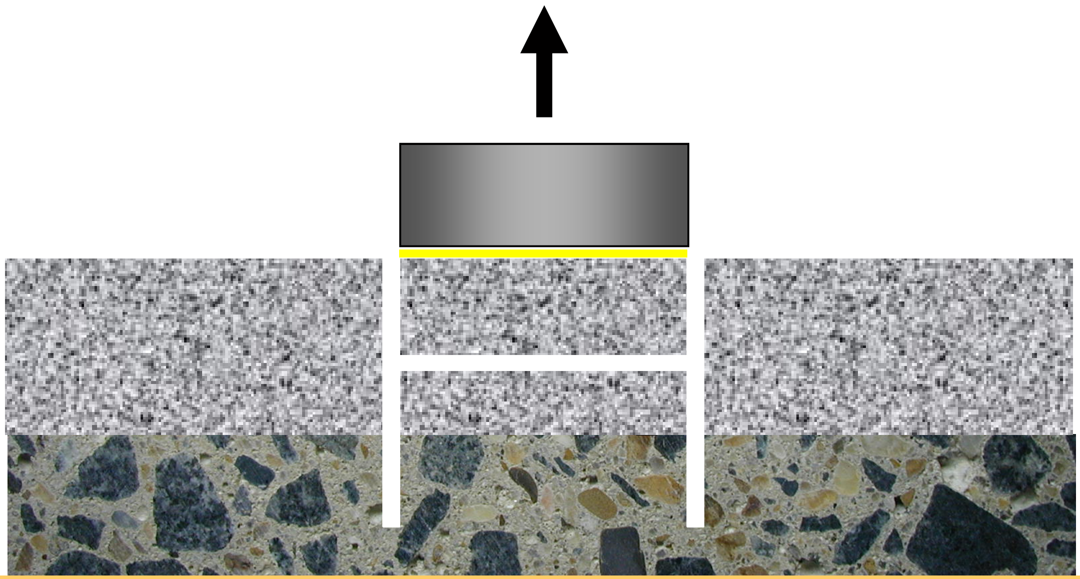
Pull-off Test Failure Locations

- Cohesive failure in the existing concrete (substrate strength)



Pull-off Test Failure Locations

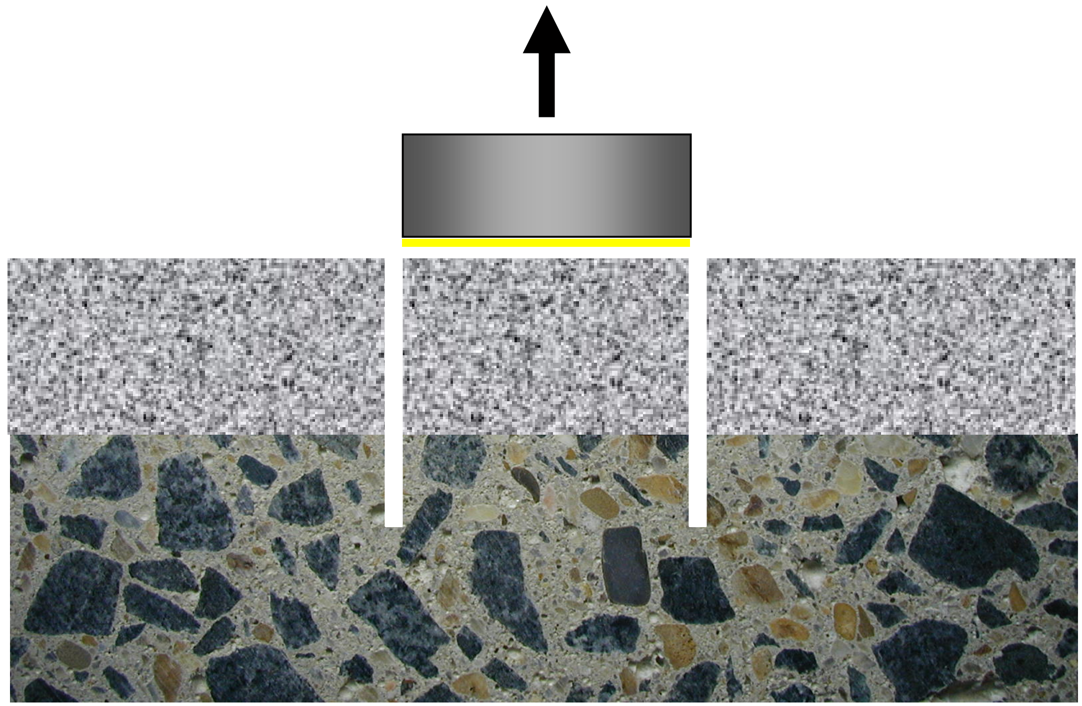
- Cohesive failure in the repair material



- Can not predict failure location
- Average the results for same failure locations

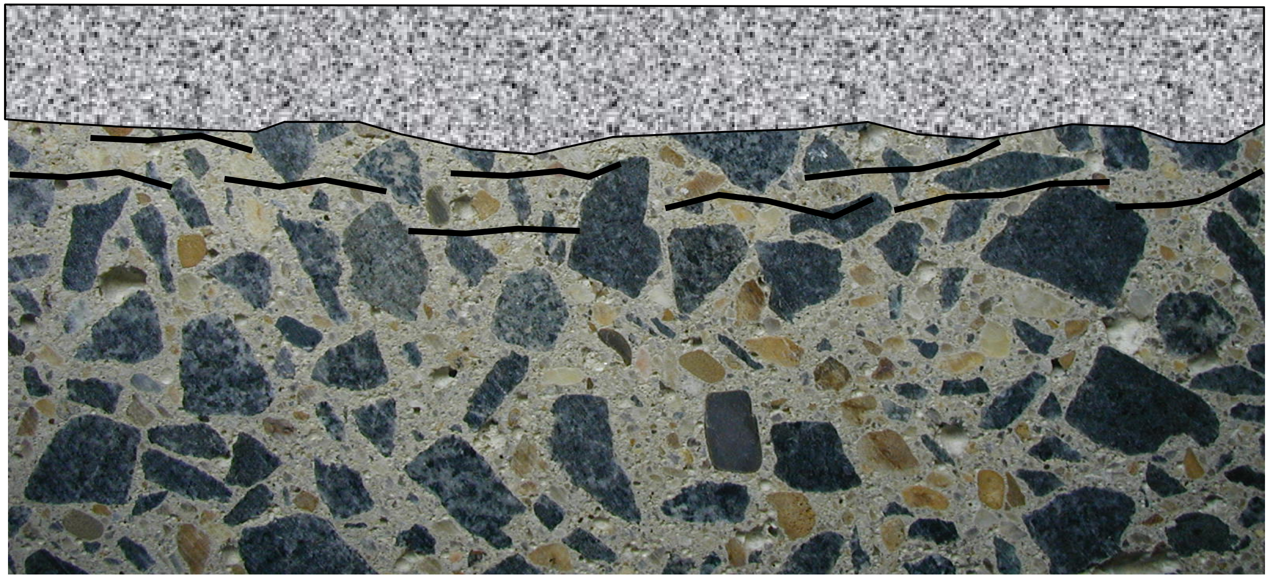
Pull-off Test Failure Locations

- Bond failure at the adhesive
- Inconclusive test—bond strength is at least failure stress



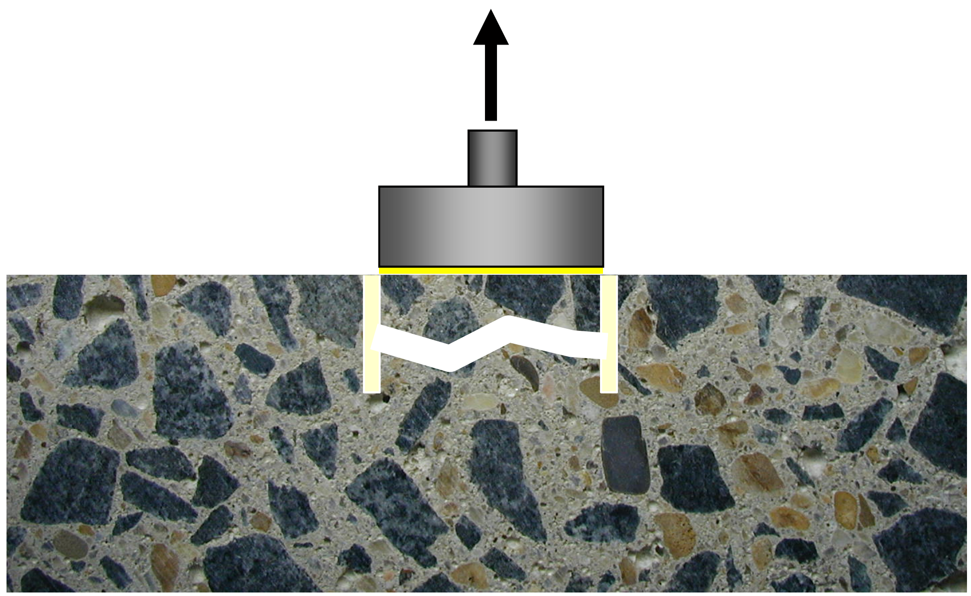
Evaluation of Surface Preparation Methods

- Surfaces to receive overlay or repair material are usually prepared to ensure good bonding
- Some repair methods can damage concrete and reduce the "apparent" bond strength



Evaluation of Surface Preparation Methods

- Test substrate before applying overlay
  - ACI 503R (Use of Epoxy Compounds with Concrete) recommends substrate pull-off strength > 175 psi (1.2 MPa)



Stretch Break

Flaw Detection

- Voids (e.g., in tendon ducts)
- Honeycombing (poor consolidation)
- Delaminations
- Thickness of members
- Corrosion of reinforcement

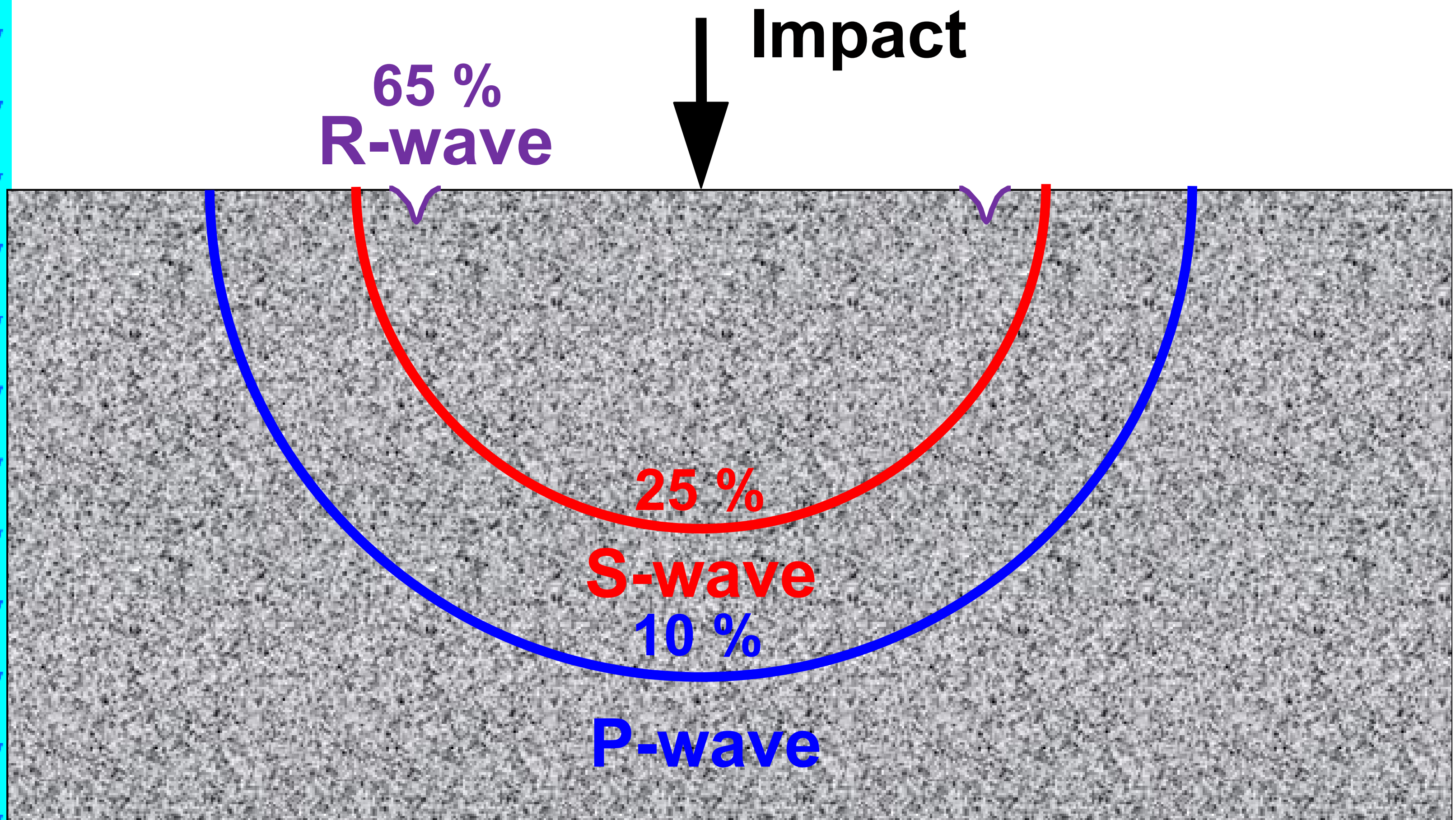
Stress-Wave Methods

- A stress wave (sound) is easy to generate
  - Mechanical impact
  - Transducers
- Travel speed affected by elastic constants and density of concrete
- Stress wave traveling through a solid (such as concrete) is reflected at an air interface
- Monitoring the arrival of reflected stress wave allows us to "look" into concrete
  - Defects
  - Thickness

Outline

- Basic principles of stress wave propagation
  - Wave types
  - Reflection
- Ultrasonic pulse velocity
- Sounding (chain drag)
- Impact-echo method
- Impulse-response
- Ultrasonic-echo method

Stress Waves due to Impact

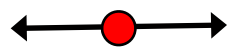
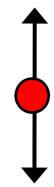
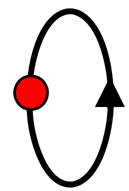


Wave Modes

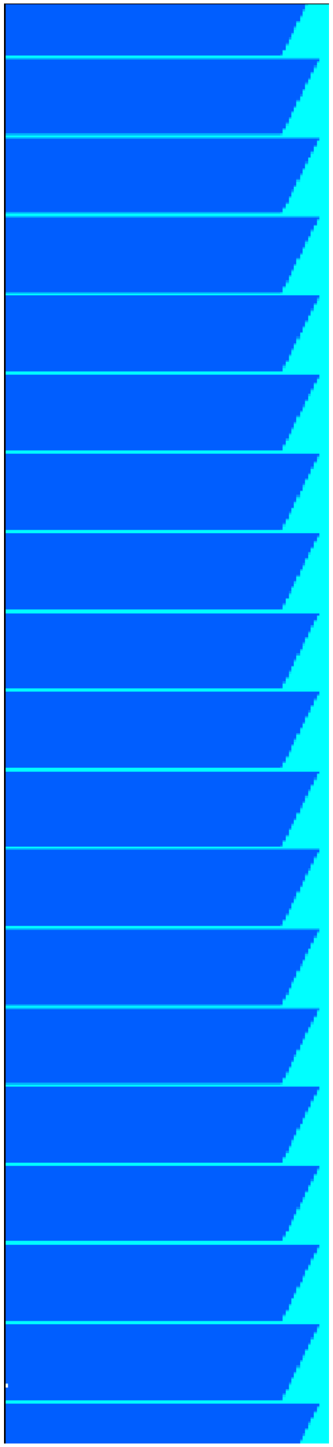
- P-wave—associated with normal stress
- S-wave—associated with shear stress
- R-wave—combination of normal stress and shear stress
- WebFiles\wavemotion.html

www.kettering.edu/~drussell/Demos/waves/wavemotion.html

Summary of Wave Modes

	Particle Motion	Wave Speed
P-Wave		$C_P = \sqrt{\dfrac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$
S-Wave		$C_S = \sqrt{\dfrac{G}{\rho}}$
R-Wave		$C_R = C_S \dfrac{0.87+1.2\nu}{1+\nu}$

Wave Propagation Direction →

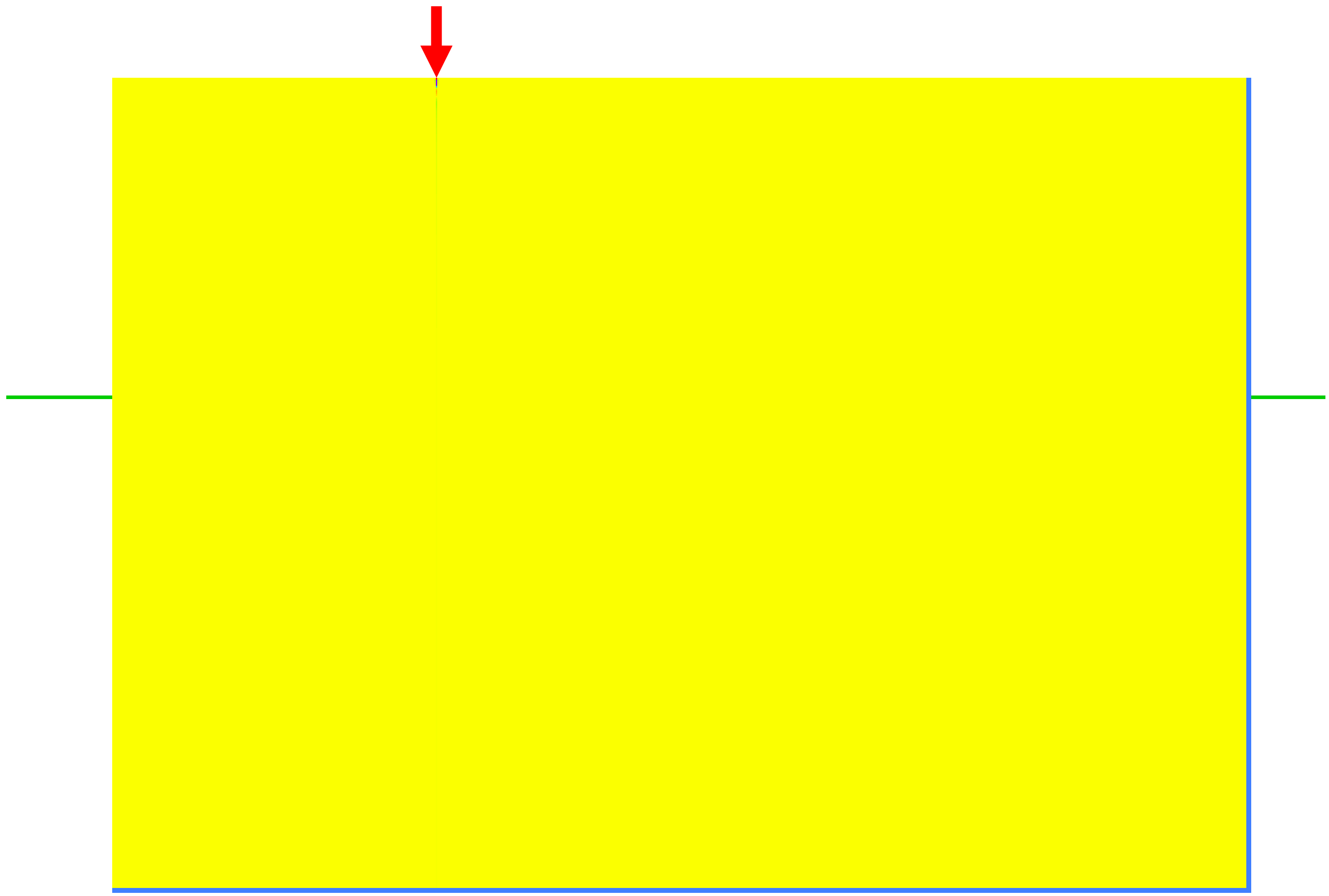


Relative Wave Speeds

(ν = 0.2)

P-Wave	$C_p = 1$
S-Wave	$C_s = 0.62\ C_p$
R-Wave	$C_R = 0.56\ C_p$

Reflection and Refraction



appliedgeophysics.berkeley.edu:7057/seismic/seismic_21.pdf

P-wave Reflection Coefficients (R)

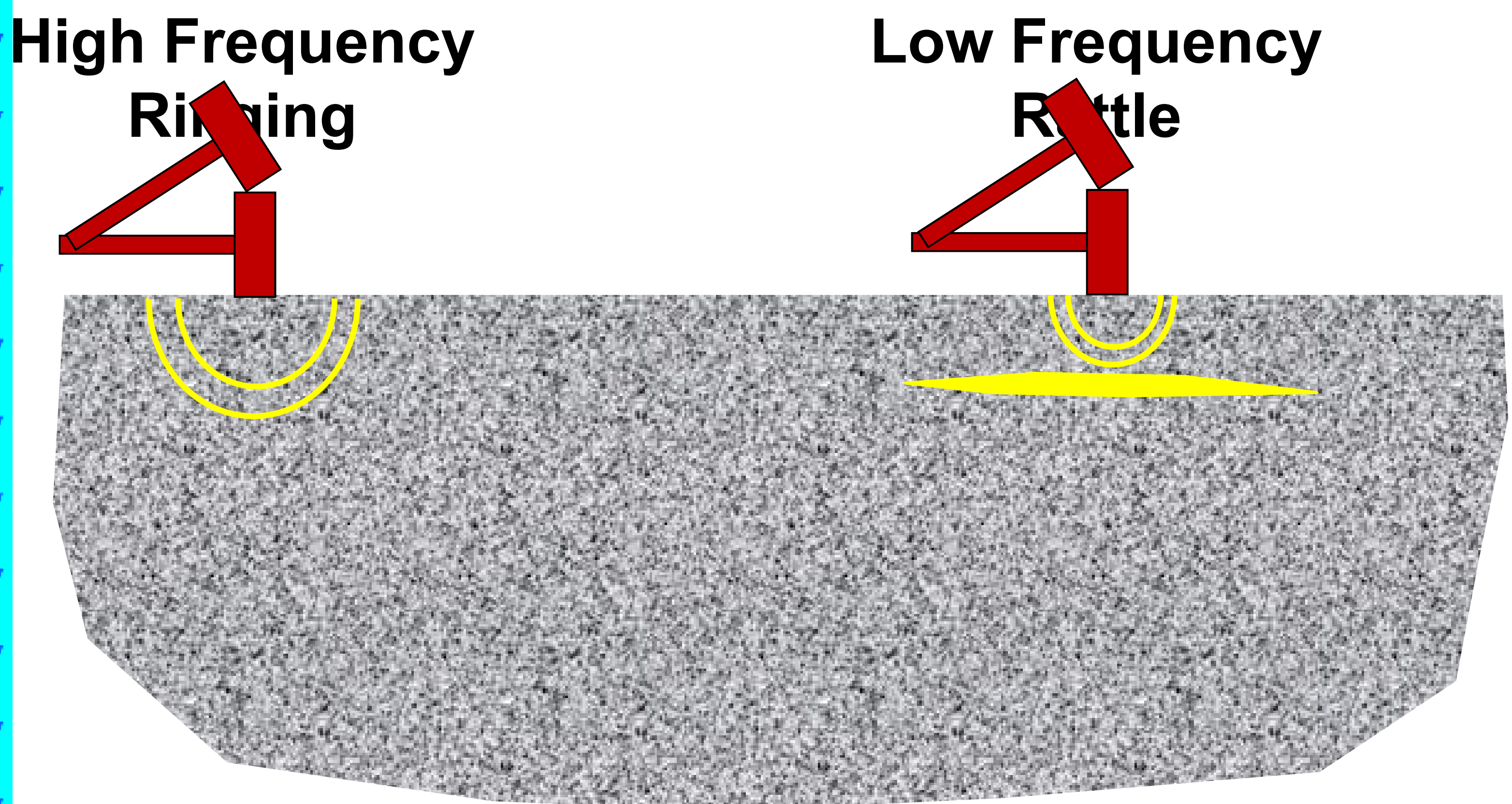
Interface	R
Concrete-Air	-1.00
Concrete-Water	-0.71
Concrete-Steel	0.68

A negative value indicates that the stress changes sign when reflected: e.g., a compressive stress wave is reflected as a tensile stress wave.

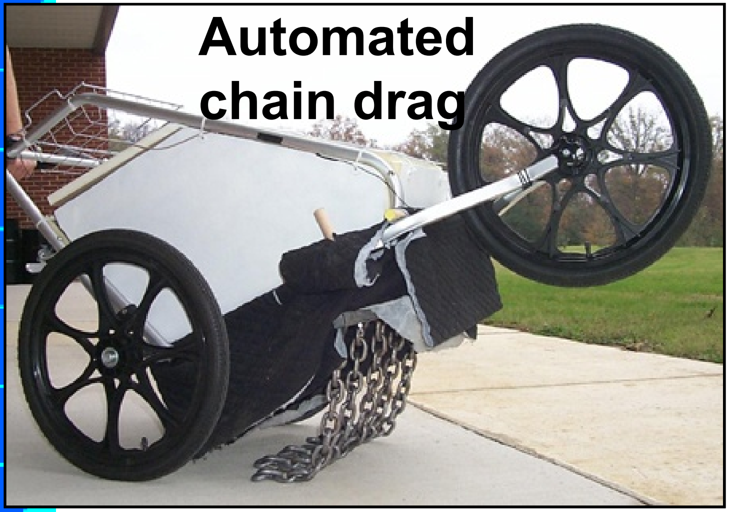
Outline

- Basic principles
    - Wave types
    - Reflection
- Ultrasonic pulse velocity
- Sounding (chain drag)
- Impact-echo method
- Impulse-response method
- Ultrasonic-echo method

ASTM D4580 Practice for Measuring Delaminations



Sounding Methods

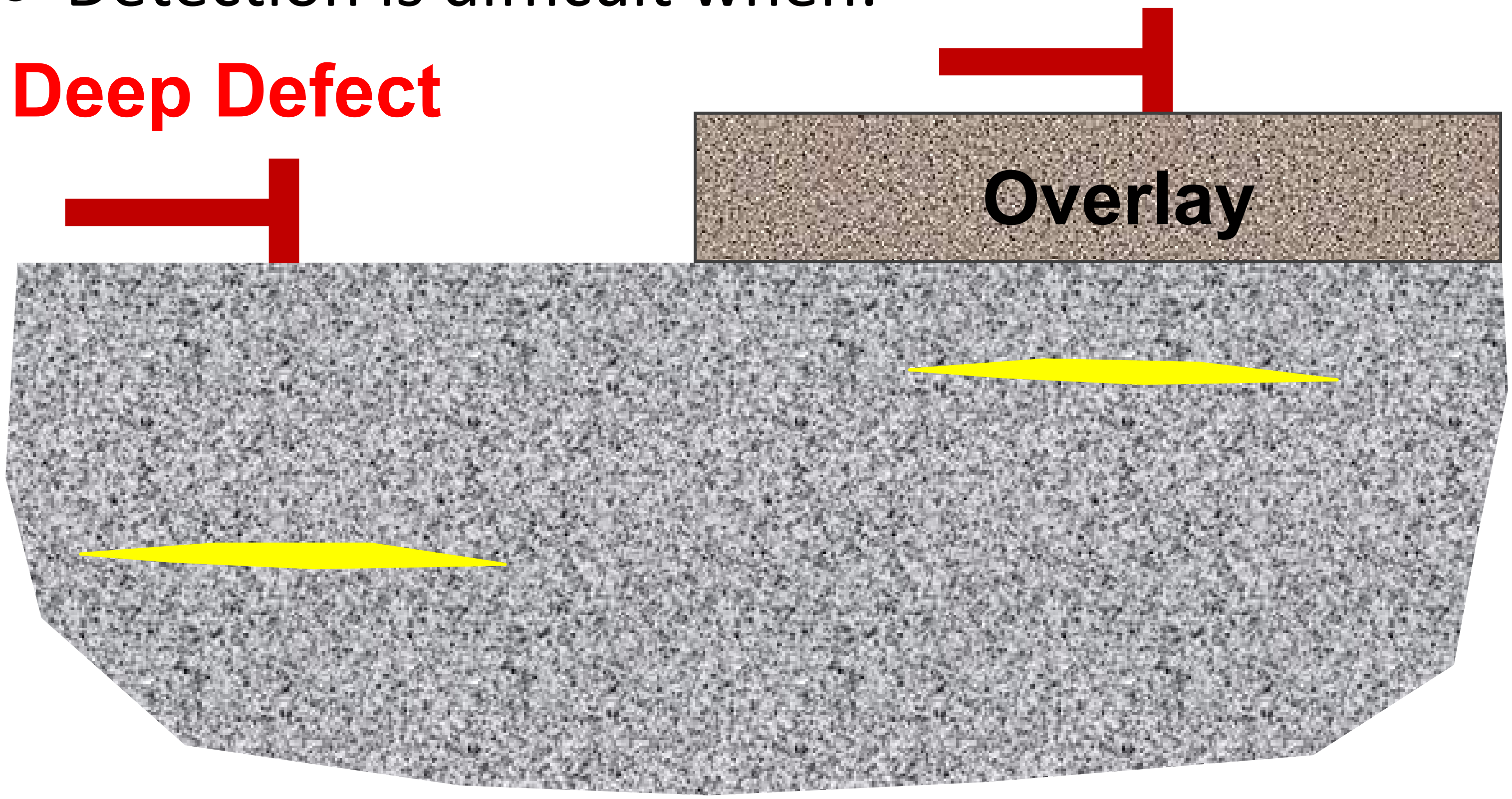


www.acoustics.org/press/146th/Costley.htm

www.soundingtech.com

Limitations

- Detection is difficult when:

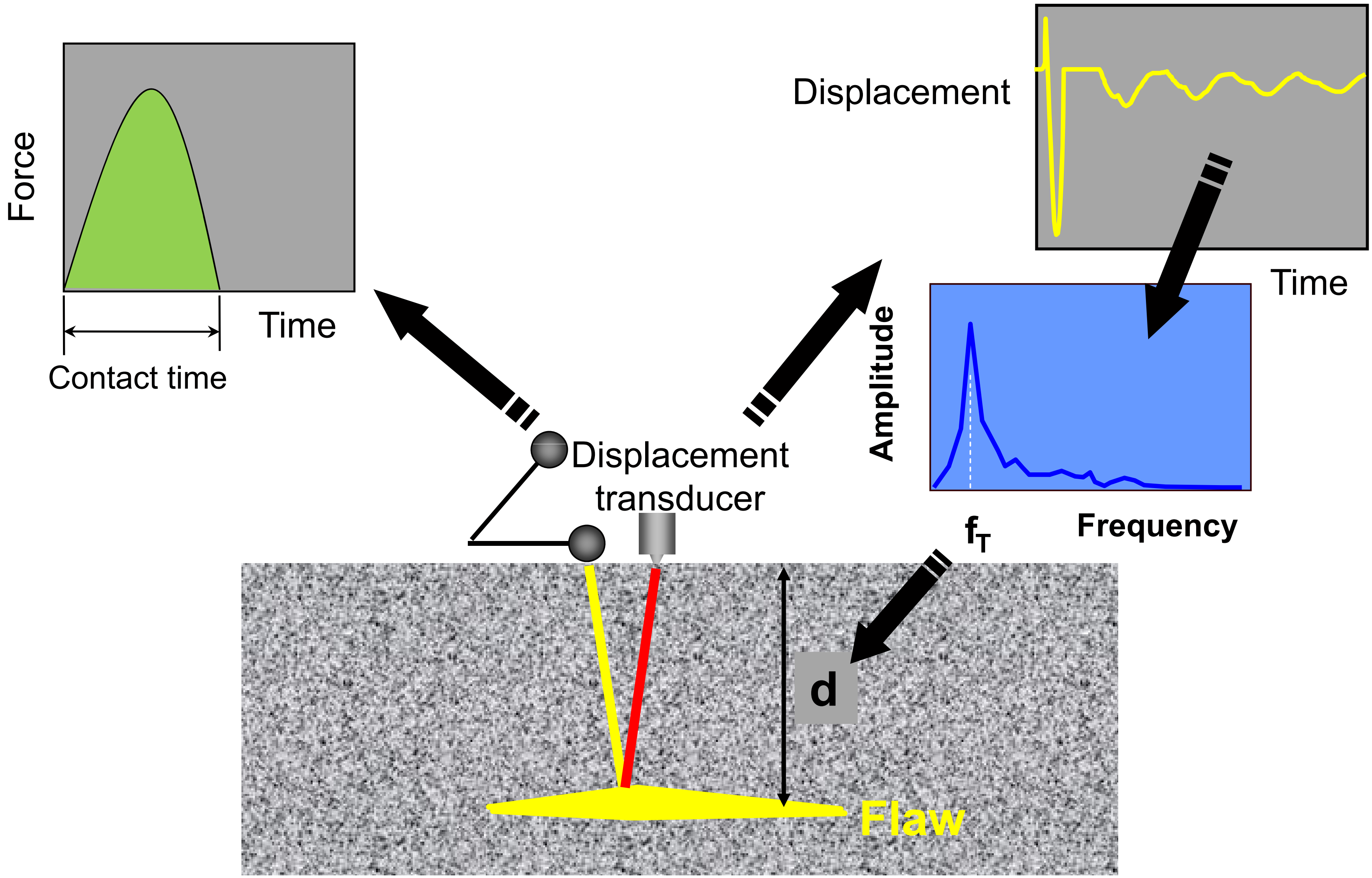


- Results are operator-dependent and may be affected by ambient noise

Impact Methods

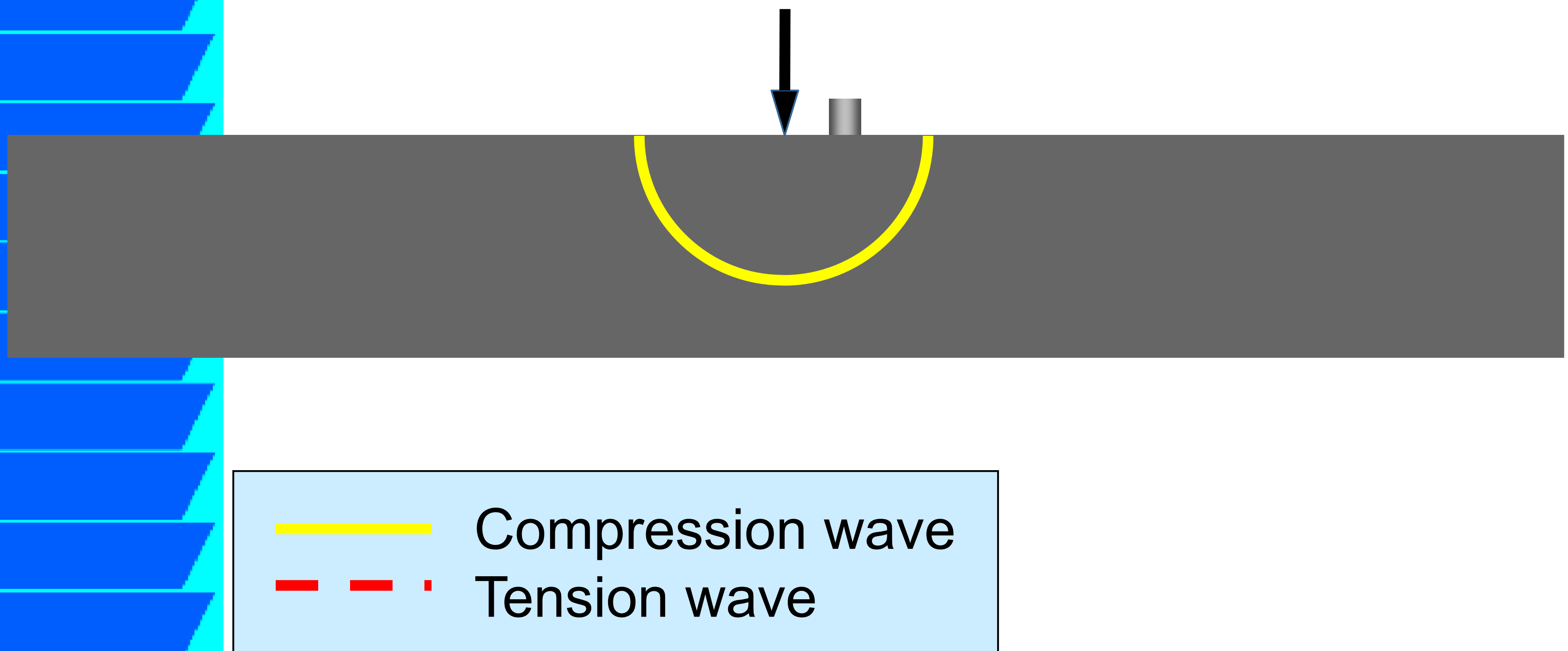
- Impact-echo method
  - Depth of reflecting interface
- Impulse-response method
  - Comparative indication of mobility
- Spectral analysis of surface waves
  - Elastic constants of layered system

Impact-Echo Method



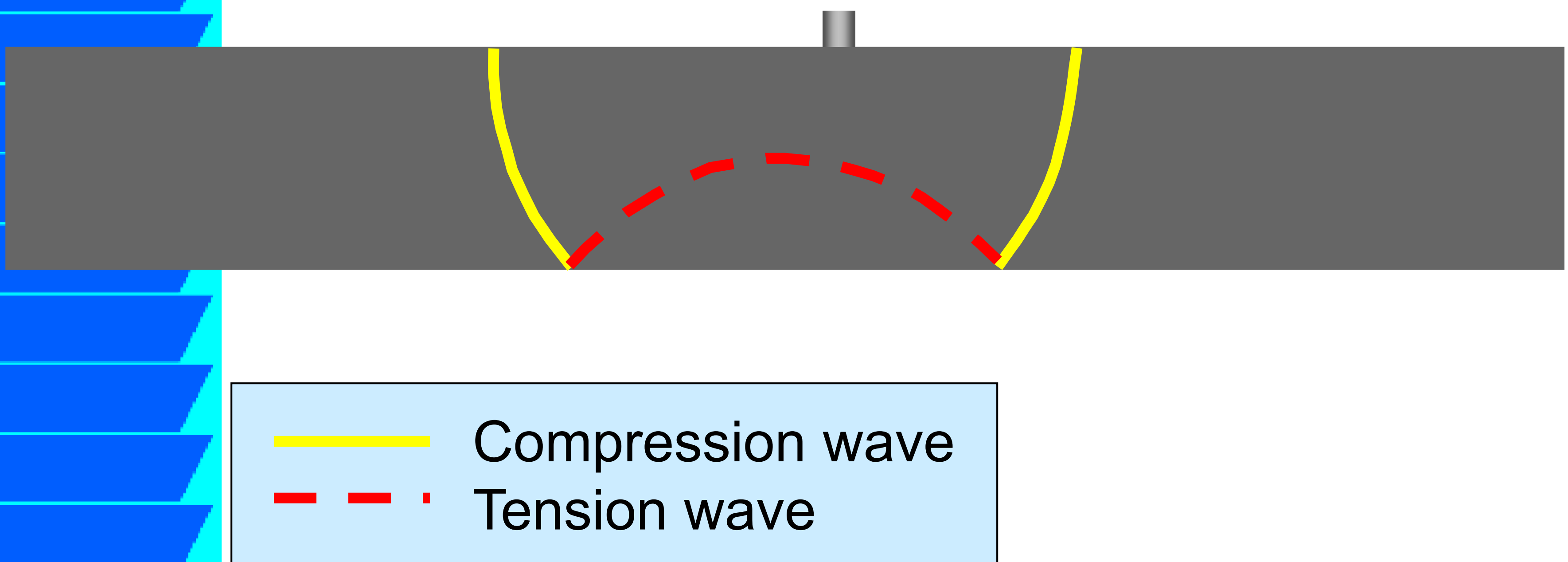
Field Testing System

Multiple Reflections of P-wave in a Plate

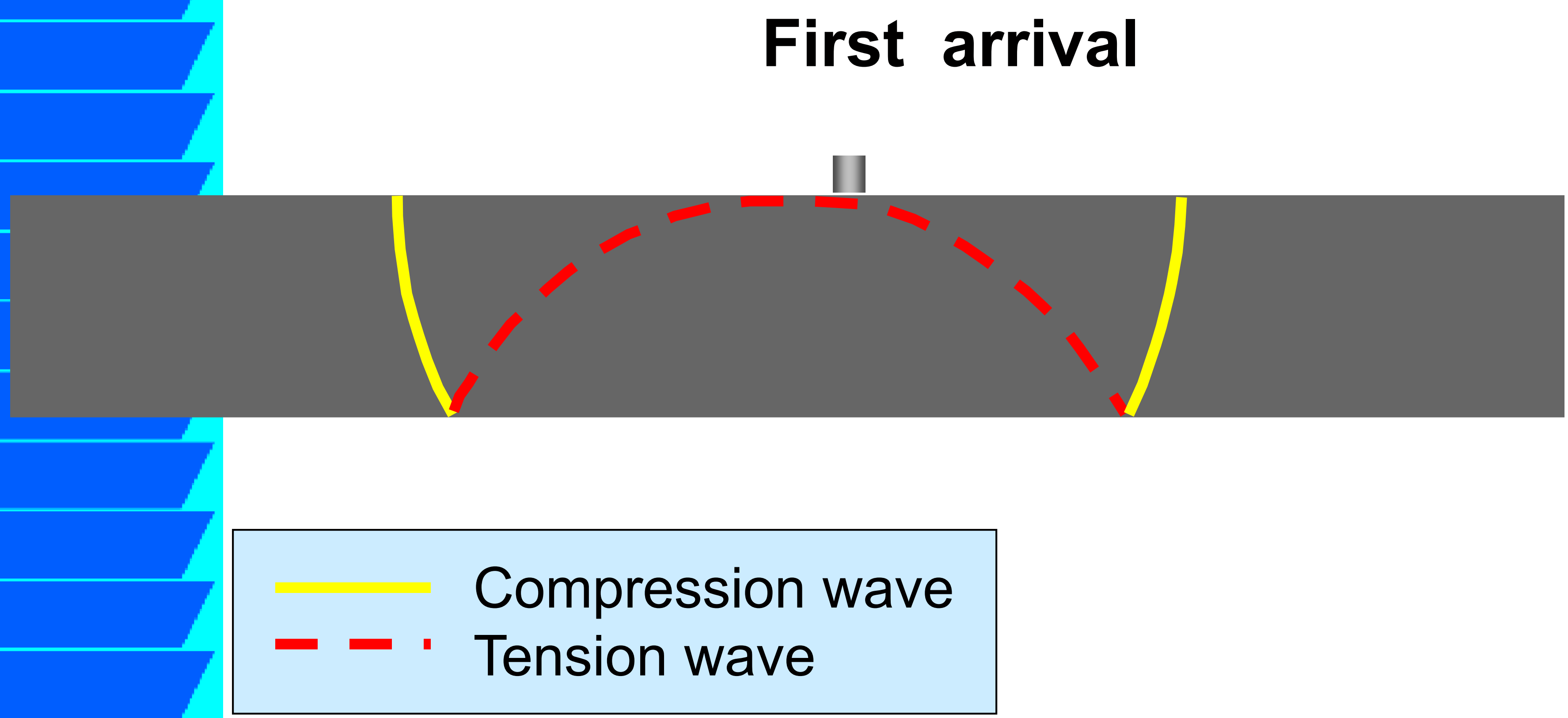


Multiple Reflections of P-wave in a Plate

Reflection from bottom

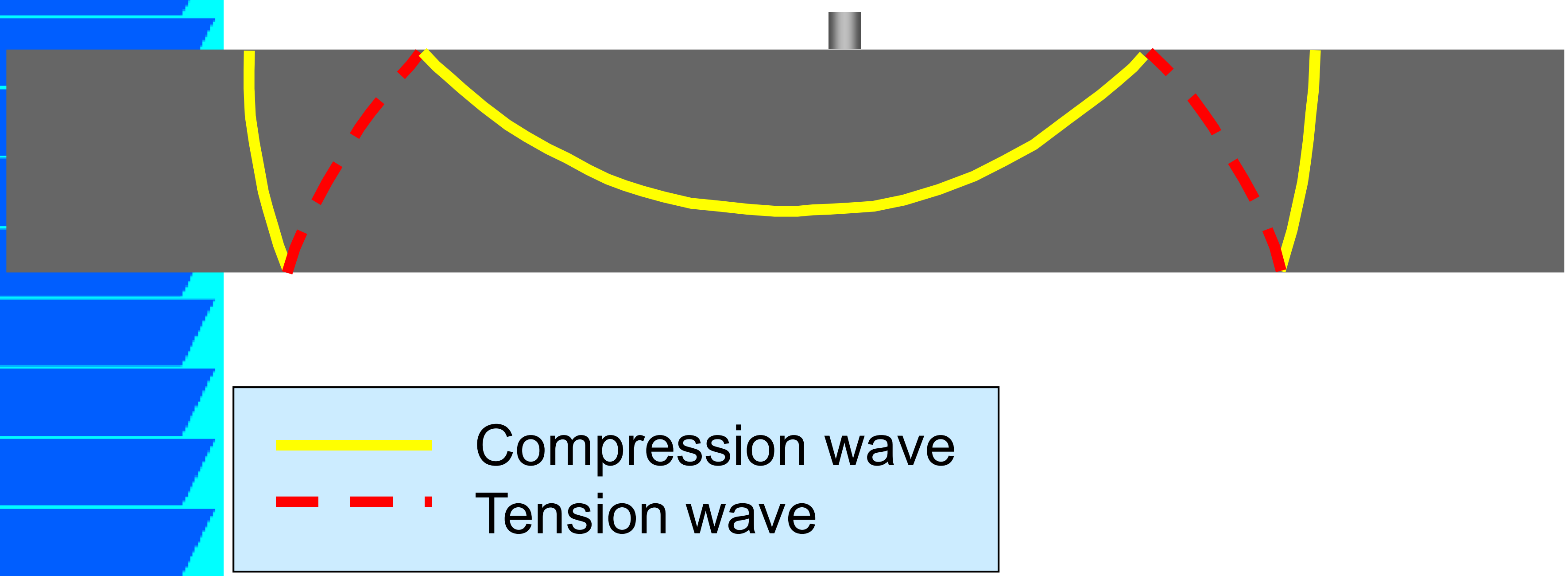


Multiple Reflections of P-wave in a Plate



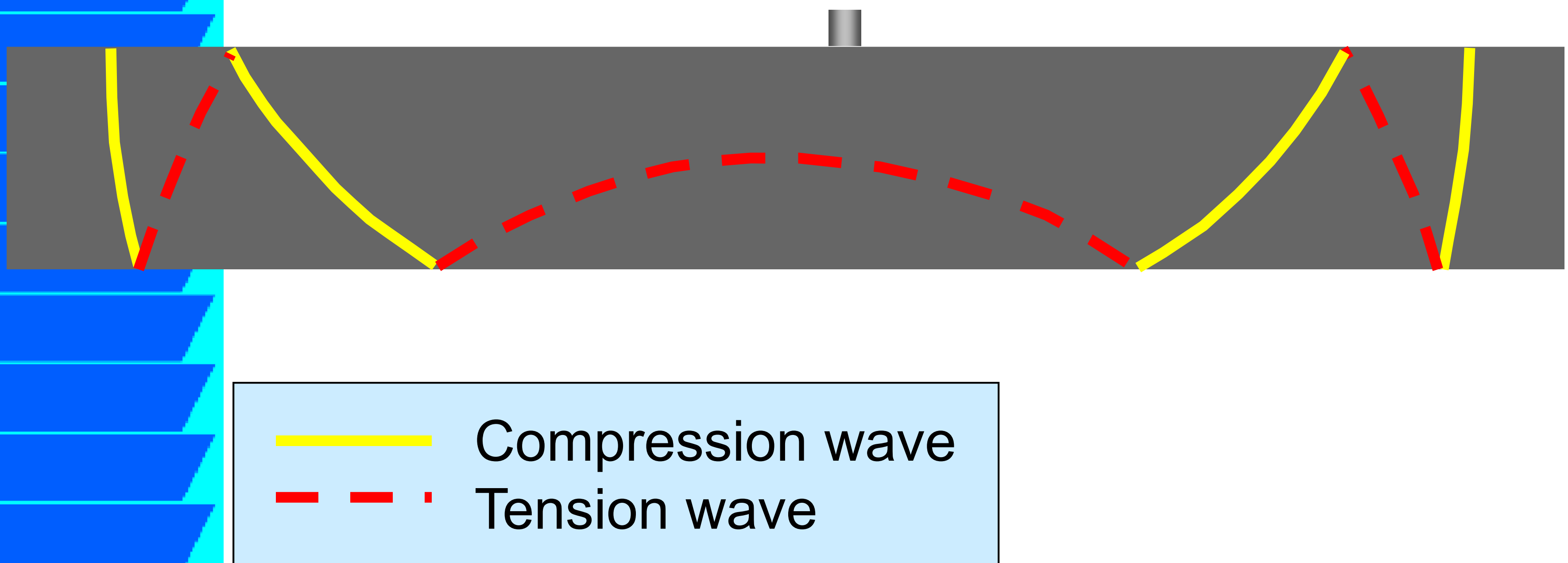
Multiple Reflections of P-wave in a Plate

Reflection from top and back to bottom



Multiple Reflections of P-wave in a Plate

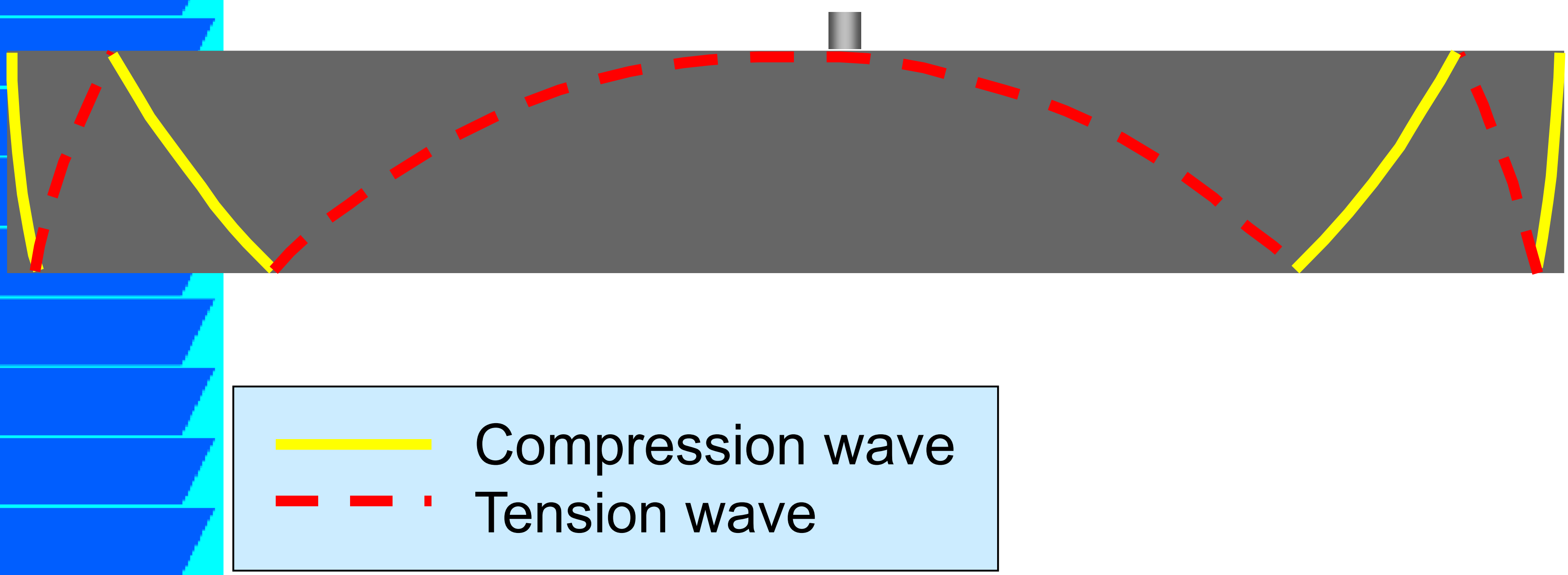
2nd reflection from bottom



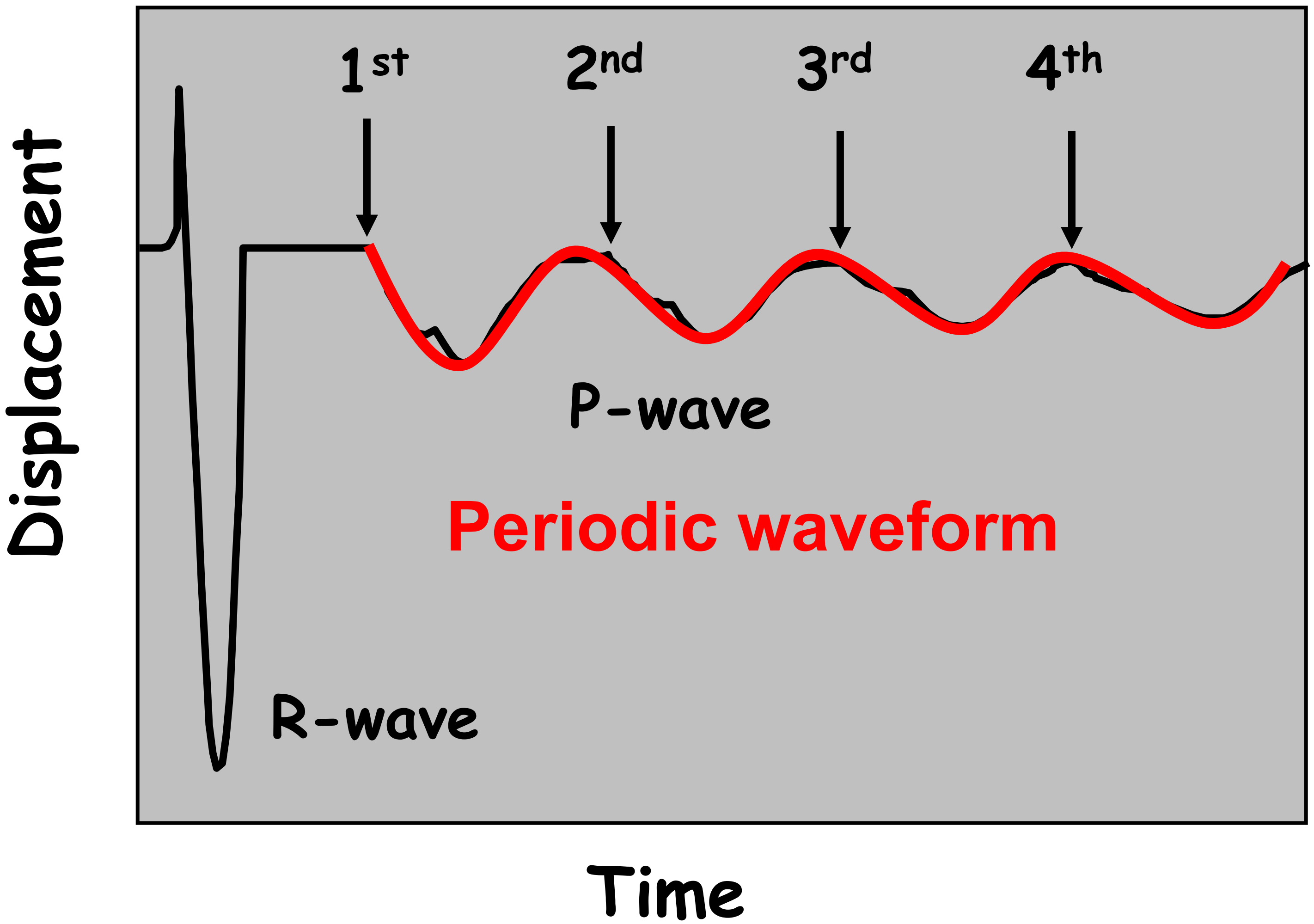
Multiple Reflections of P-wave in a Plate

Reflected wave arrives at top surface in a periodic fashion

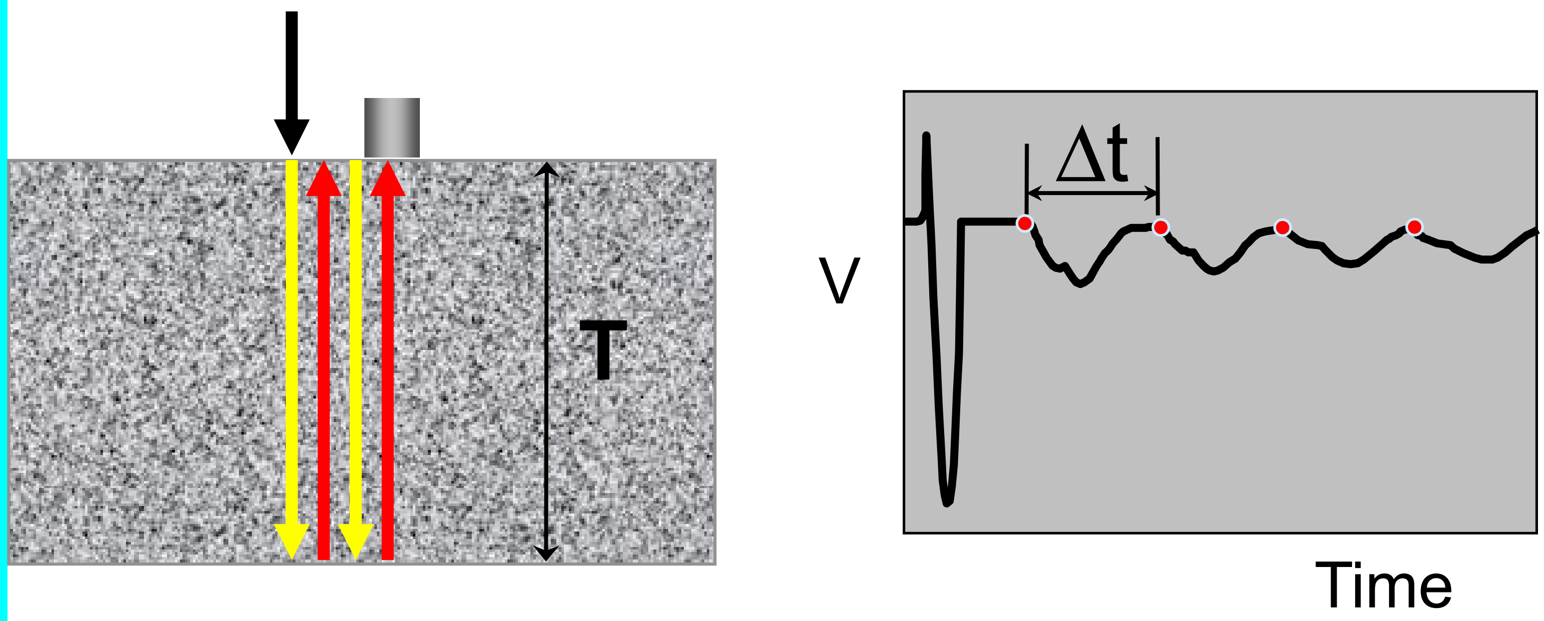
2nd arrival at top



Surface Displacement Waveform



Frequency Analysis



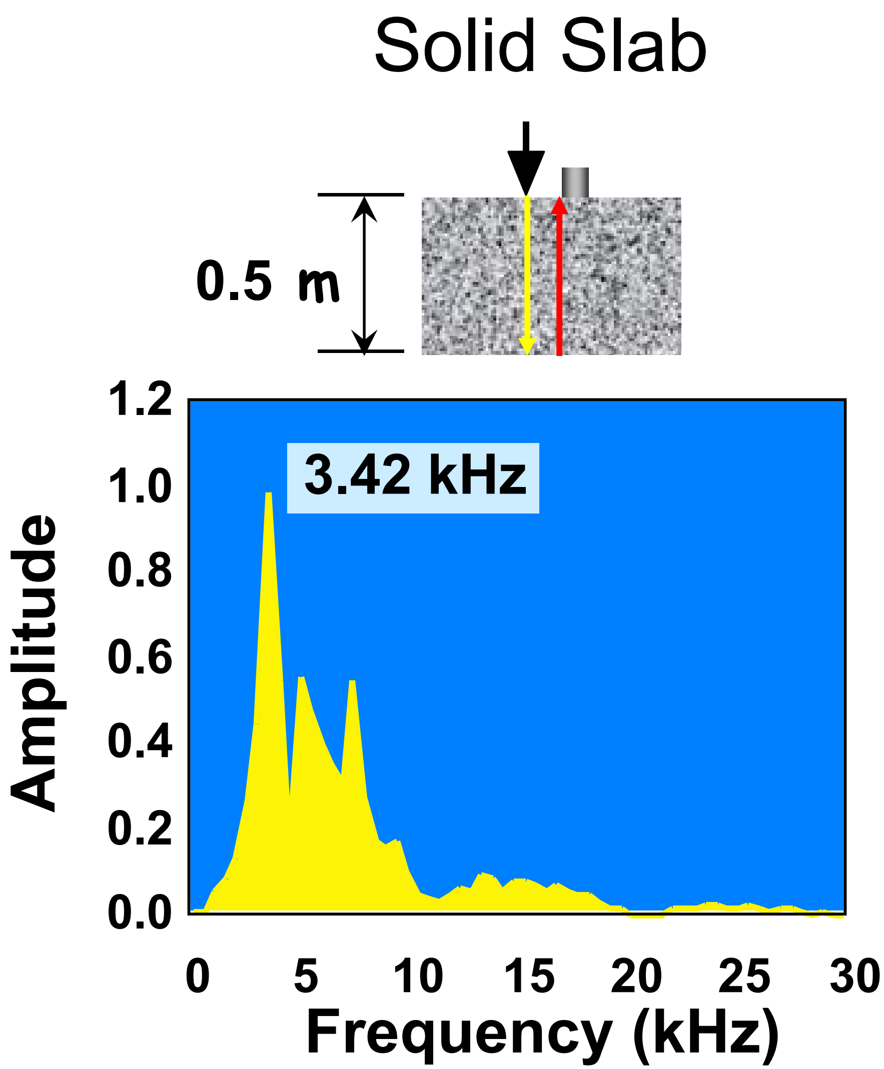
$$\Delta t = \frac{2T}{C_p} \qquad f = \frac{1}{\Delta t} \quad \Rightarrow \quad \boxed{T = \frac{C_p}{2f}}$$

How do we determine f ?

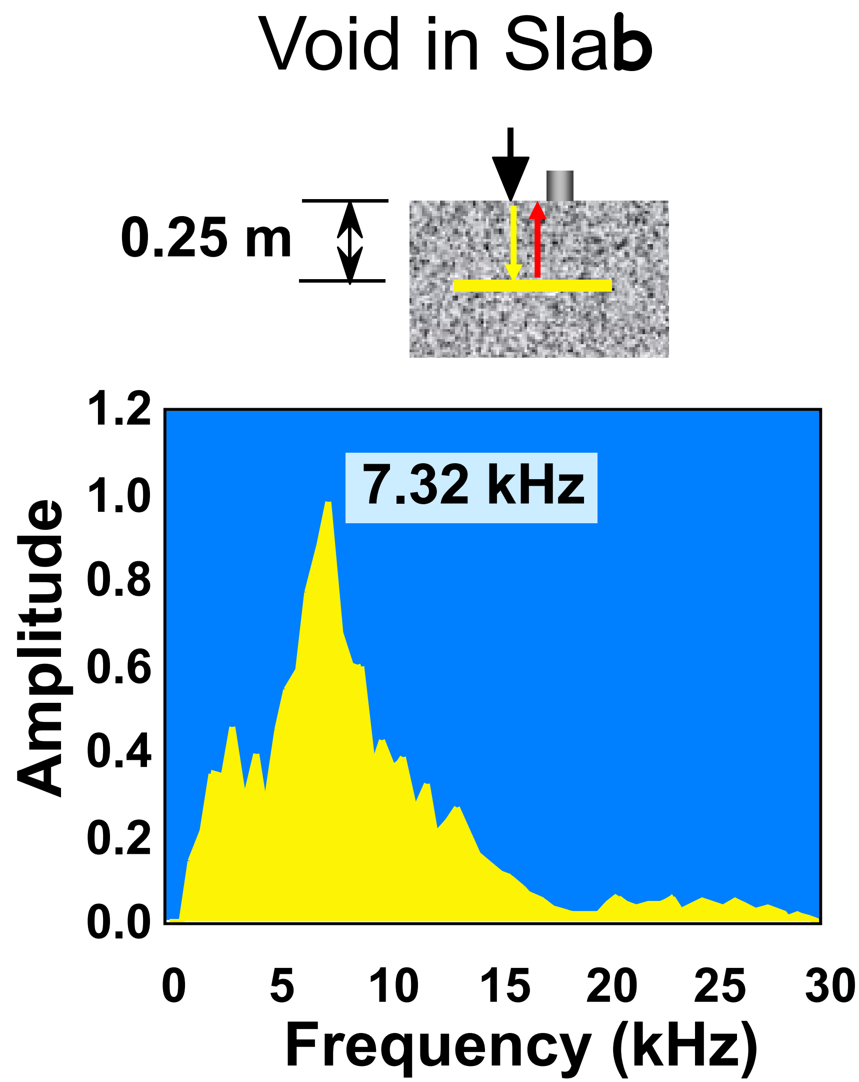
Amplitude Spectrum

- By signal processing (FFT), waveform is converted into frequency domain to obtain amplitude spectrum
- Amplitude spectrum represents the amplitudes of the frequency components in the signal
- For a plate, the thickness frequency is the predominant peak in the spectrum

Examples



Solid Slab
0.5 m
3.42 kHz
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Amplitude
0
5
10
15
20
25
30
Frequency (kHz)



Void in Slab
0.25 m
7.32 kHz
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Amplitude
0
5
10
15
20
25
30
Frequency (kHz)

Applications

- Voids or honeycombing
- Delaminations (at reinforcement, asphalt/concrete interface, overlay, repair)
- Voids in grouted tendon ducts
- Bond "quality" –porosity at interface
- Thickness of plate-like structures (ASTM C1383)

ASTM C1383

INTERNATIONAL

Designation: C 1383 – 04

Standard Test Method for Measuring the P-Wave Speed ... Concrete Plates Using the Im...

Procedure A:

Determine wave speed

This standard is issued under the fixed designation C 1383; the ... original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

Procedure B:

Thickness frequency

1. Scope*

1.1 This test method covers procedures for determining the thickness of concrete slabs, pavements, bridge decks, walls, or other plate-like structure using the impact-echo method.

1.2 The following two procedures are covered in this test method:

1.2.1 *Procedure A: P-Wave Speed Measurement*—This procedure measures the time it takes for the P-wave generated by a short-duration, point impact to travel between two transducers positioned a known distance apart along the surface of a structure. The P-wave speed is calculated by dividing the distance between the two transducers by the travel time.

1.2.2 *Procedure B: Impact-Echo Test*—This procedure measures the frequency at which the P-wave generated by a

... Concrete

E 1316 Terminology for Nondestructive Examinations

3. Terminology

3.1 *Definitions:*

3.1.1 *acoustic impedance*—the product of P-wave speed and density that is used in computations of characteristics of stress wave reflection at boundaries.

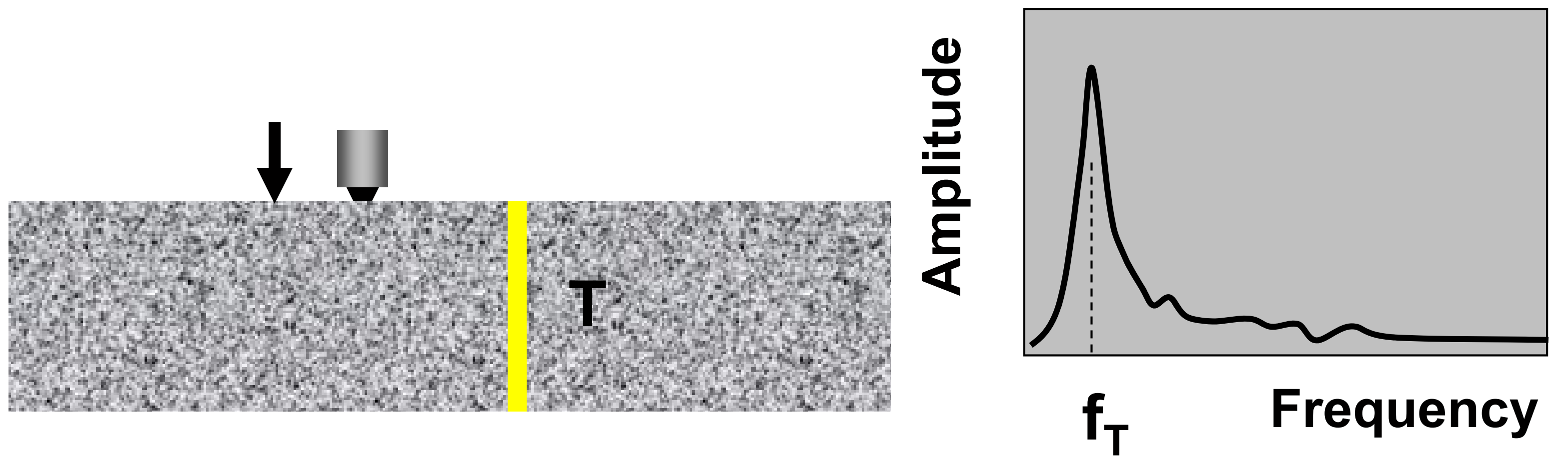
3.1.2 *amplitude spectrum*—a plot of relative amplitude versus frequency that is obtained from the waveform using a Fourier transform technique.

3.1.3 *Fourier transform*—a numerical technique used to

Procedure A: Determine C_p

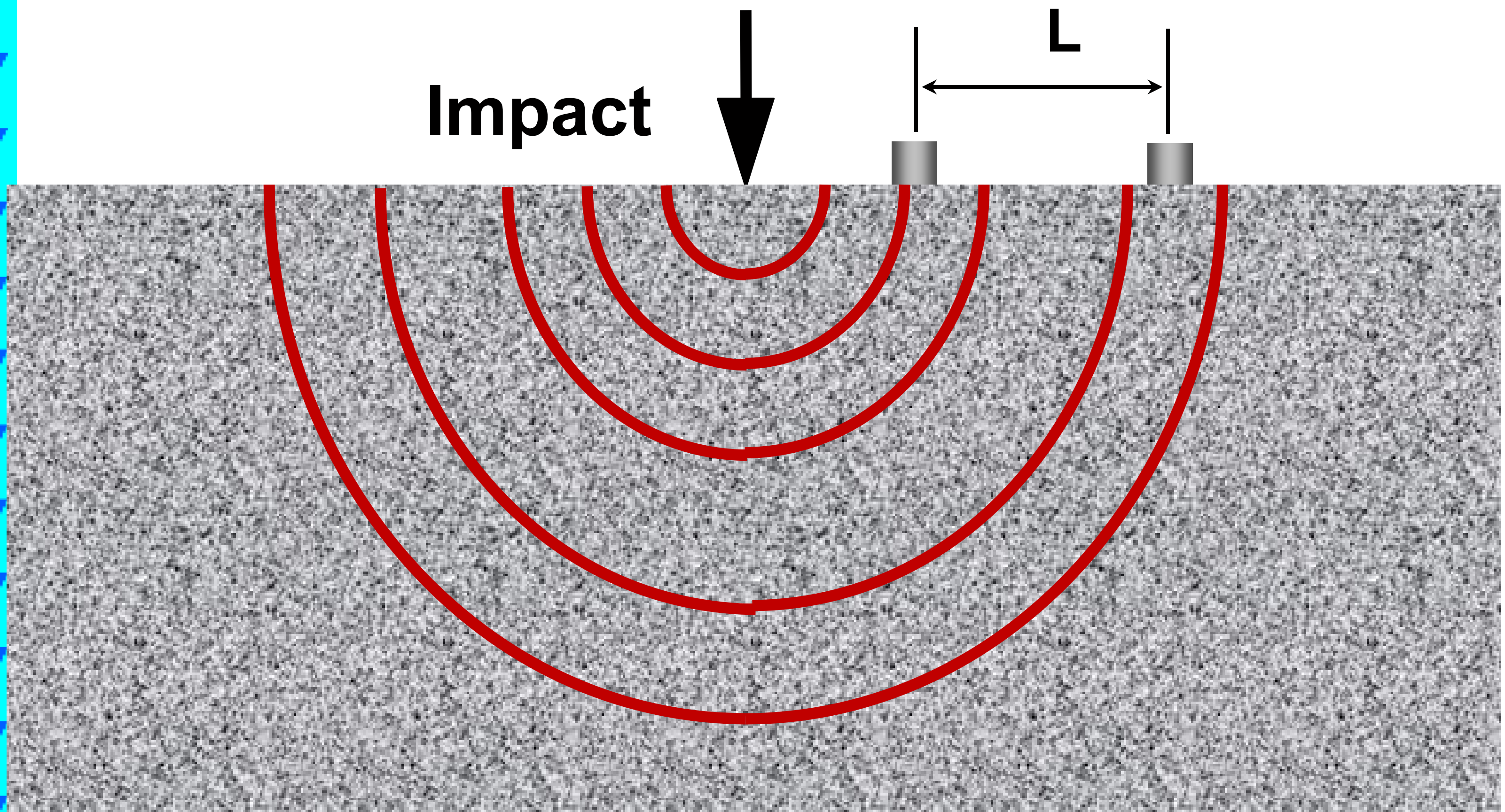
- Perform impact-echo test and measure thickness at corresponding point
- Surface measurement of P-wave: C_p^s
  - Travel time between two transducers

Hole Drilling Method

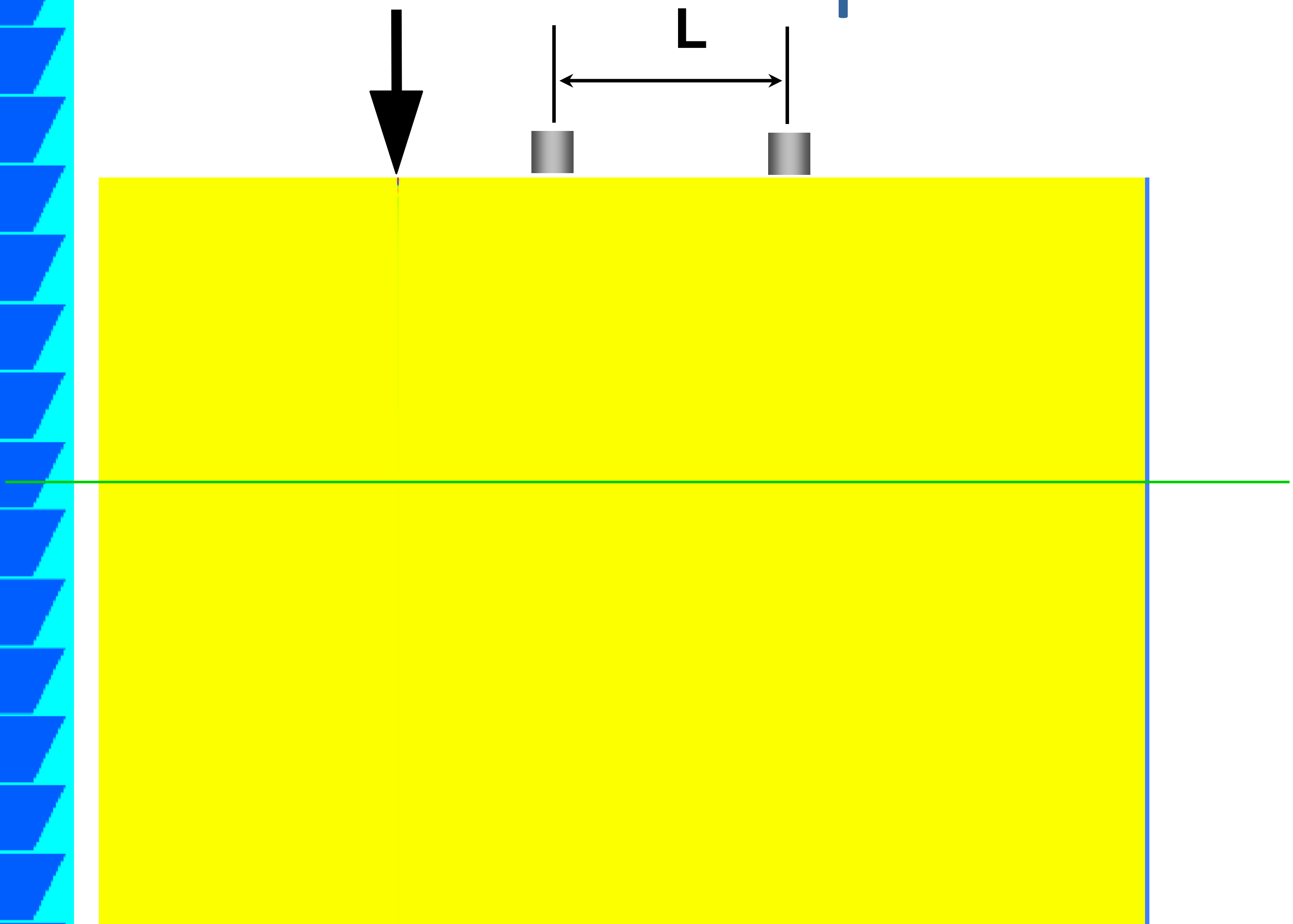


$$C_p = 2 f_T T$$

Surface Measurement of P-Wave Speed

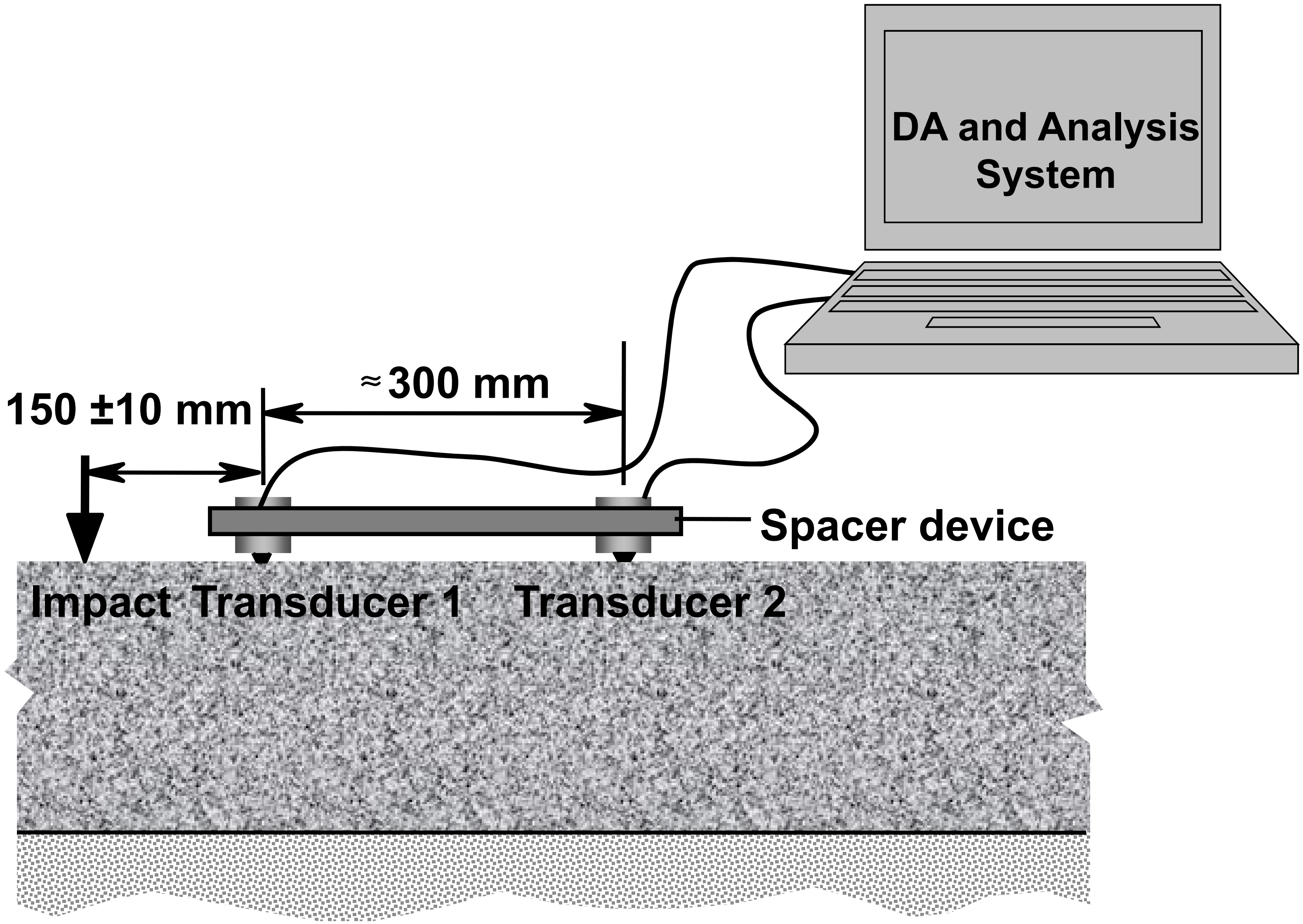


Surface Measurement of P-Wave Speed



appliedgeophysics.berkeley.edu:7057/seismic/seismic_21.pdf

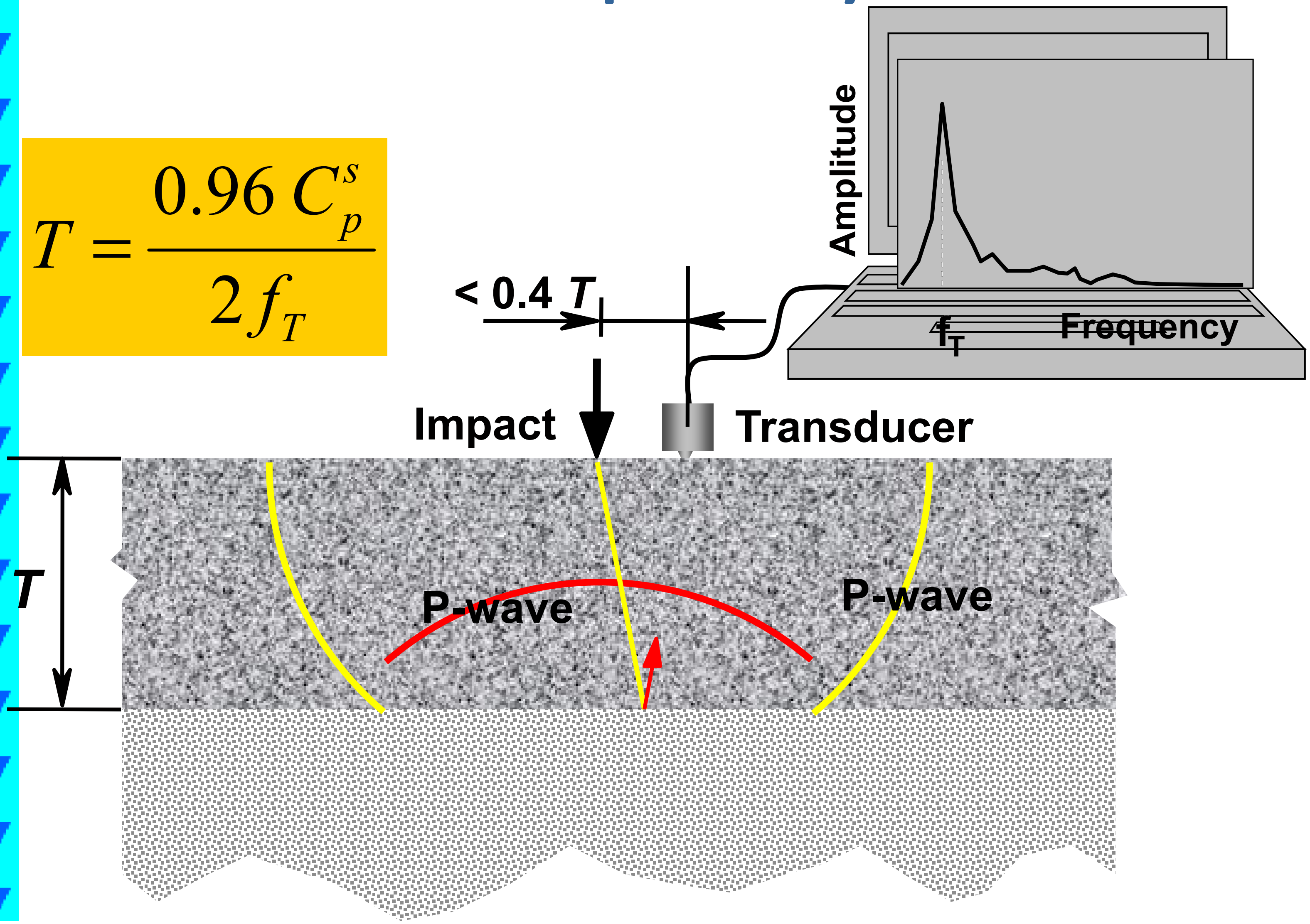
Surface Measurement




Impactor

Procedure B: Thickness Frequency

$$T = \frac{0.96\, C_p^s}{2 f_T}$$



Impact-Echo Limitations

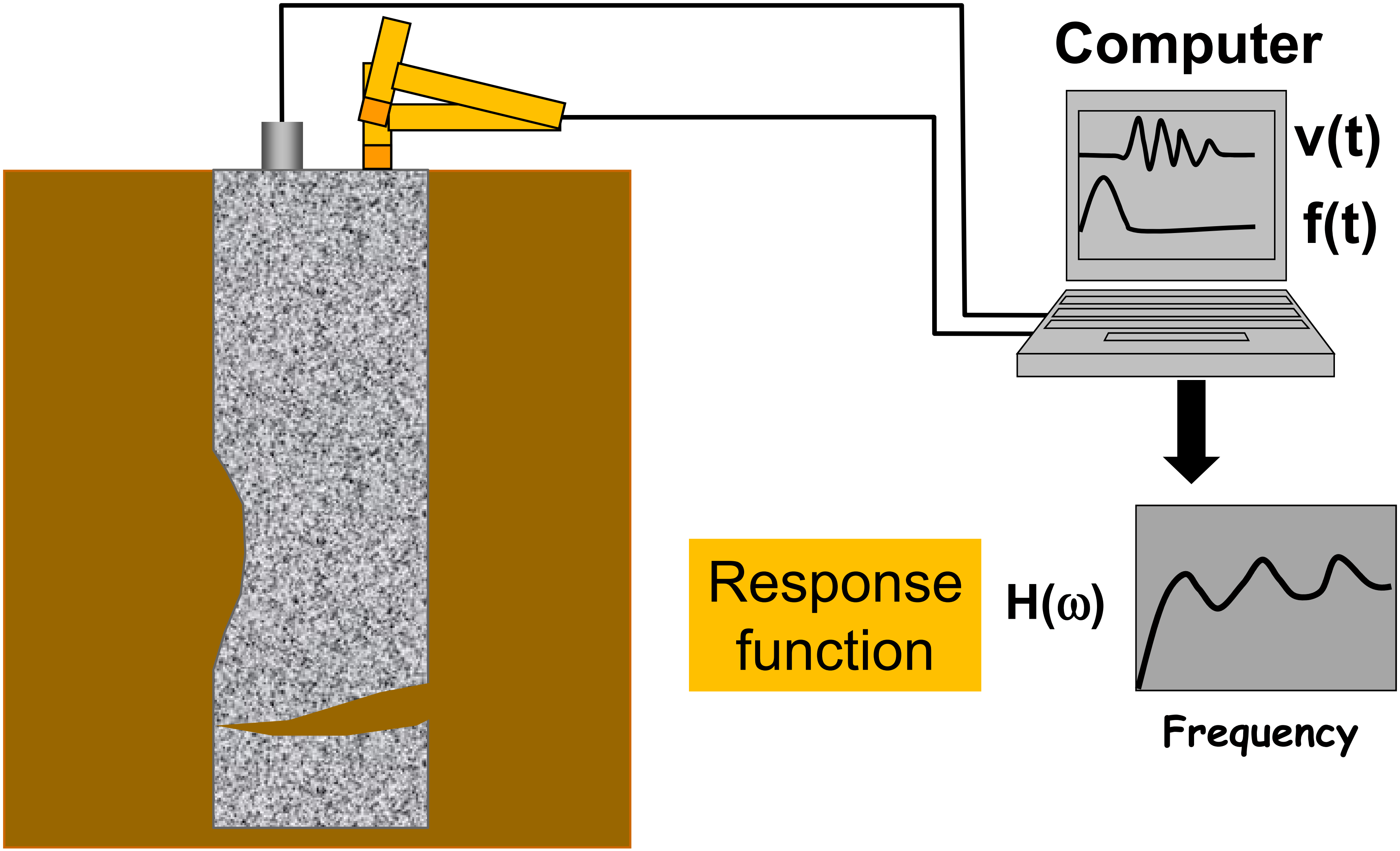
- Complexity
- Point-to-point testing
- Takes time to evaluate test surface
- Closely spaced testing required for “visualization” methods

New multi-sensor system based on ultrasonic-echo technique overcomes some of these limitations

Impulse-Response Method

- Originated as method to test deep foundations
- Requires measurement of impact force
- Signal processing examines the impact response per unit of applied force as a function of frequency
- Lower frequency than impact-echo

Impulse-Response for Shafts

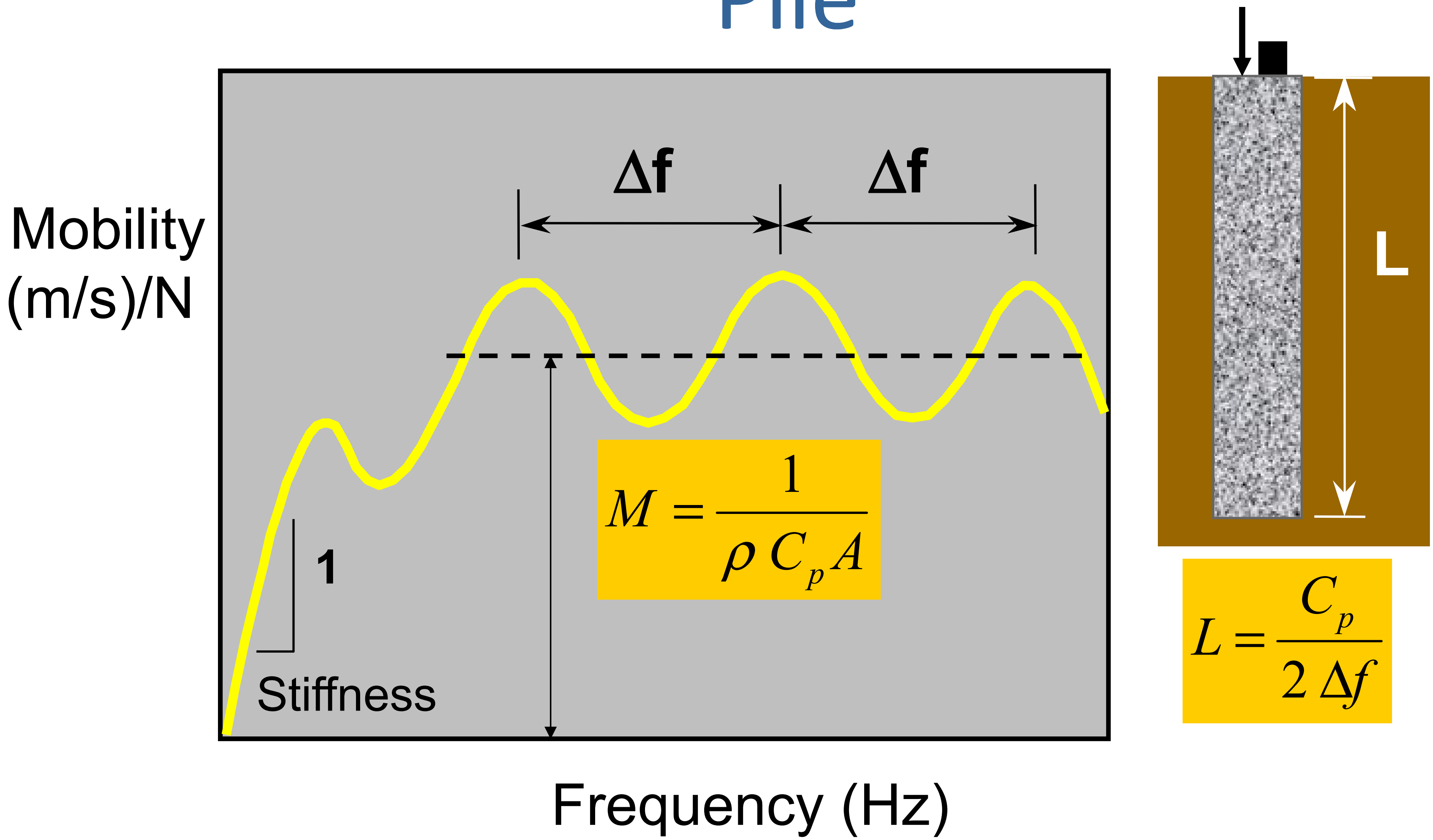


Impulse-Response Test System

Transfer Functions

Measured Response	Transfer Function	Units
Displacement	Dynamic Compliance	L/F
Velocity	**Mobility**	**(L/s)/F**
Acceleration	Accelerance	$(L/s^2)/F$

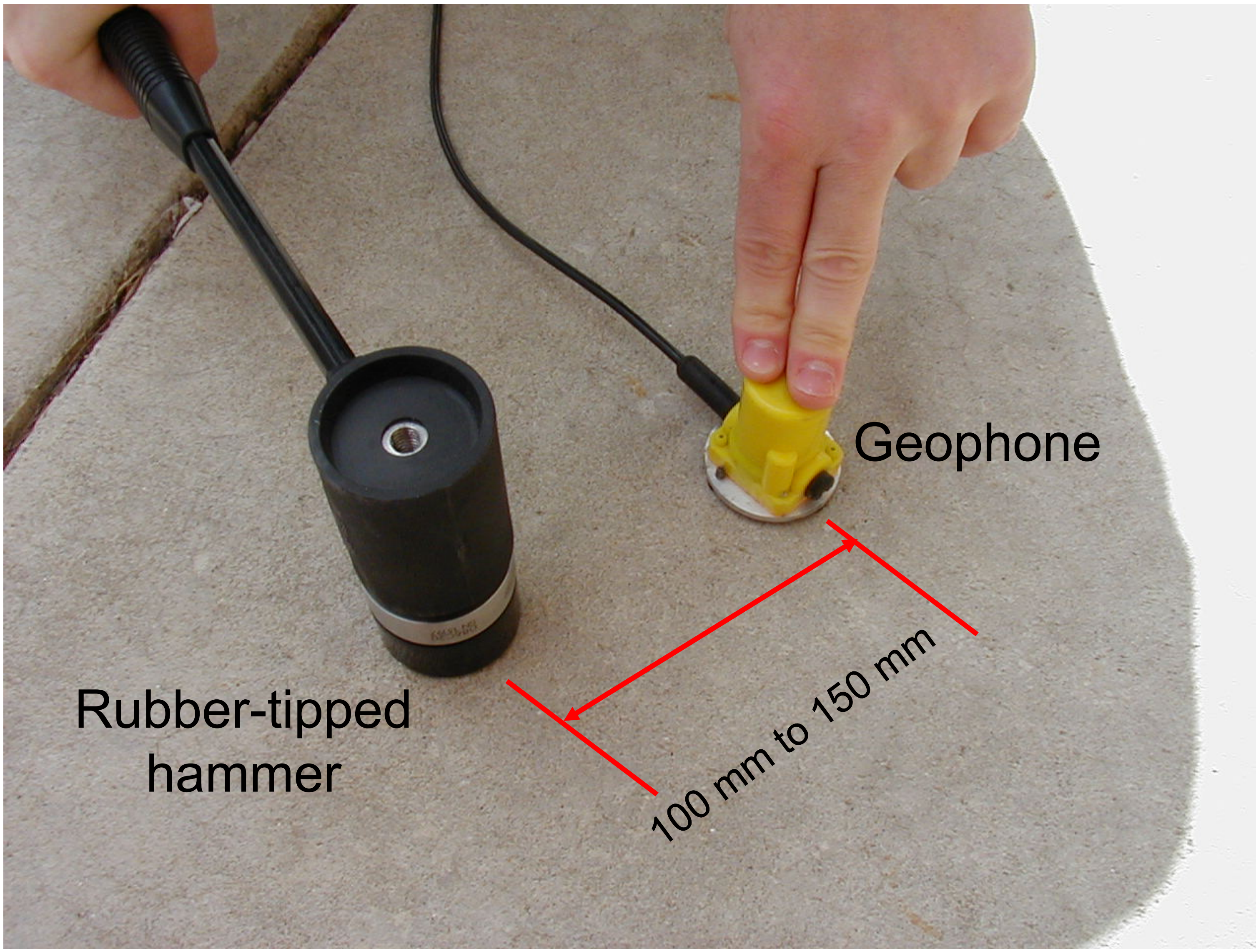
Idealized Mobility Plot of Pile



Application to Plates

- Impulse-response testing has it's origin in the testing of drilled shafts and piles
- Recent work has demonstrated that it can also be used successfully to assess plate-like structures
- Comparative test to assess differences in response to impact force
  - Locate anomalous regions

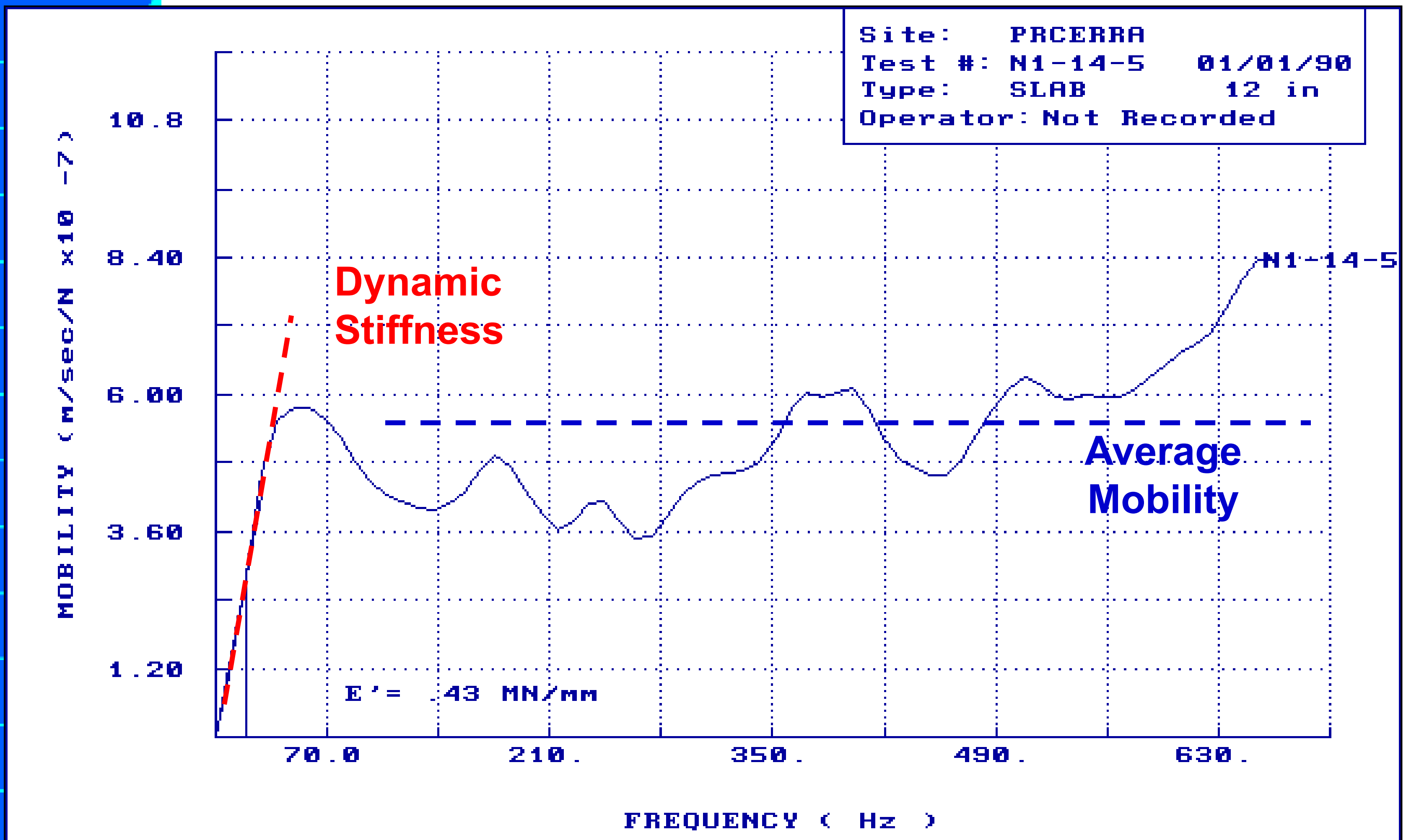
Hammer and Geophone Position



Impulse-Response Testing of Plate-like Structures

- Permits rapid screening of suspect structures
- Various features of mobility plot are used as indicators of conditions
  - Dynamic stiffness (initial slope 0 to 50 Hz)
  - Average mobility (100 to 800 Hz)
  - Slope of mobility vs. frequency
  - Ratio of low frequency peak mobility to mean mobility
- ASTM Standard under development

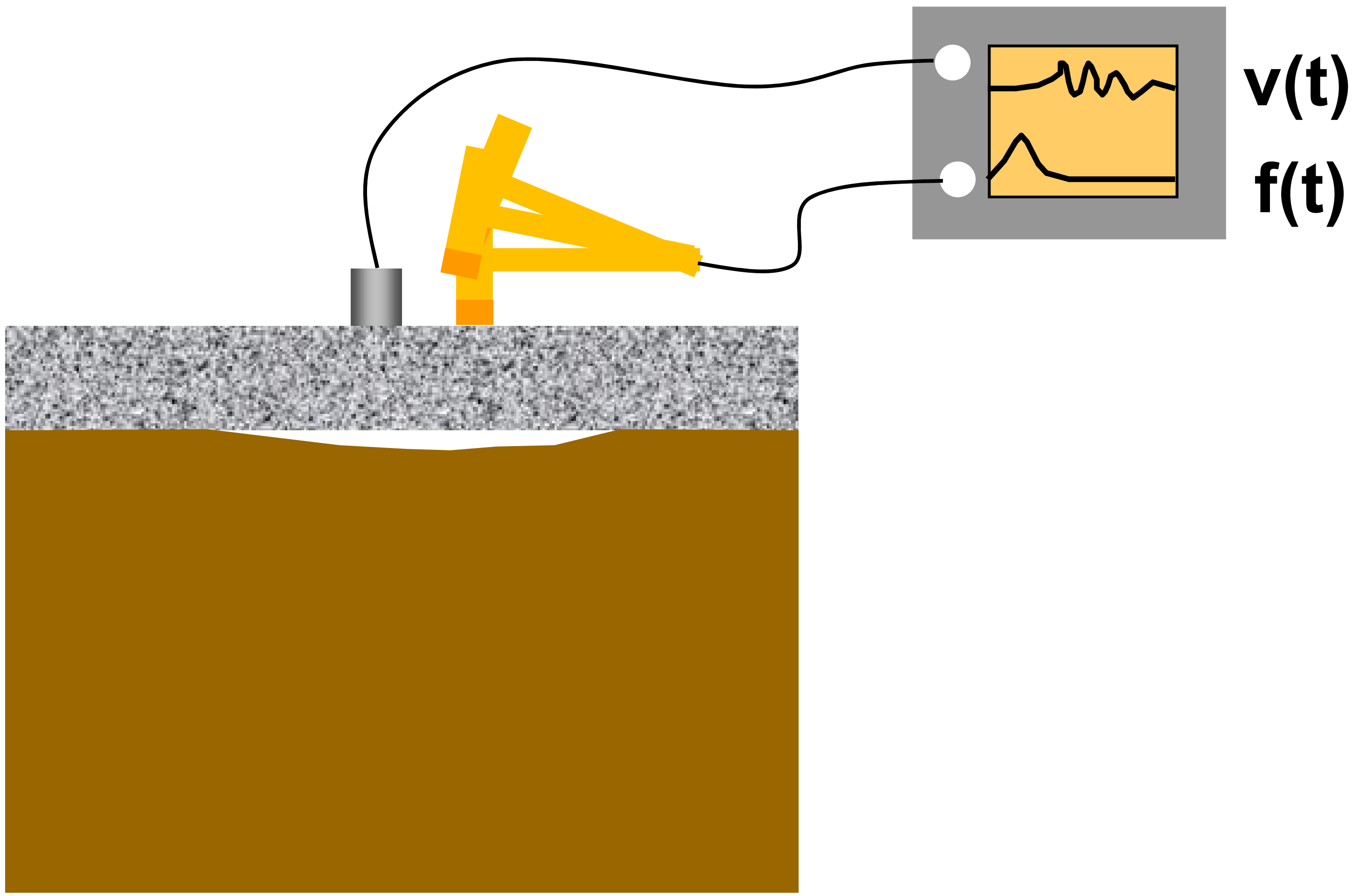
Example of I-R Test of Slab



Average Mobility of Slab

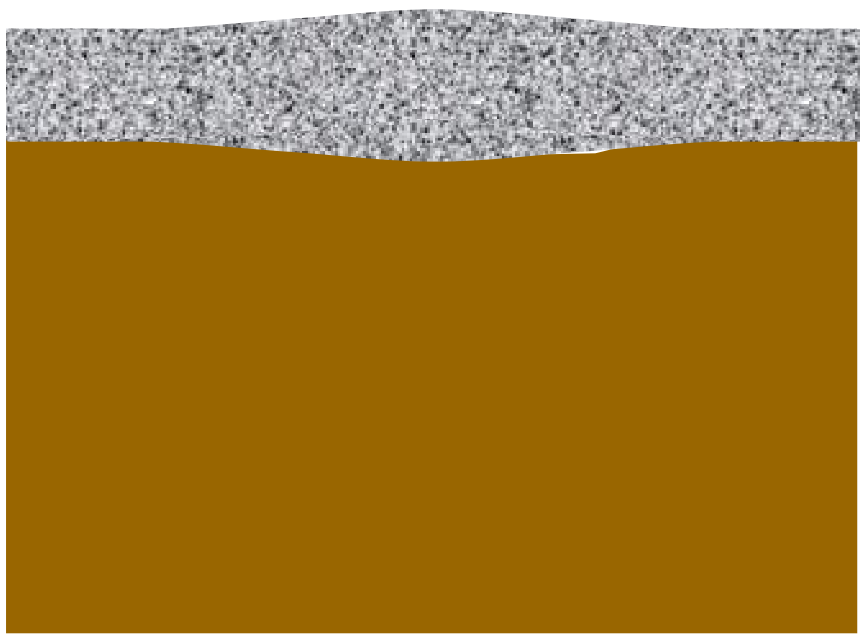
- I-R test causes flexural vibration of slab within vicinity of impact
- Average mobility is affected by
  - Quality of the concrete (C_p)
  - Presence of internal voids
  - Plate thickness
  - Support conditions

Void Below Slab

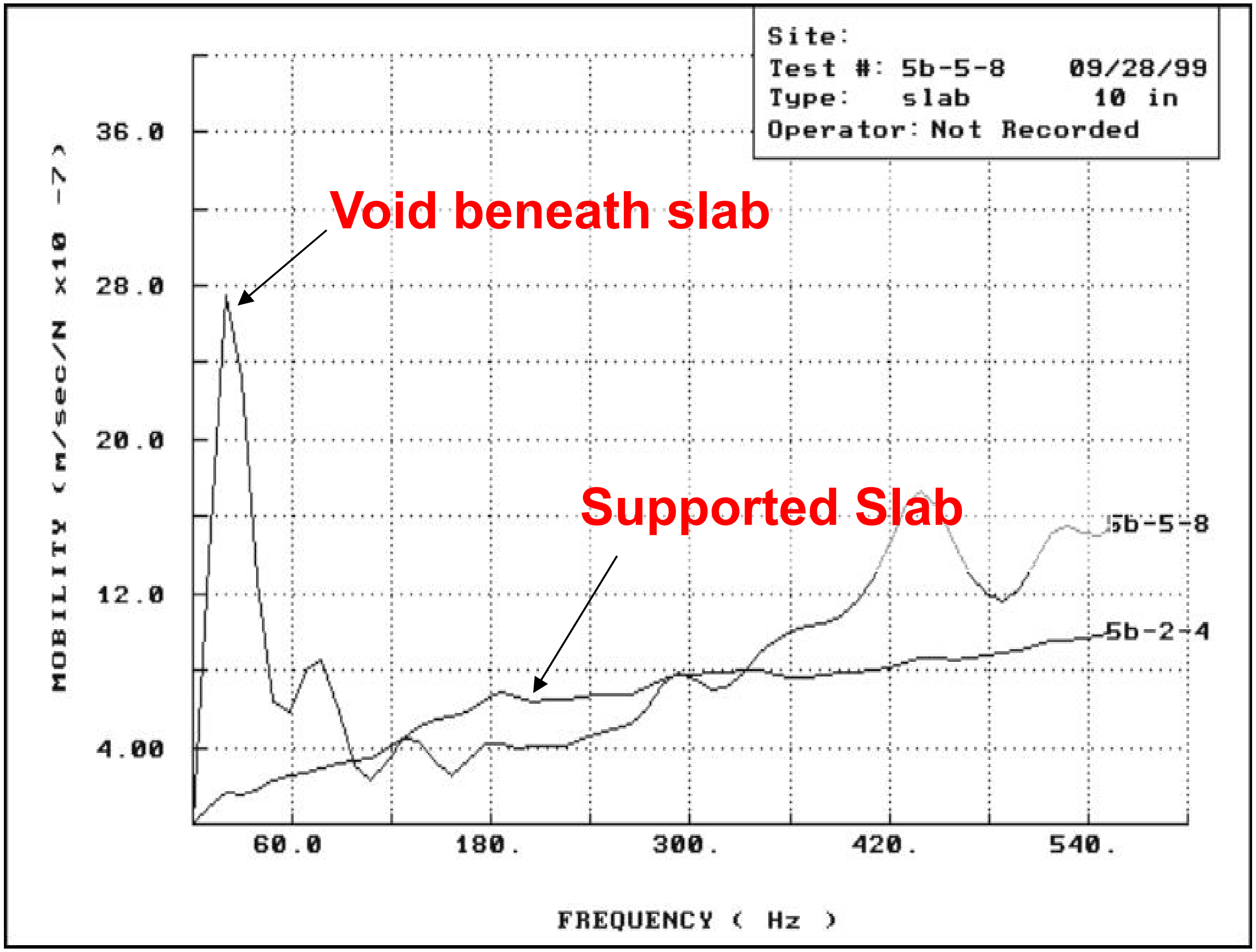


Void Below Slab

Low frequency flexural vibration



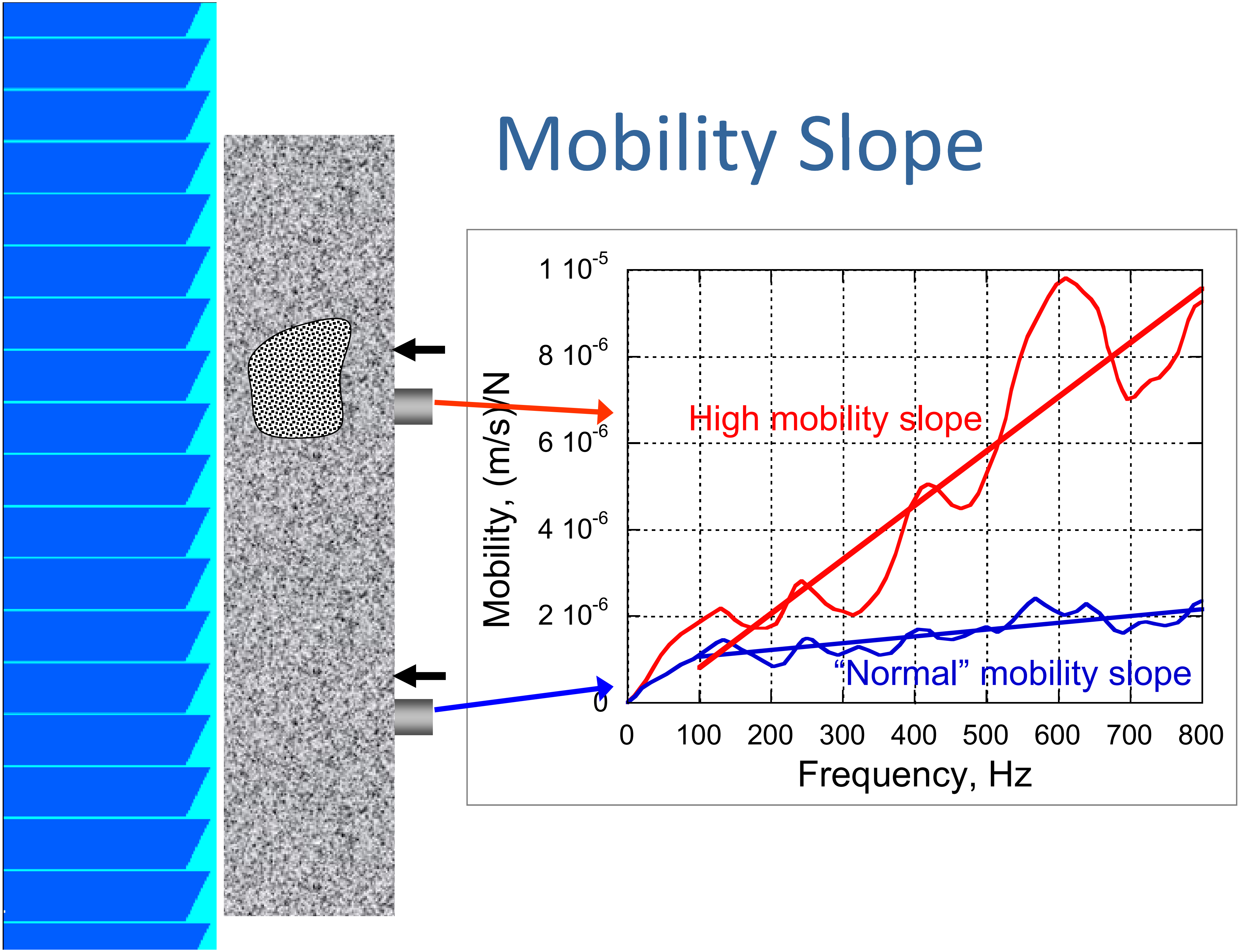
Void Below Slab: High Peak at Low Frequency



Mobility Slope

- Slope of best-fit line to mobility spectrum between 100 and 800 Hz
- A high mobility slope has been found to be indicative of poorly consolidated concrete

Mobility Slope

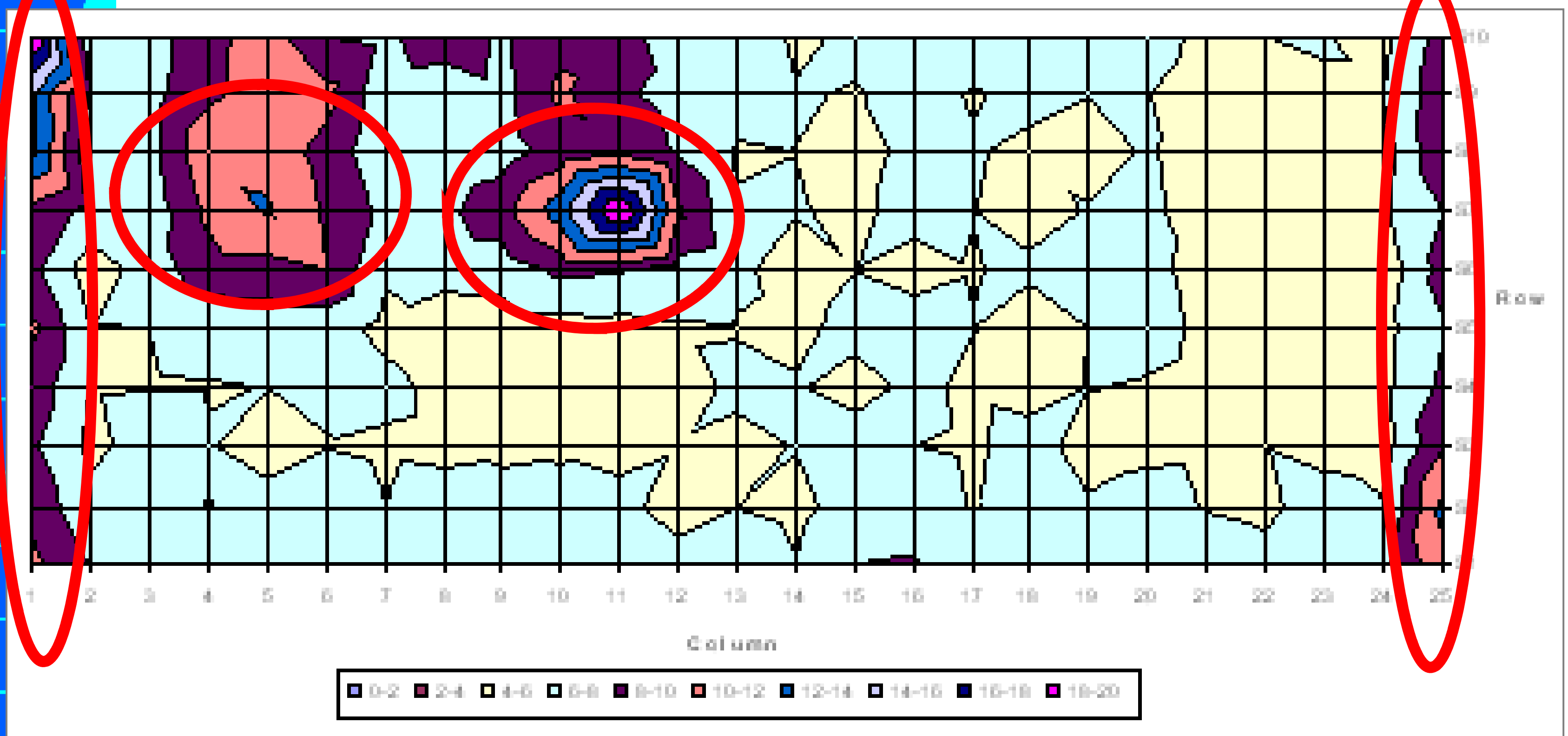


Applications

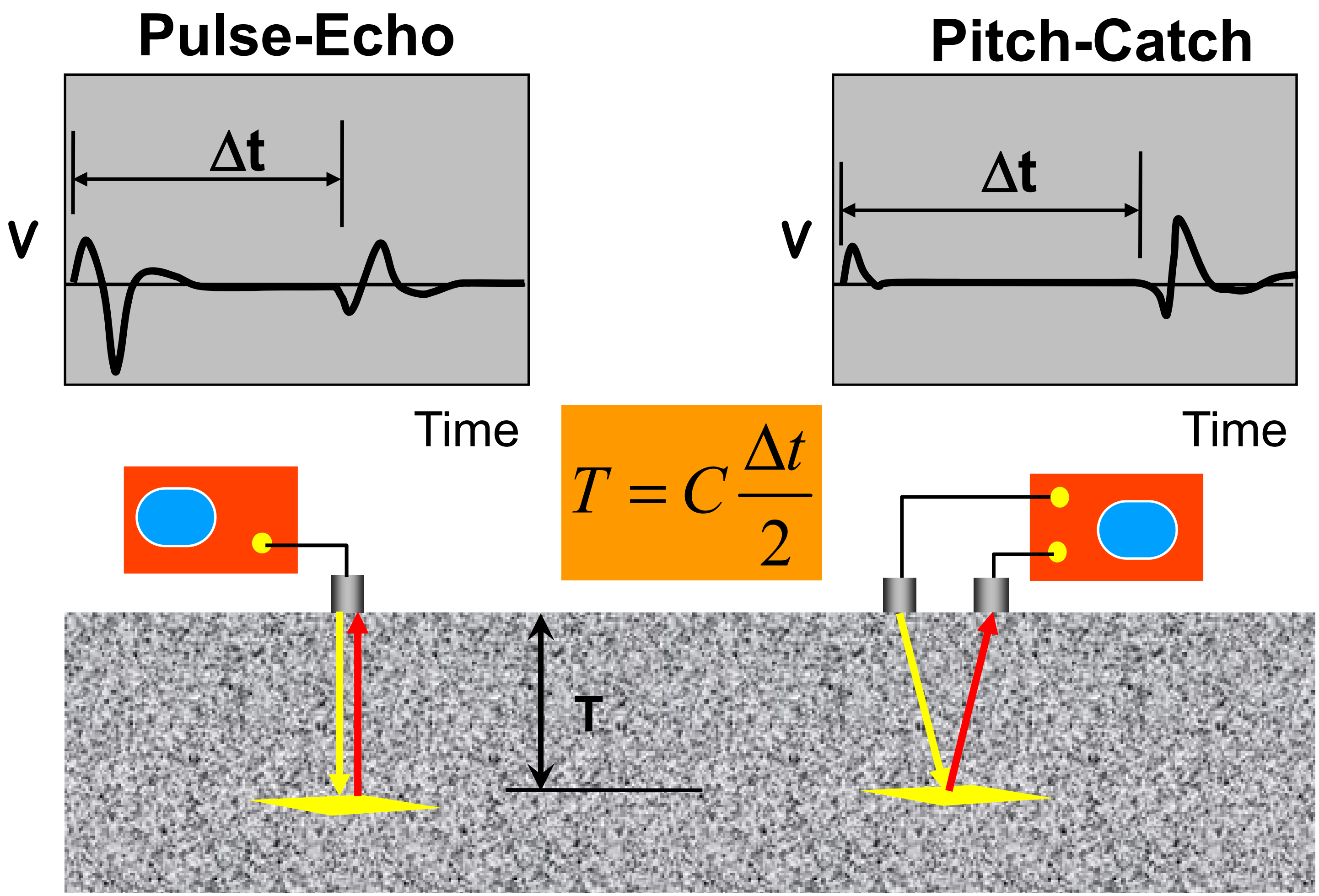
- Detecting voids beneath slabs-on-ground
- Detecting delaminations and honeycombing
- Detecting slab curling
- Evaluation of anchorage of exterior wall panels
- Location of areas of distributed cracking (F-T, ASR)
- Evaluation of load transfer at construction joints

Example

Contour plot of average mobility



Ultrasonic Echo Methods

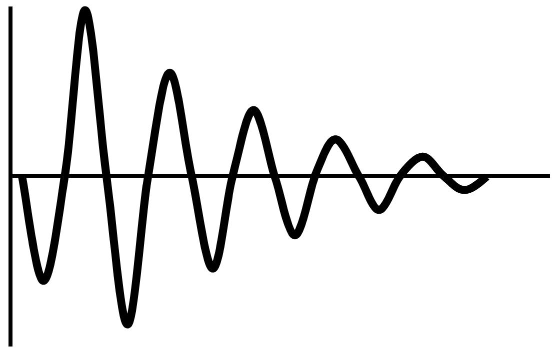


$$T = C\frac{\Delta t}{2}$$

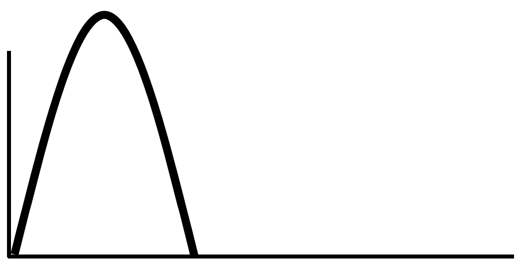
Ultrasonic-Echo Methods

- Limited success before the 1990s
- Developments since the 1990s
  - Low frequency (50 to 100 kHz), broadband, dry coupled, point transducers
    - Compressional and shear waves
  - Availability of computing power
    - Use of transducer arrays
    - Digital signal processing
    - Visualization methods

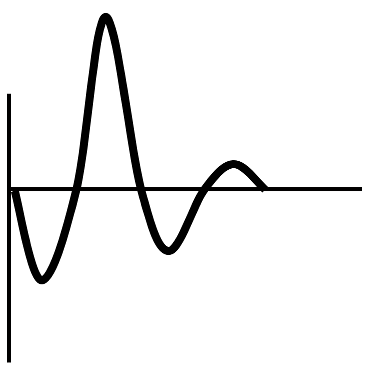
Pulse Shapes



- Lightly damped or narrow band transducer (UPV)



- Impact (I-E)



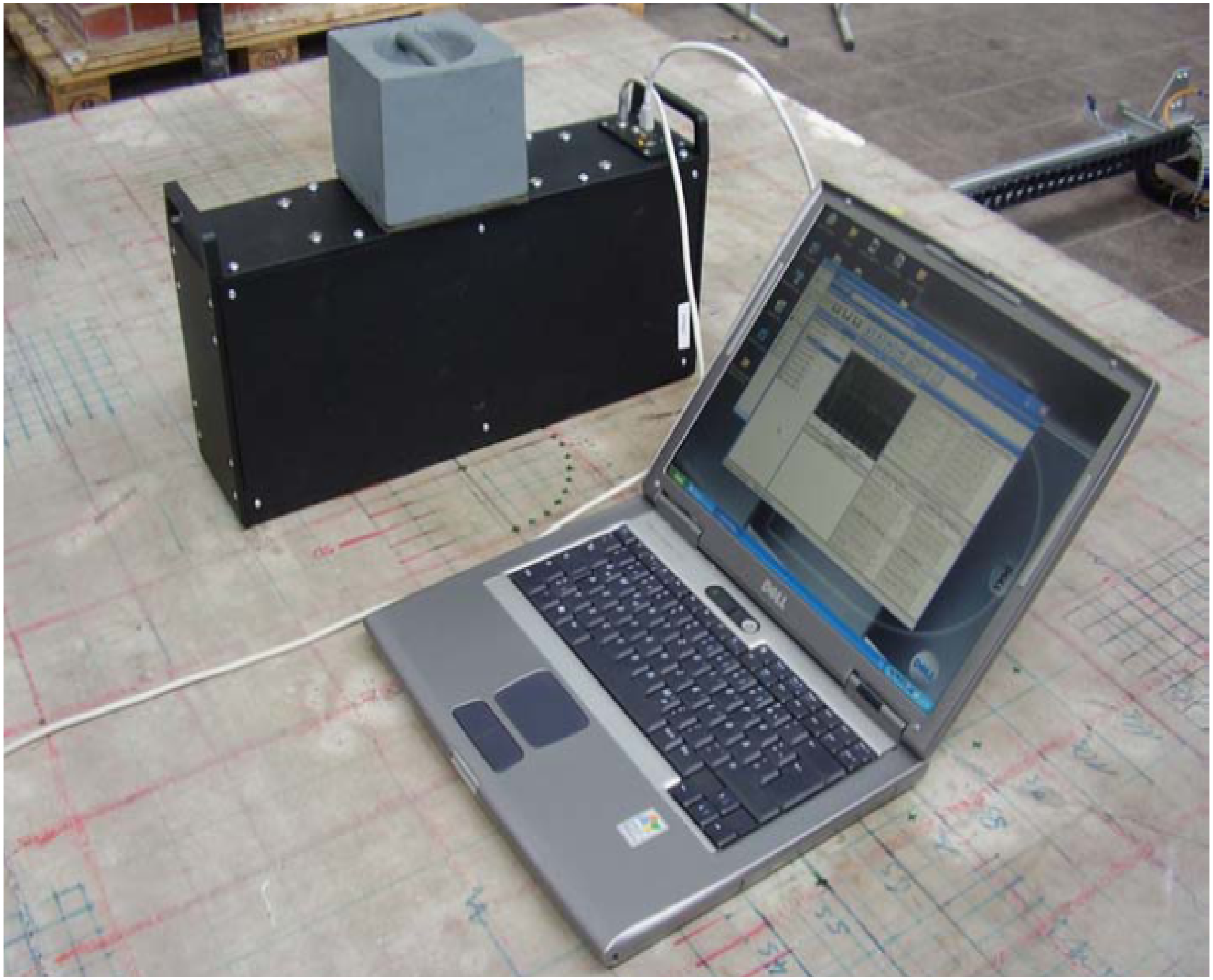
- Damped or broadband transducer (U-E)

Shear-Wave Phased Arrays

EyeCon
4 x 6

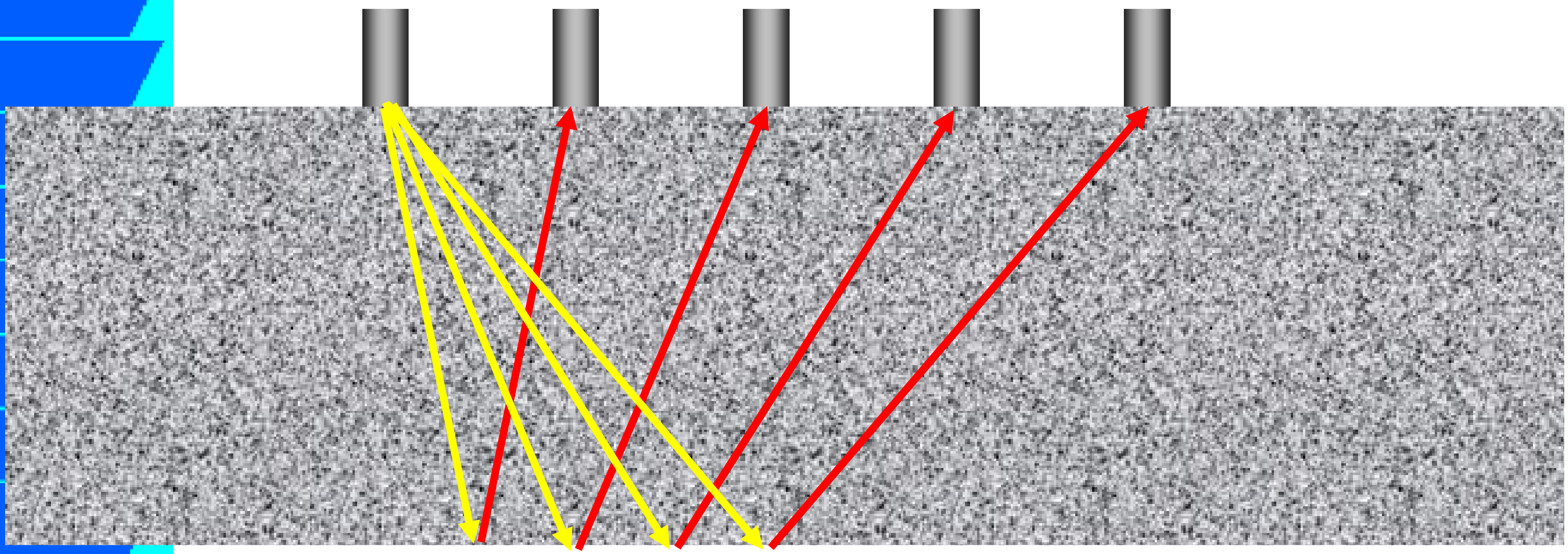
MIRA
4 x 10

MIRA



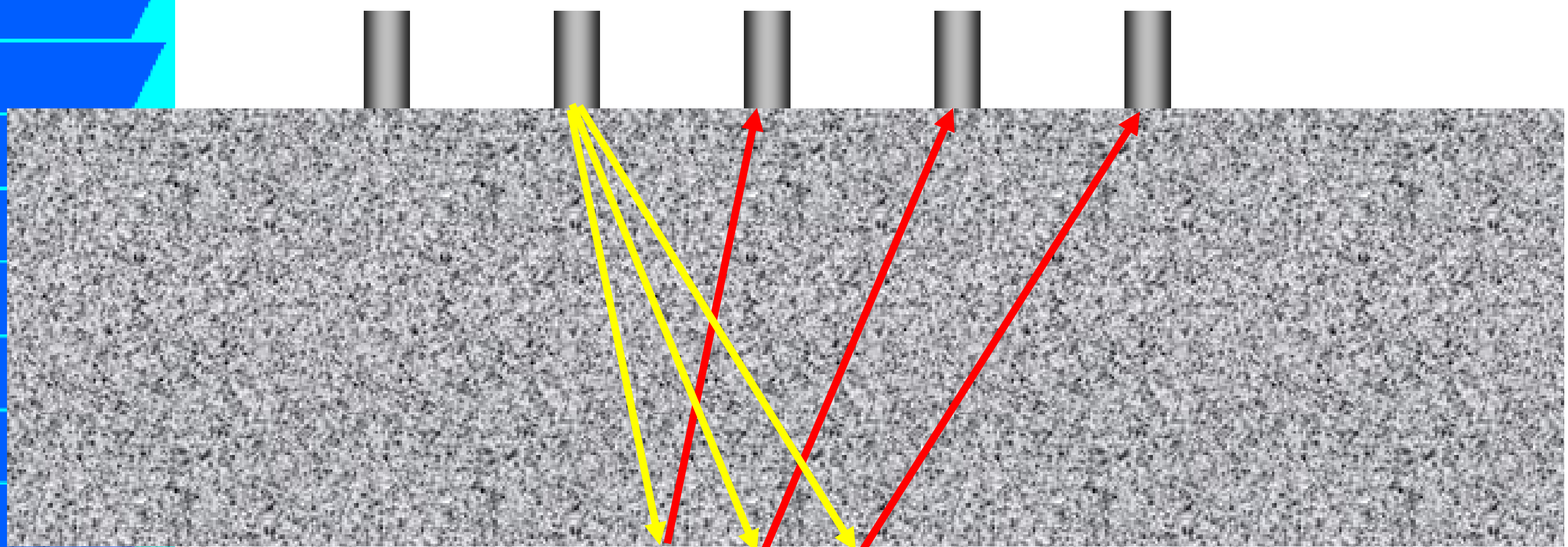
Transducer Array System

Multiple pitch-catch tests

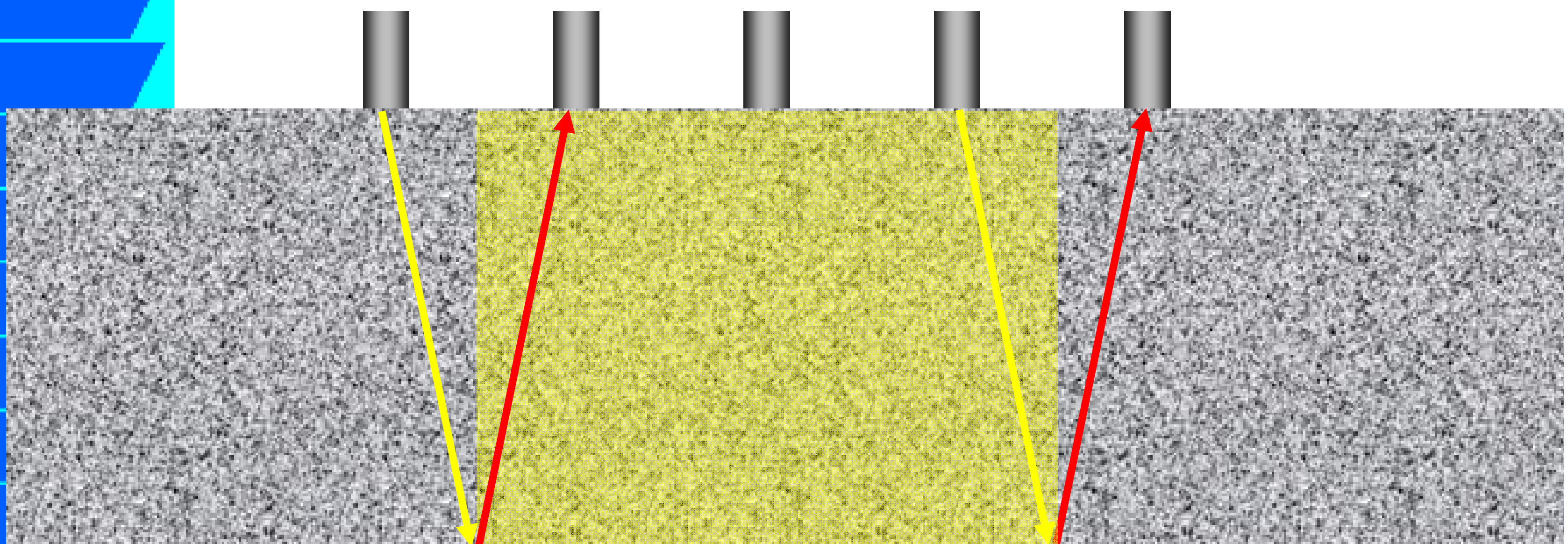


Transducer Array System

Transducers function as transmitters and receivers; results in multiple ray paths



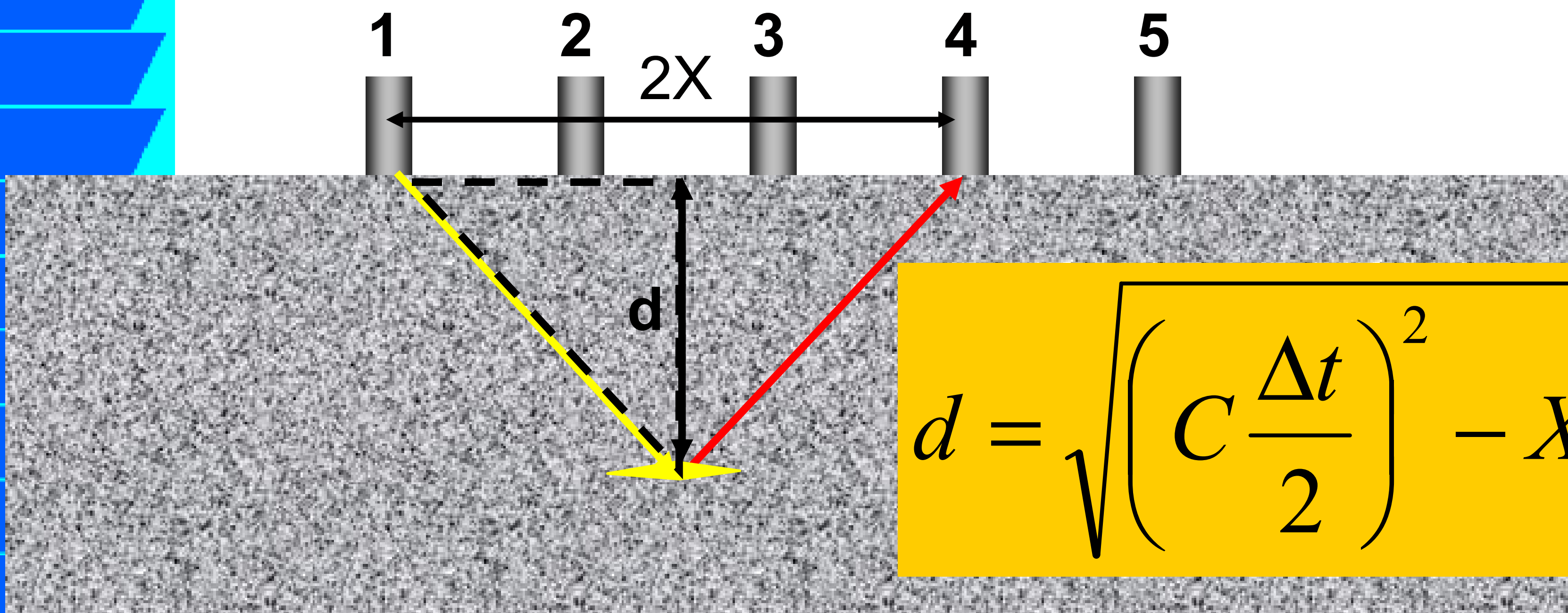
Detection Range



Detection Range
"Aperture"

Depth Correction

Depth of reflector based on measured travel time



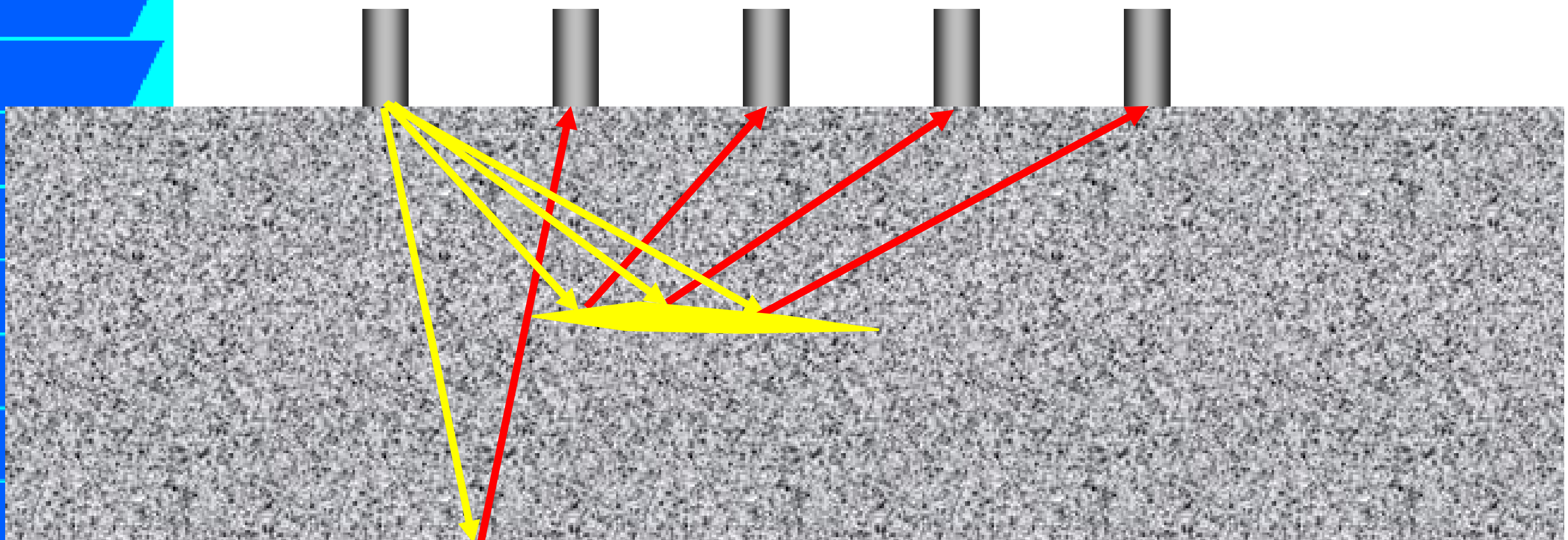
$$d = \sqrt{\left(C\frac{\Delta t}{2}\right)^2 - X^2}$$

C = wave speed

Δt = total travel time

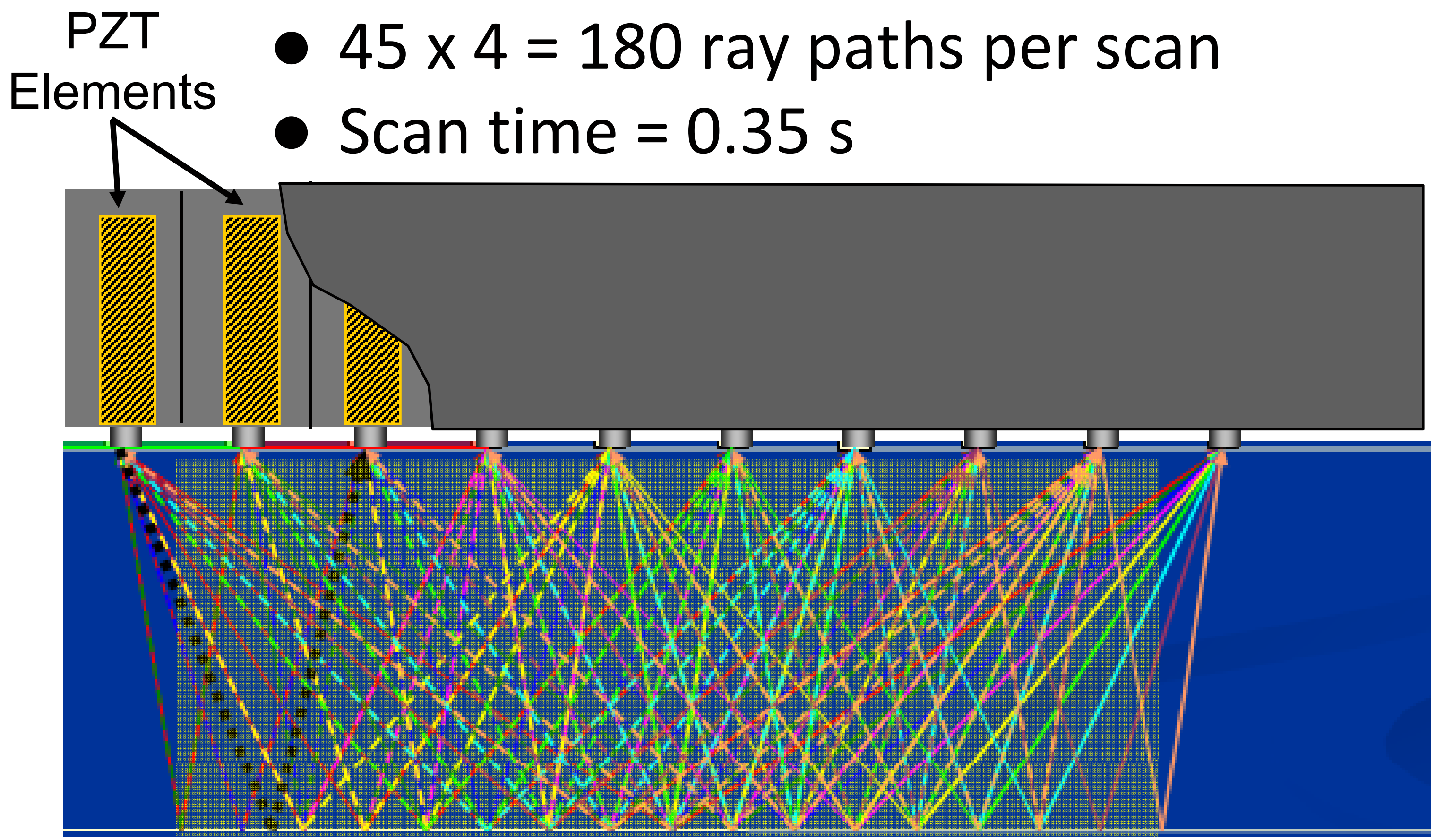
Transducer Array System

Presence of large reflecting interface results in detection by multiple sensors

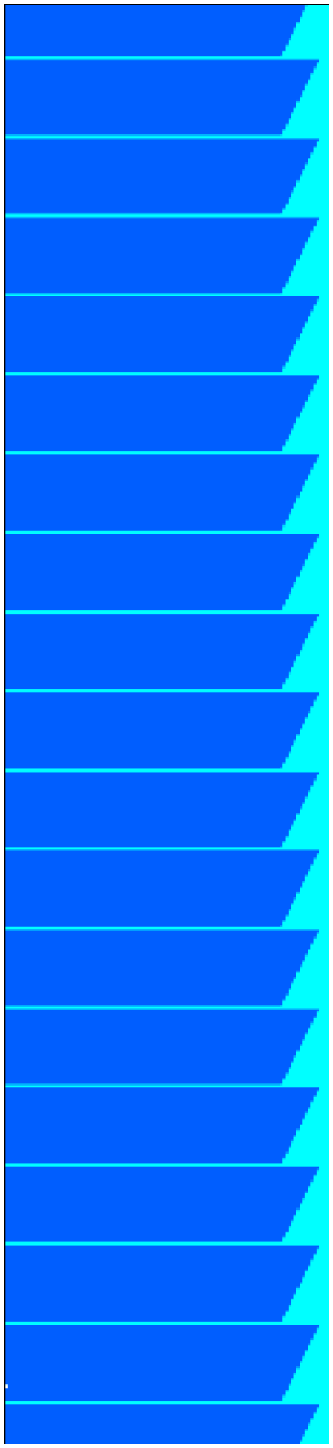


MIRA Antenna

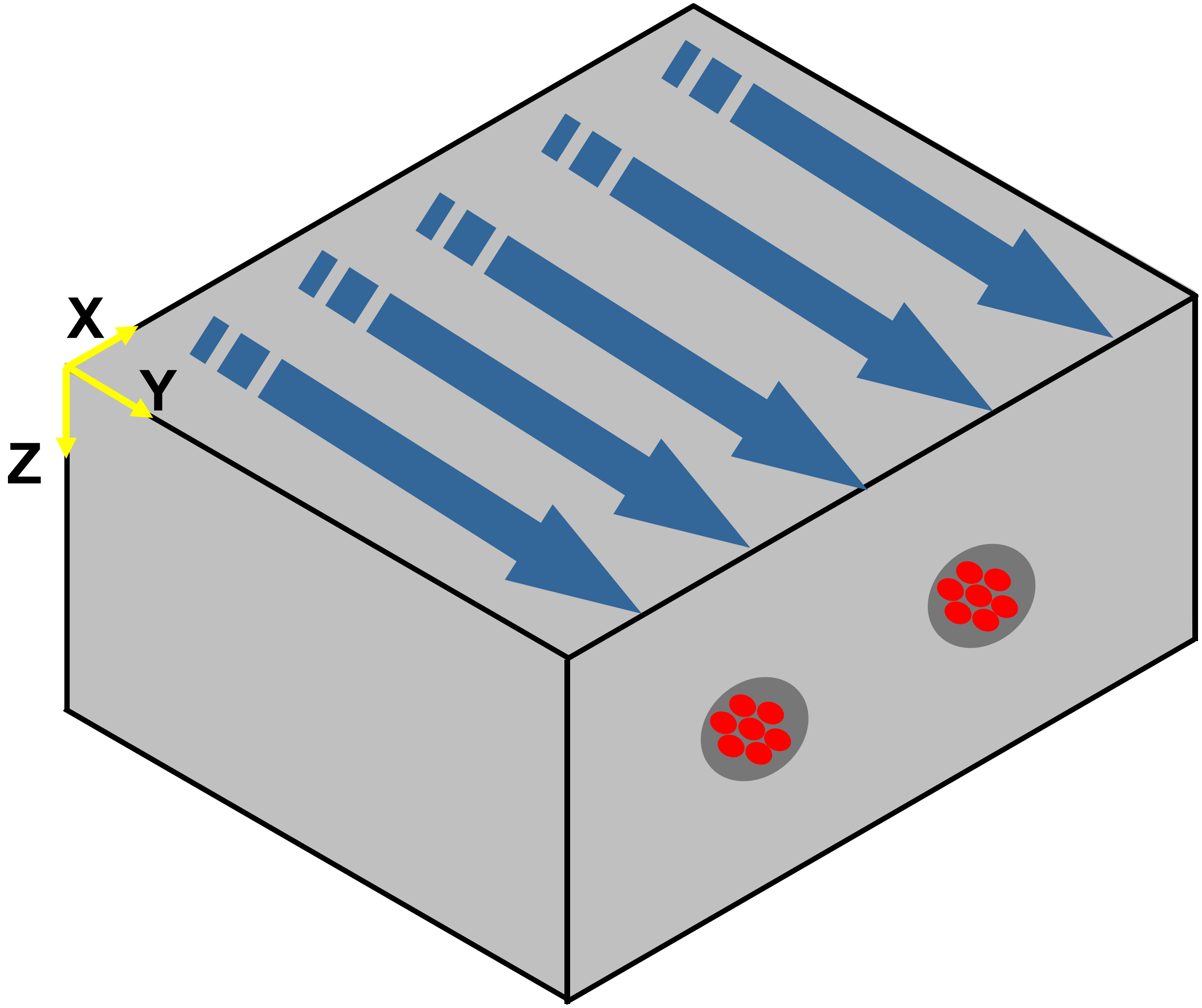
- 4 x 10 transducer array
- 45 x 4 = 180 ray paths per scan
- Scan time = 0.35 s



Scanning



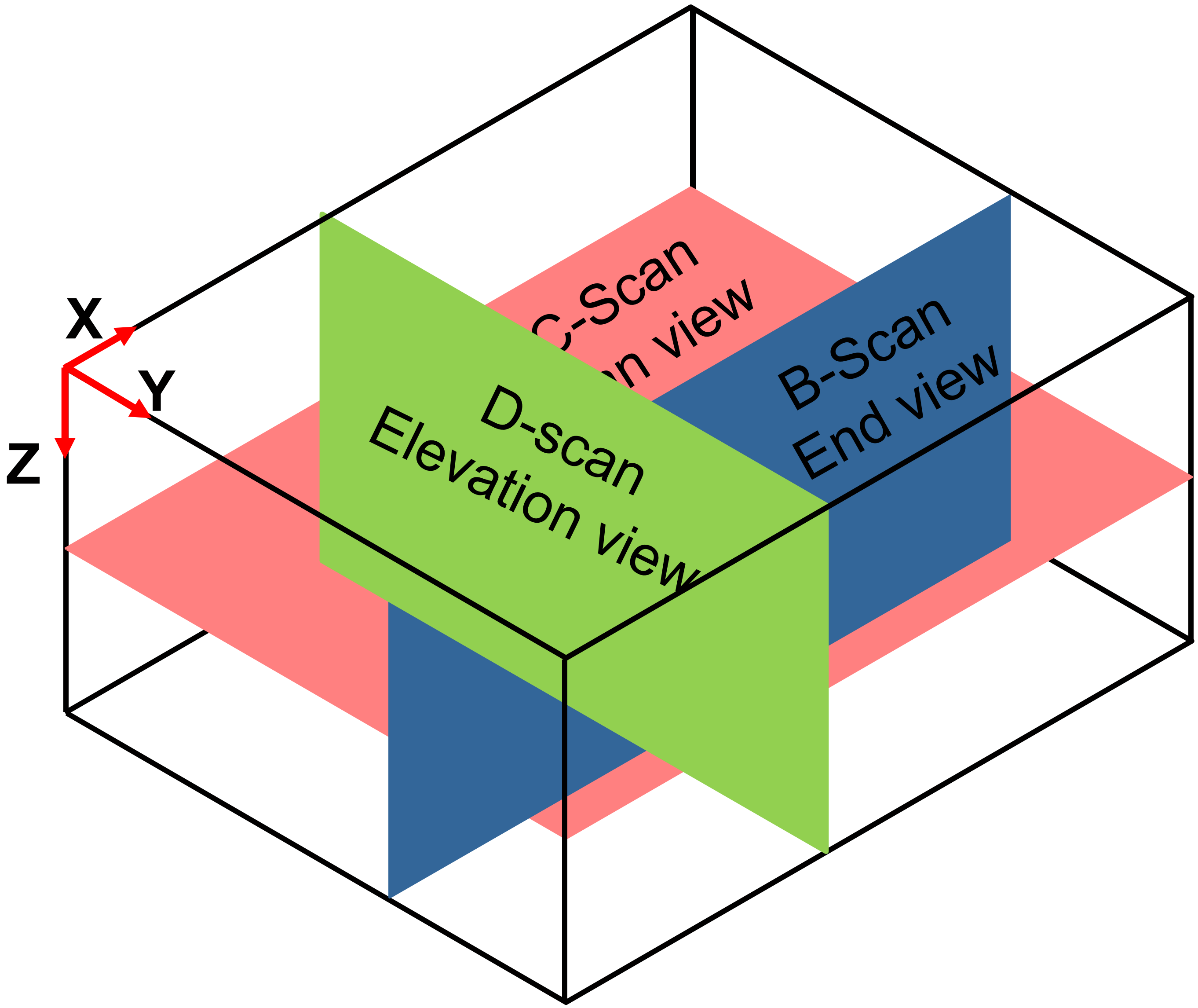
2-D Scan



Synthetic Aperture Focusing Technique (SAFT)

- Times of flight obtained from 2-D scan with transducer array are used to reconstruct location of reflecting interfaces
- The result is a 3-D image of the internal reflectors
  - View in three image planes

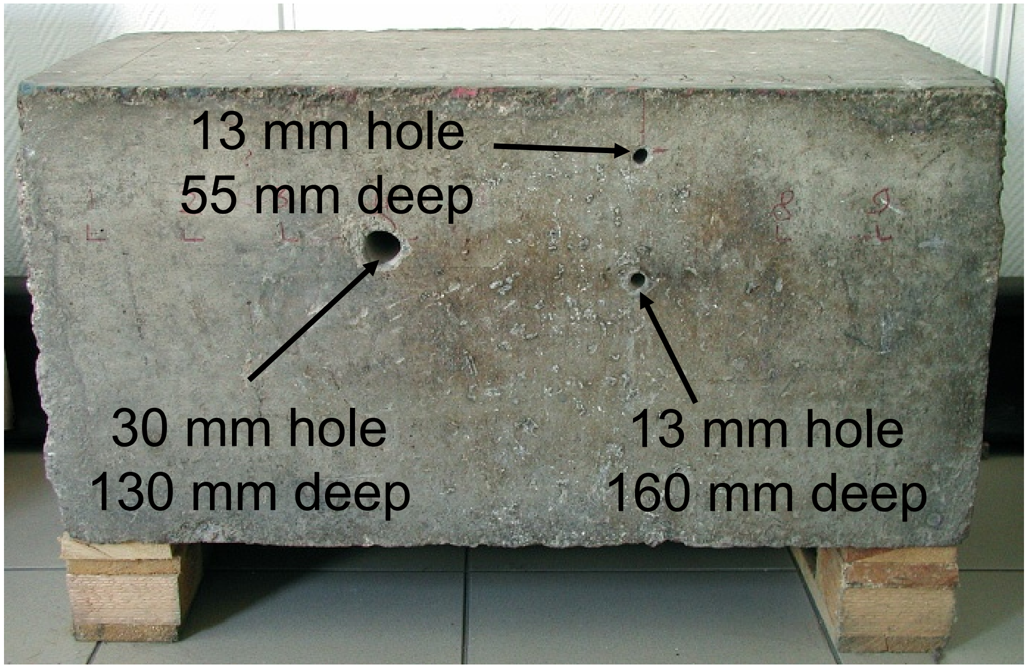
Image Planes



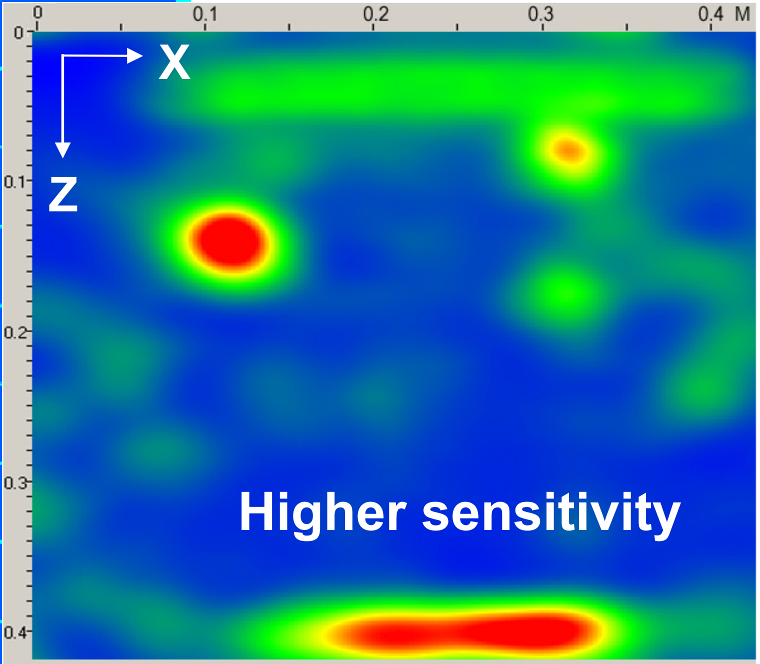
Example

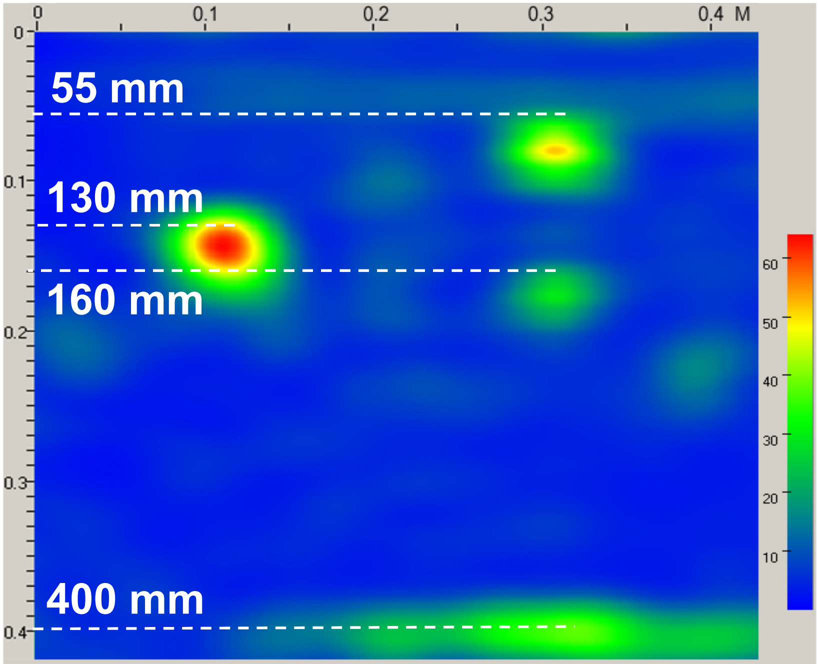
0.8 m x 0.4 m x 0.4 m

C_s= 2385 m/s



B-Scan

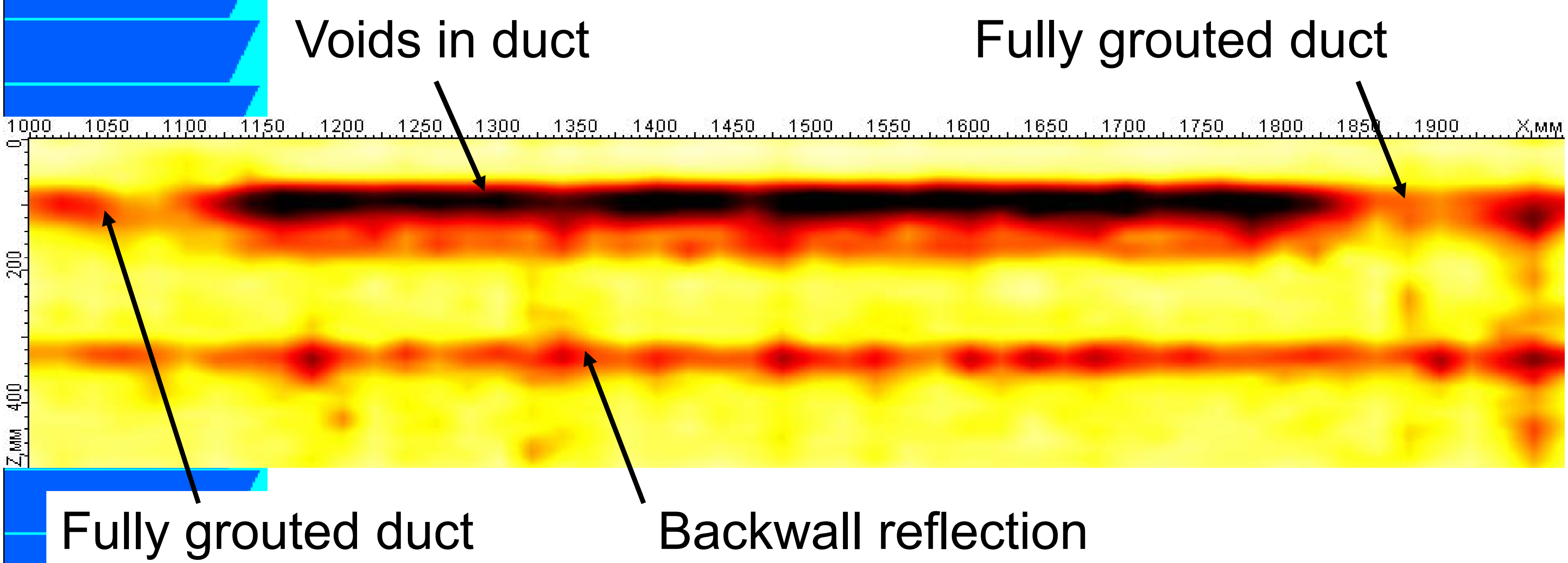




Grouted Tendon Duct

Duct diameter: 60 mm
Cover depth: 80 mm
Slab thickness: 300 mm

D-Scan Elevation



Stress-Wave Methods

- Ultrasonic pulse velocity
- Sounding (chain drag)
- Impact-echo method
- Impulse-response method
- Ultrasonic-echo method

Assessment of Reinforcement

- Location and size
  - Covermeters
  - Radar (location)
- Corrosion condition
  - Half-cell potential (likelihood of corrosion)
  - Polarization resistance (corrosion rate)
  - Concrete resistivity
  - Depth of carbonation
  - Chloride ion concentration

Reinforcement Corrosion

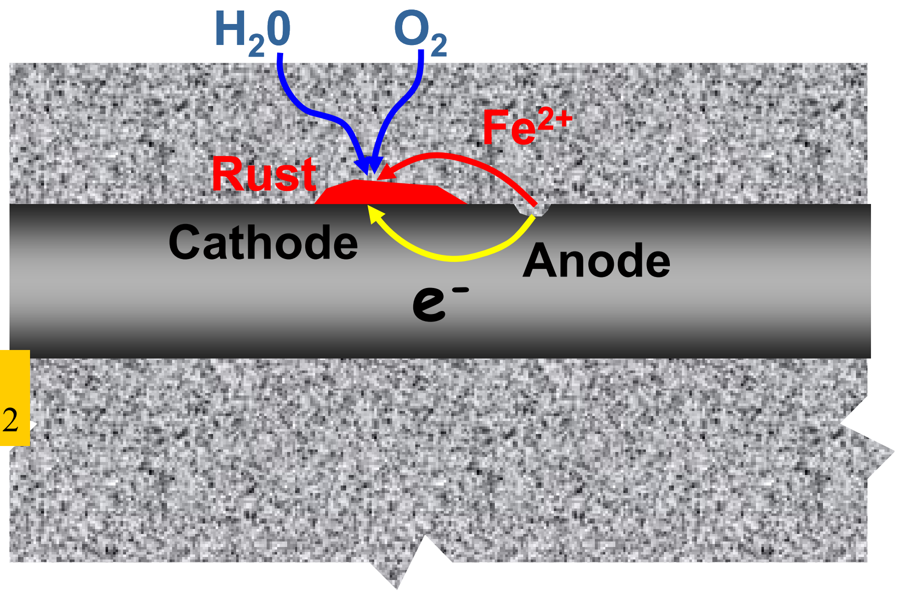
- Anodic and cathodic sites exist on bar
- Iron goes into solution at active sites (anode)
- Electrons travel through bar and iron ions travel through concrete
- Rust forms rust at cathode

Anodic Reaction:

$$Fe \Rightarrow Fe^{+2} + 2e^{-}$$

Cathodic Reaction:

$$2Fe^{+2} + 2H_2O + O_2 + 4e^{-} \Rightarrow 2\,Fe(OH)_2$$

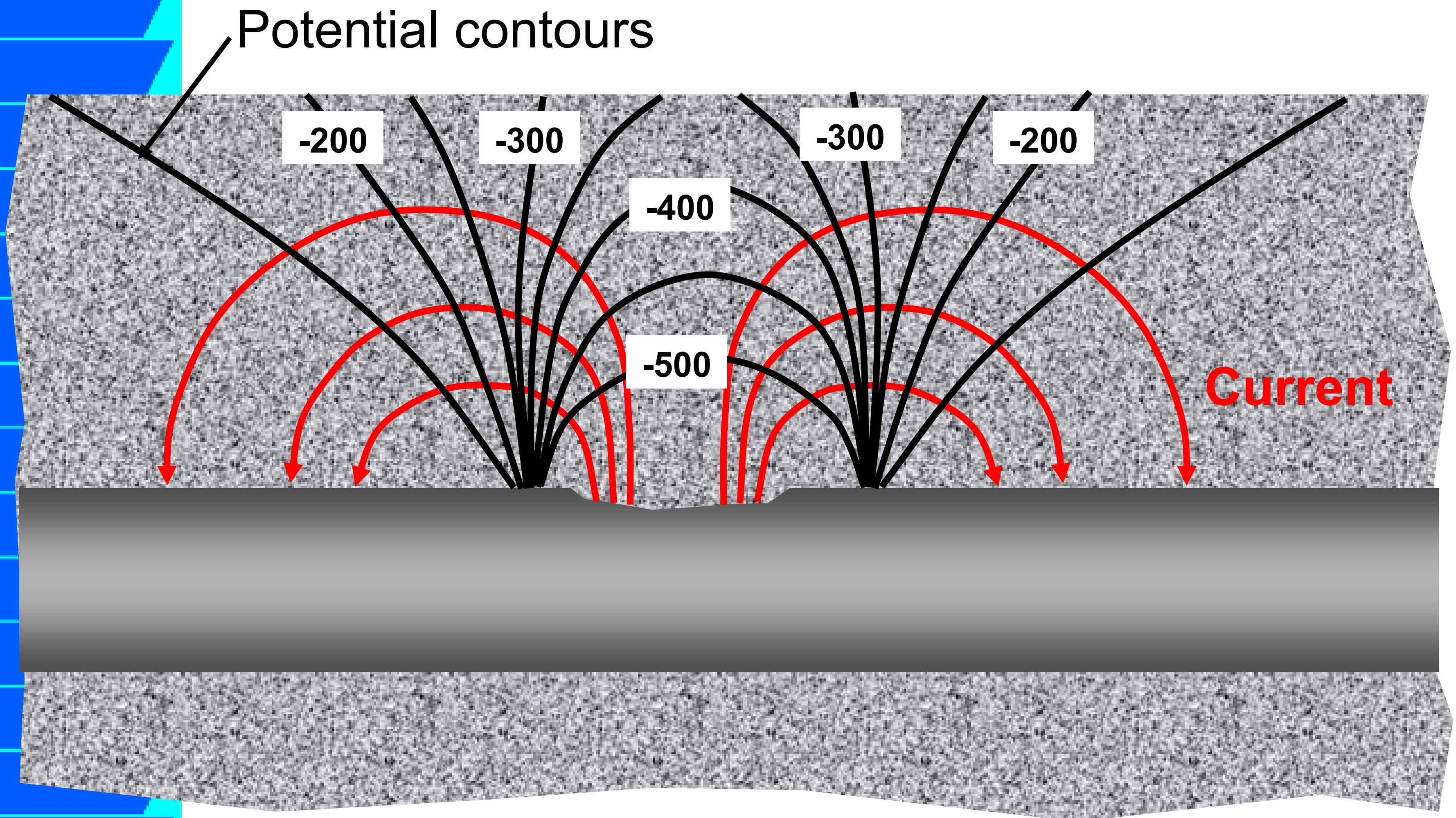


Half-Cell Potential Method

ASTM C876

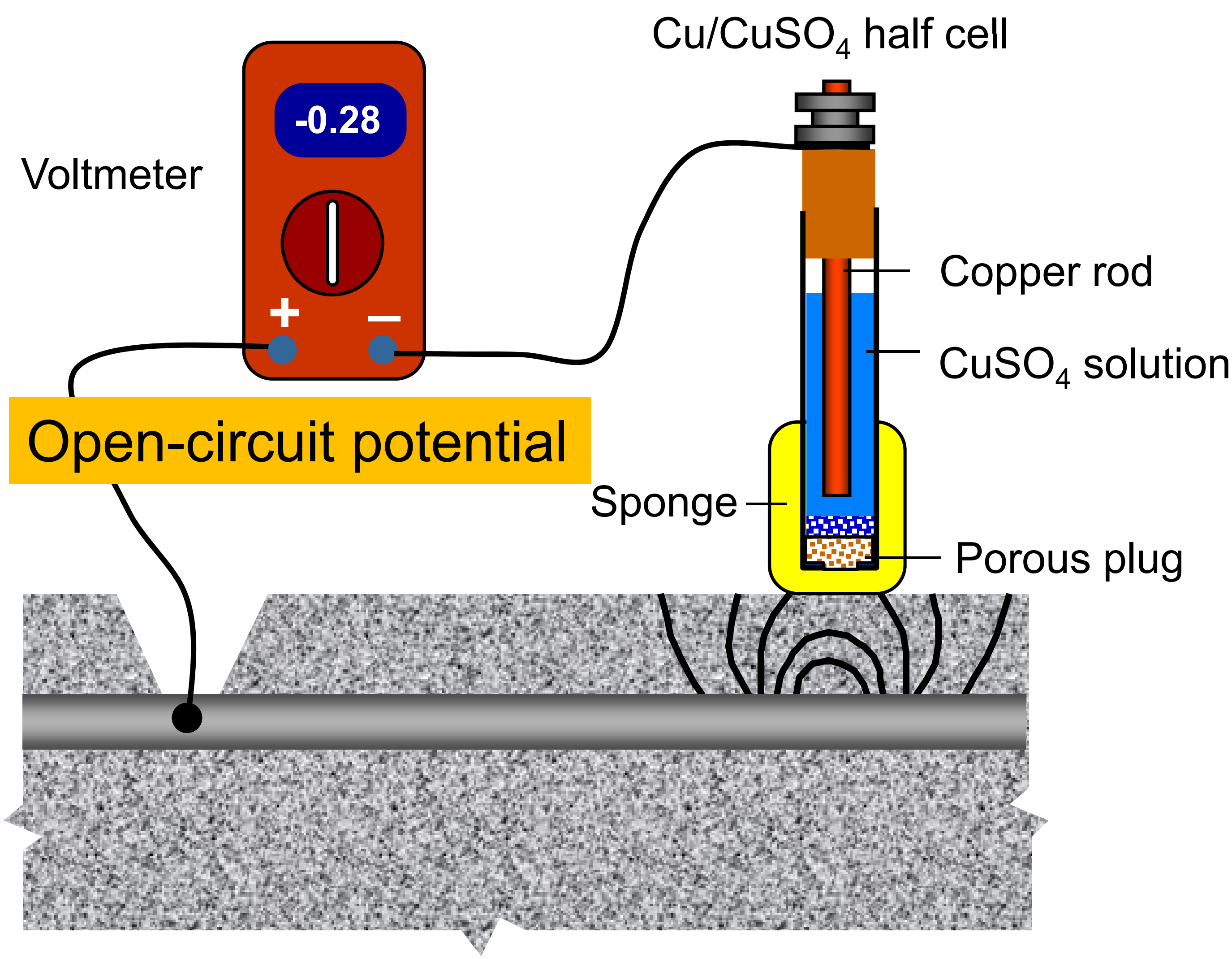
- When bar is corroding, charge flow through concrete is associated with an electrical field
- Measure the electrical potential (voltage) of the field at the concrete surface
- Magnitude of the measured voltage, relative to a standard half-cell, is indicative of corrosion activity
- Higher voltage indicates higher likelihood of active corrosion

Potential Field

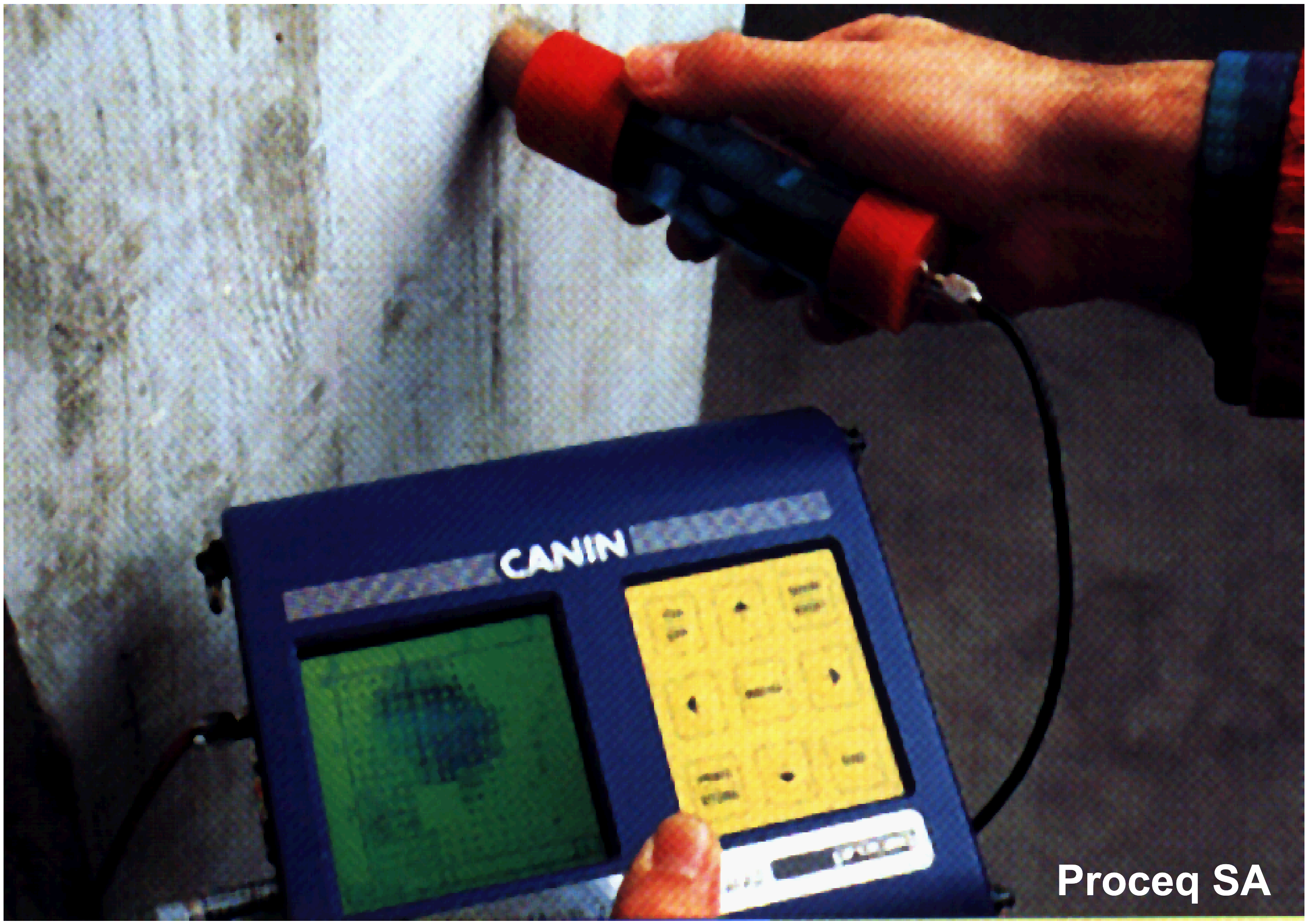


Elsner and Bohni, *ASTM STP 1065*, 1990

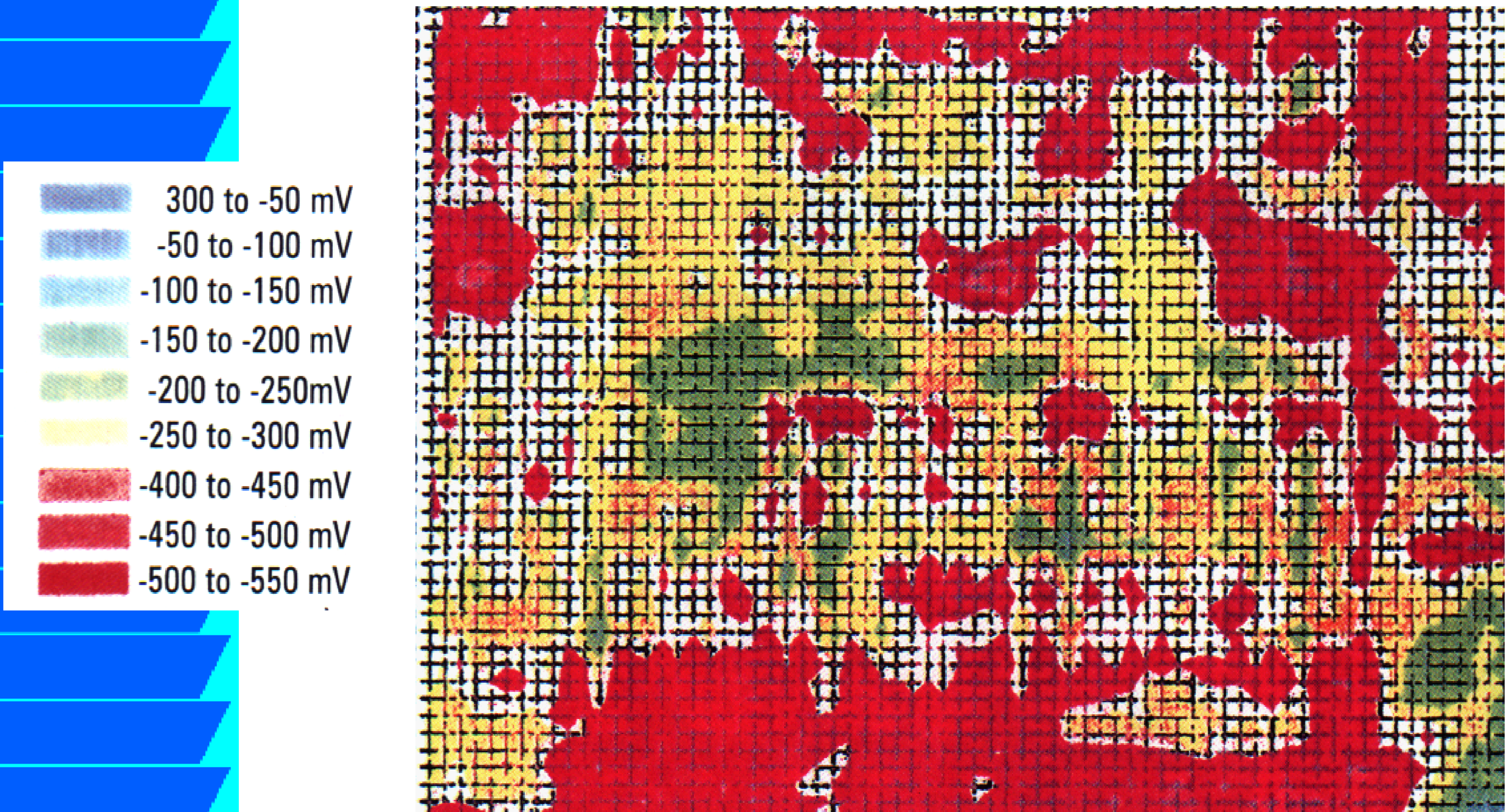
Half-Cell Potential Method
ASTM C876



Example



Half-Cell Potential Contour Plot



J. Woodhouse, “Quantifying the Invisible,” *Concrete Repair Bulletin*, July/August 1996

Considerations

- Concrete must be sufficiently moist
  - ASTM C876 provides criterion
- Provides only indication of likelihood of active corrosion
  - More positive than -200 mV: corrosion unlikely
  - More negative than -350 mV: corrosion likely
  - -200 to -350 mV: ???????
- Other factors have to be considered (see ASTM C876)

Polarization Resistance

- Half-cell potential provides information on likelihood that corrosion is occurring
- Polarization resistance provides indication of corrosion current (or corrosion rate)
  - At the time of testing
  - Rate affected by in-place conditions (moisture, oxygen, temperature)

Polarization

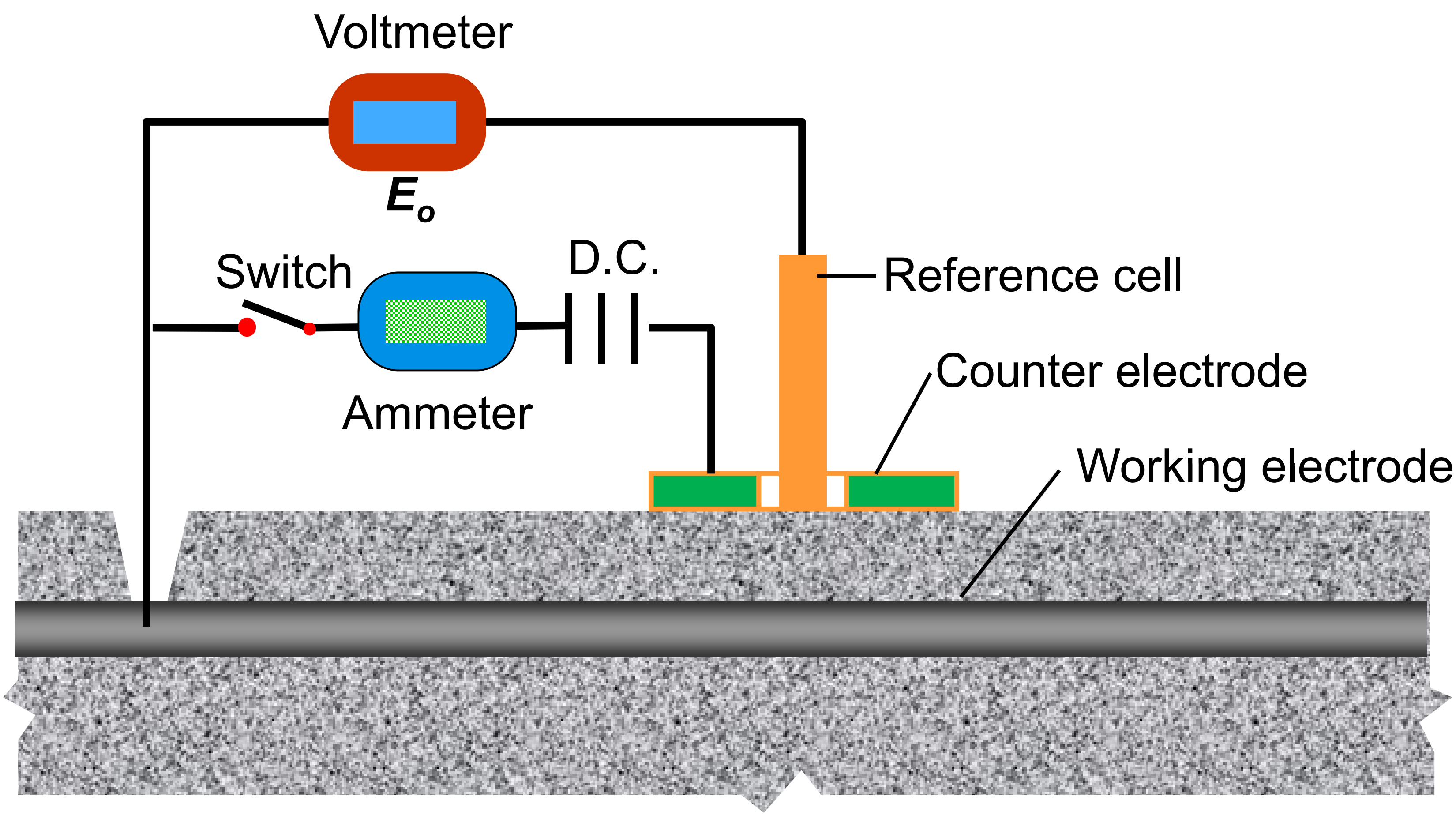
- Change from the open-circuit potential as a result of passage of current
- A bar that is actively corroding will have small change in potential when external current is applied to the bar

Polarization Resistance Apparatus

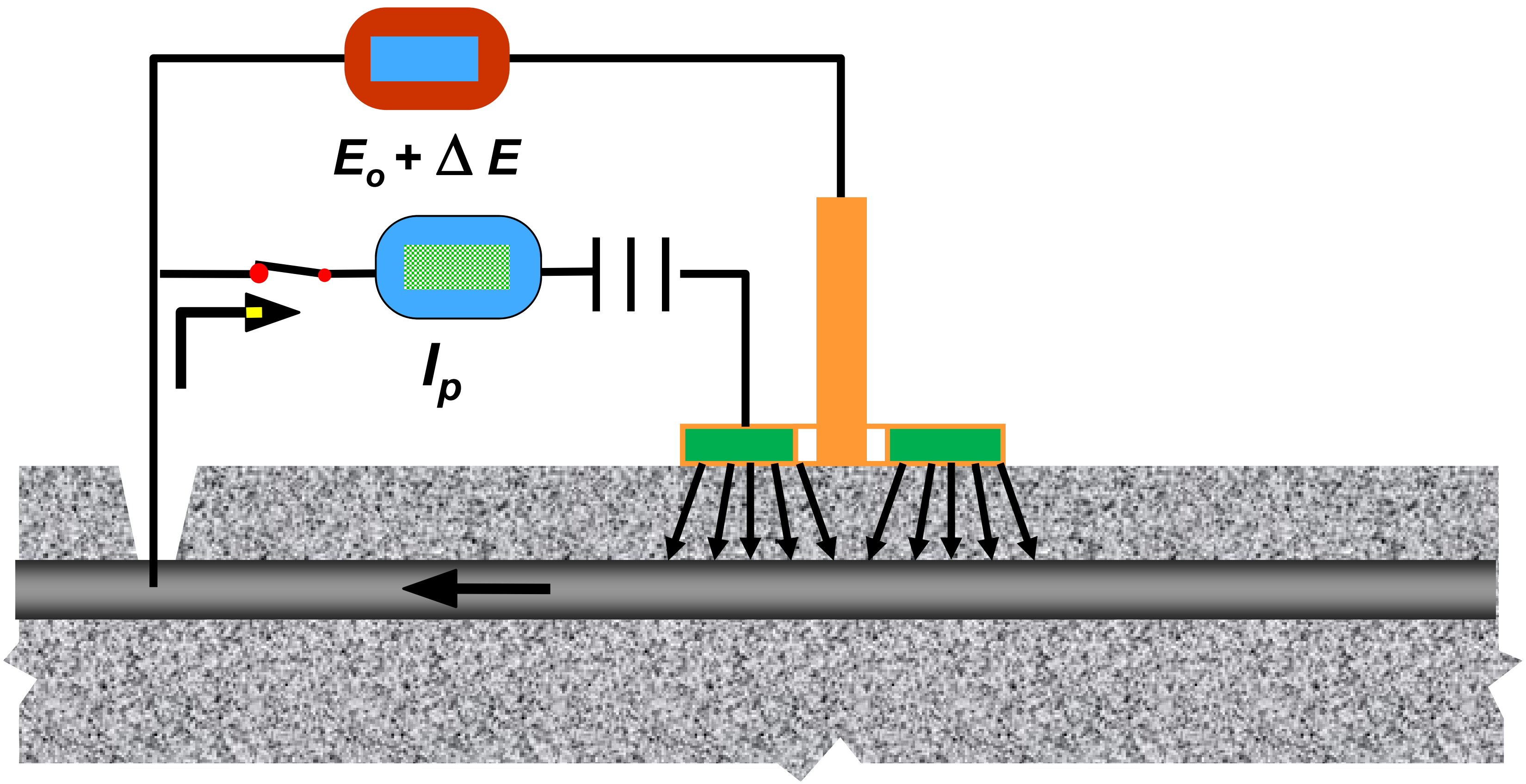
- **Working electrode** - the reinforcing bar
- **Counter electrode** - provides current flow to bar
- **Reference electrode** – measure change in potential
- Polarization system
    - Current supply
    - Voltmeter
    - Ammeter
- Hardware and software to acquire and analyze data

Polarization Resistance 3LP

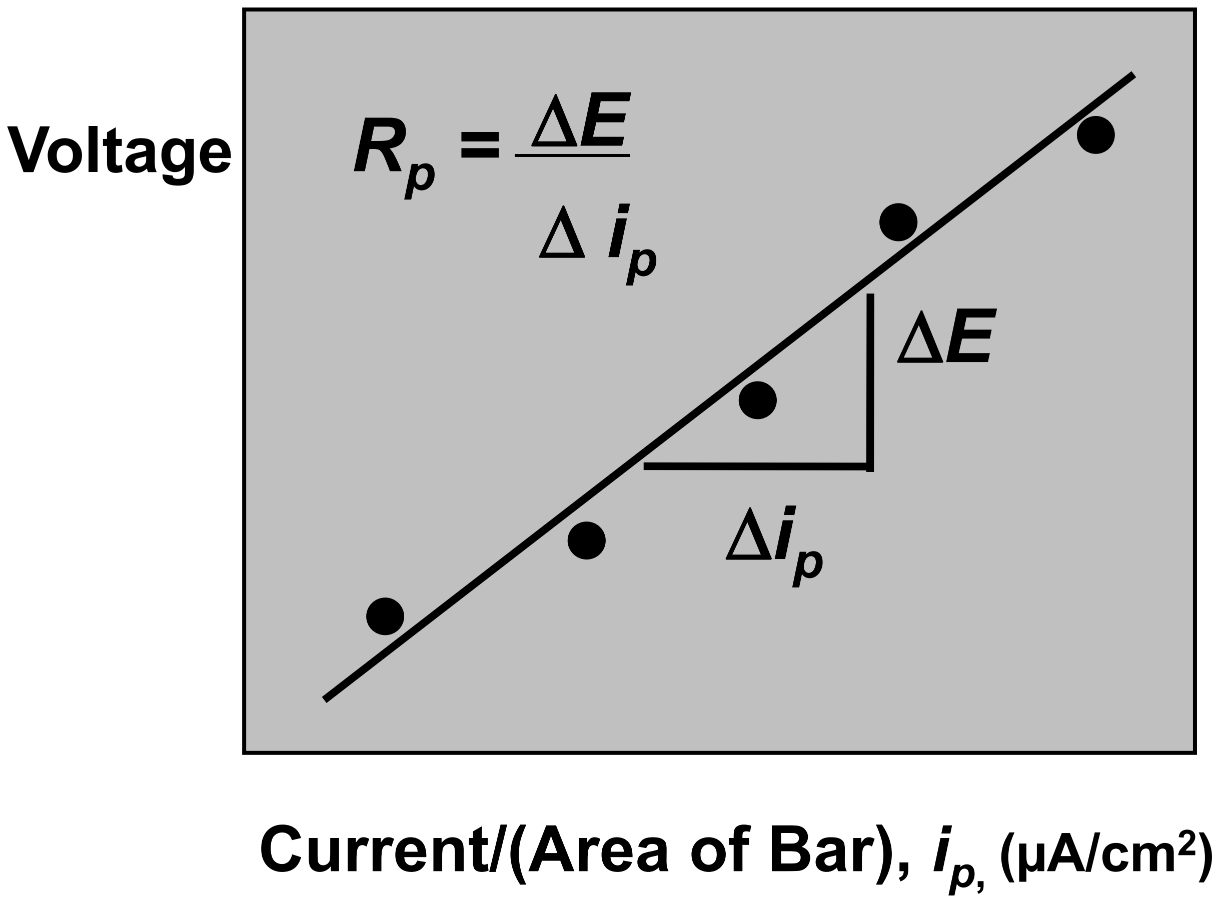
- Measure open circuit potential, E_o



- Close switch and apply small current, I_p
- Measure change in voltage
- Increase current, and repeat measurement
- Divide current by area of bar that is polarized, i_p
- Plot voltage vs. current density



Polarization Resistance, R_p



Corrosion Rate

- **Stern-Geary** corrosion rate relationship:

$$i_{corr} = \frac{B}{R_p} \quad (\mu A/cm^2)$$

B = 25 to 50 mV
(active   less active)

- **Faraday' law** can be sued to convert i_{corr} to uniform metal loss:

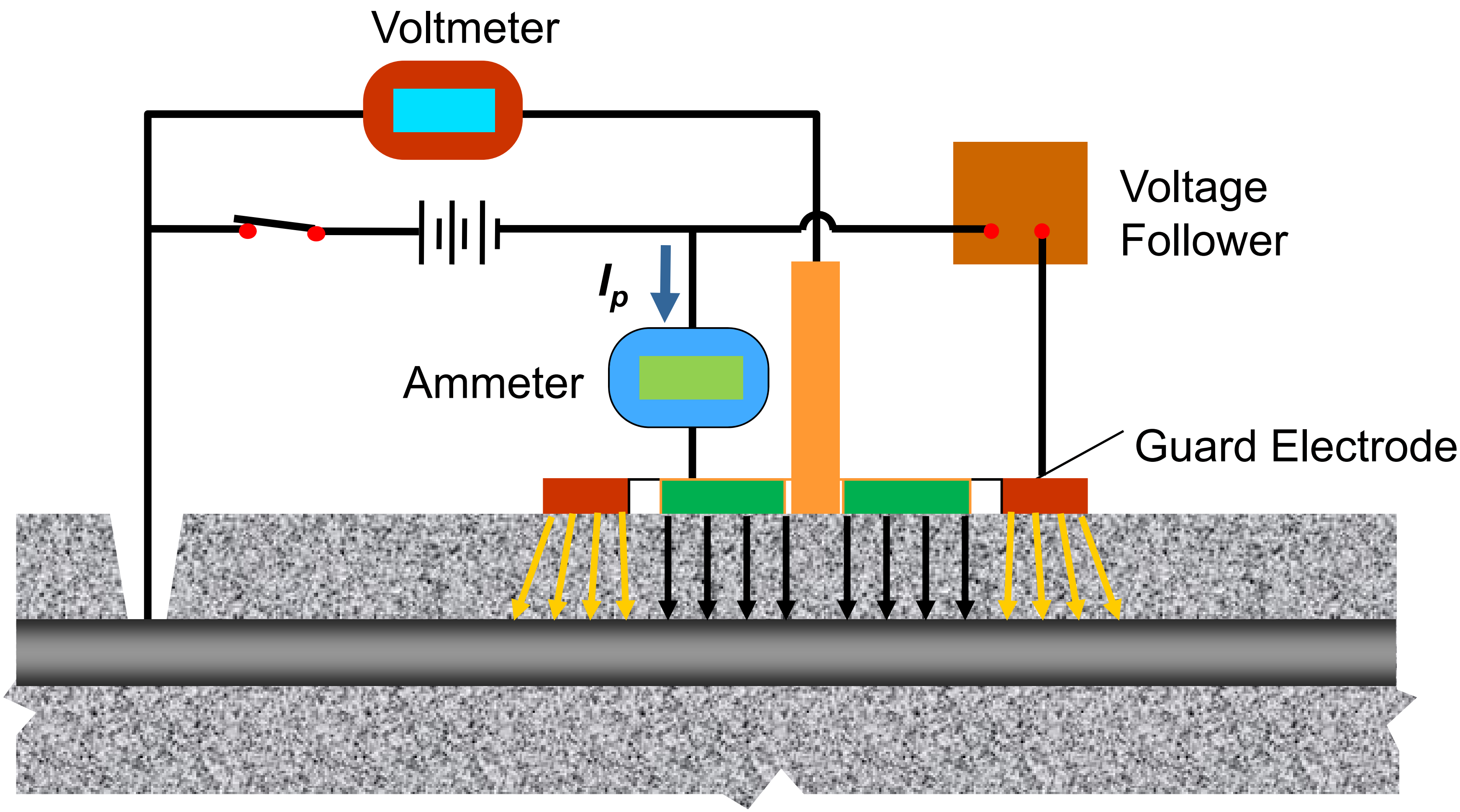
$$1\ \mu A/cm^2 = 0.012\ mm/y$$

Guard Electrode

- Current density is based on area of bar that is polarized by applied current
- Area of steel that is polarized is not well known in 3LP method
- Use of outer (guard) electrode confines current to portion of bar below guard ring
- Results in more accurate measure of current density

Guard-Electrode Method

Confines current so that polarized area of bar is well defined



Example of Guard-Electrode

James Instruments

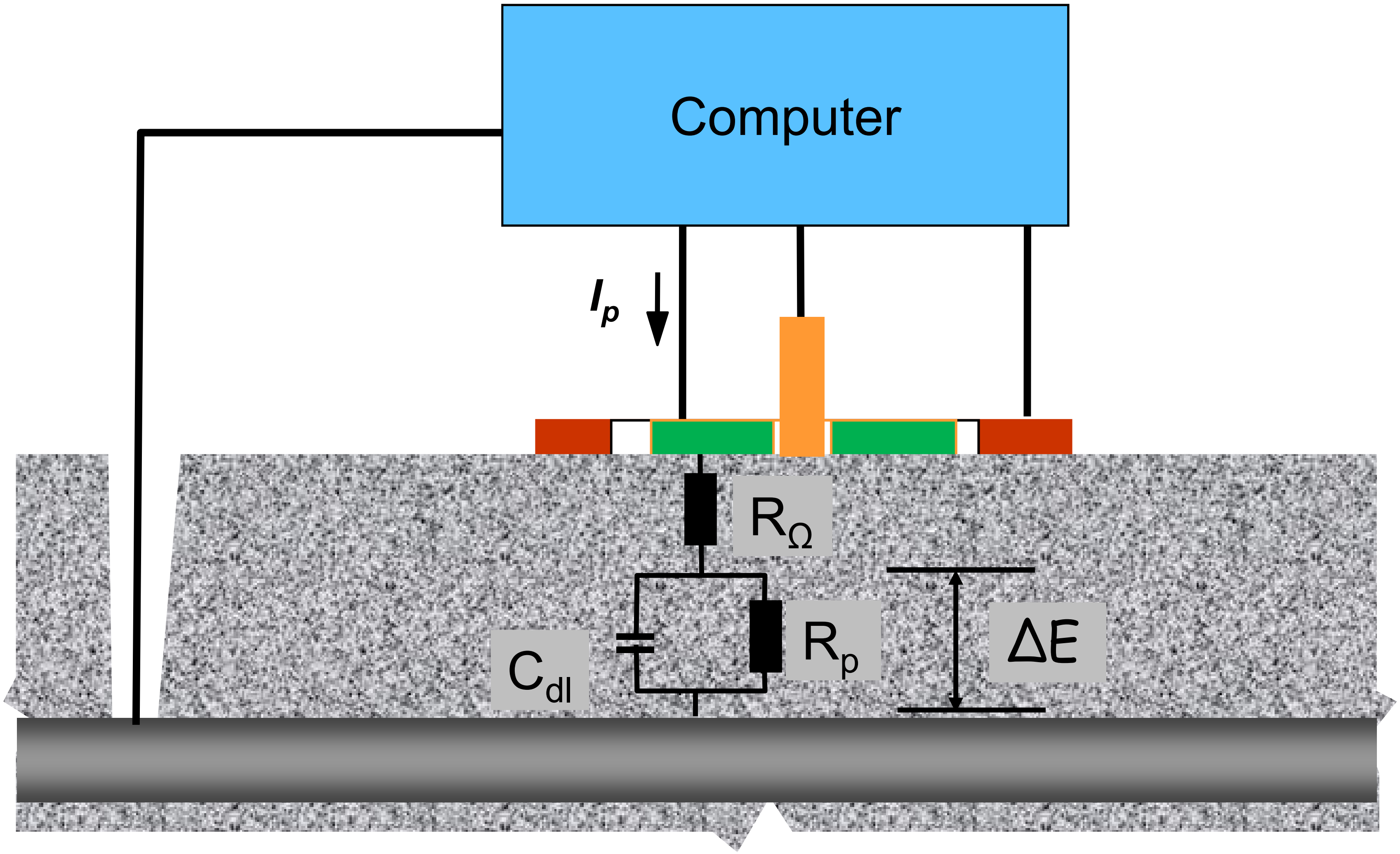
Static vs. Pulse Methods

- The polarization resistance technique that has been discussed is time consuming; 3 to 5 min at each point
  - Voltage (or current) is increased in several steps
  - Equilibrium conditions need to be established at each step
- Pulsed methods allow faster measurement

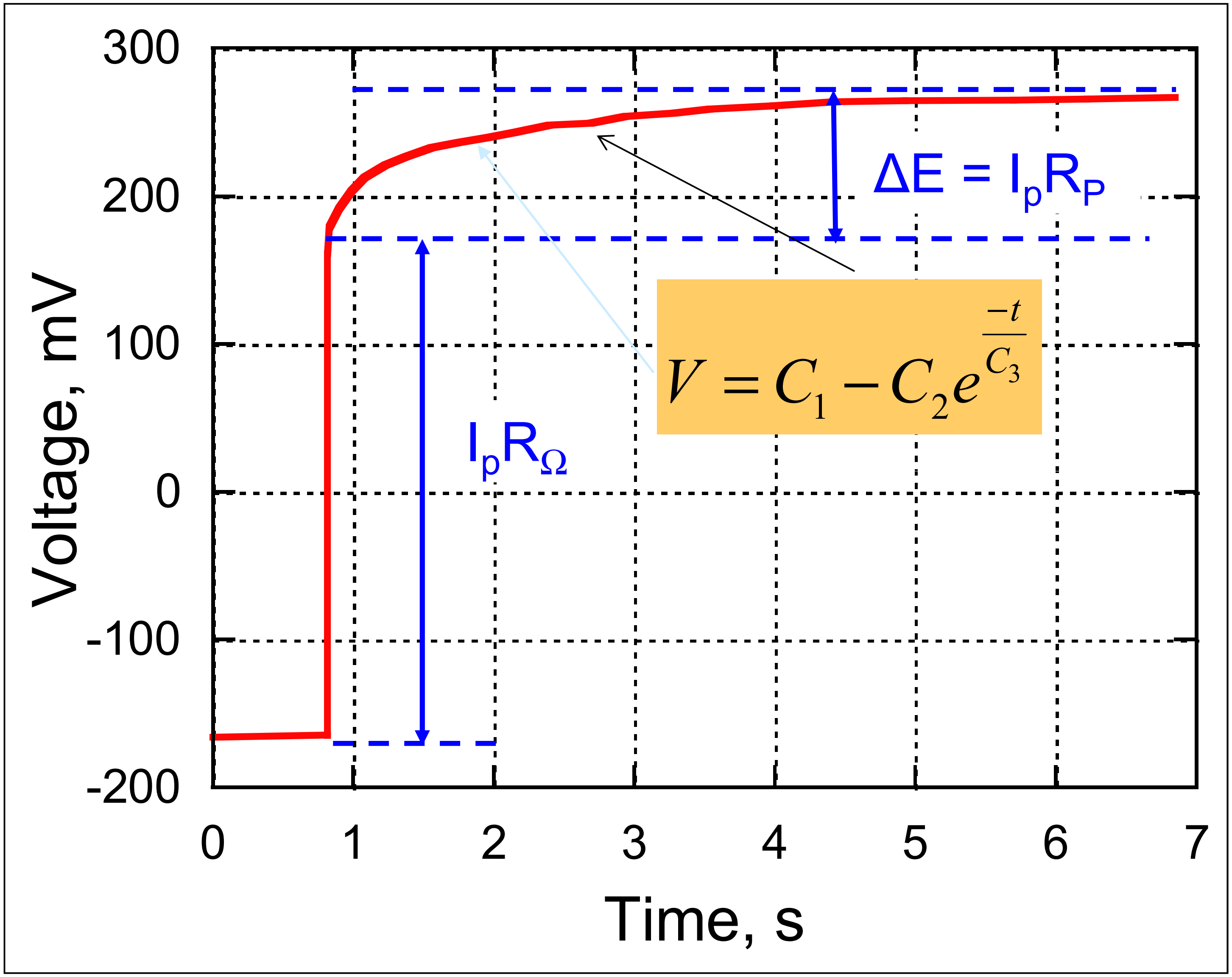
Galvanic Pulse Method

- Apply constant current pulse ($\approx$ 10 s)
- Guard electrode is used
- Monitor potential change of working electrode (bar)
- From recorded voltage history, evaluate polarization resistance, R_p, by regression analysis
  - Assumes Randles equivalent circuit to represent corrosion activity

Randles Equivalent Circuit



Voltage-Time Curve



Instrumentation

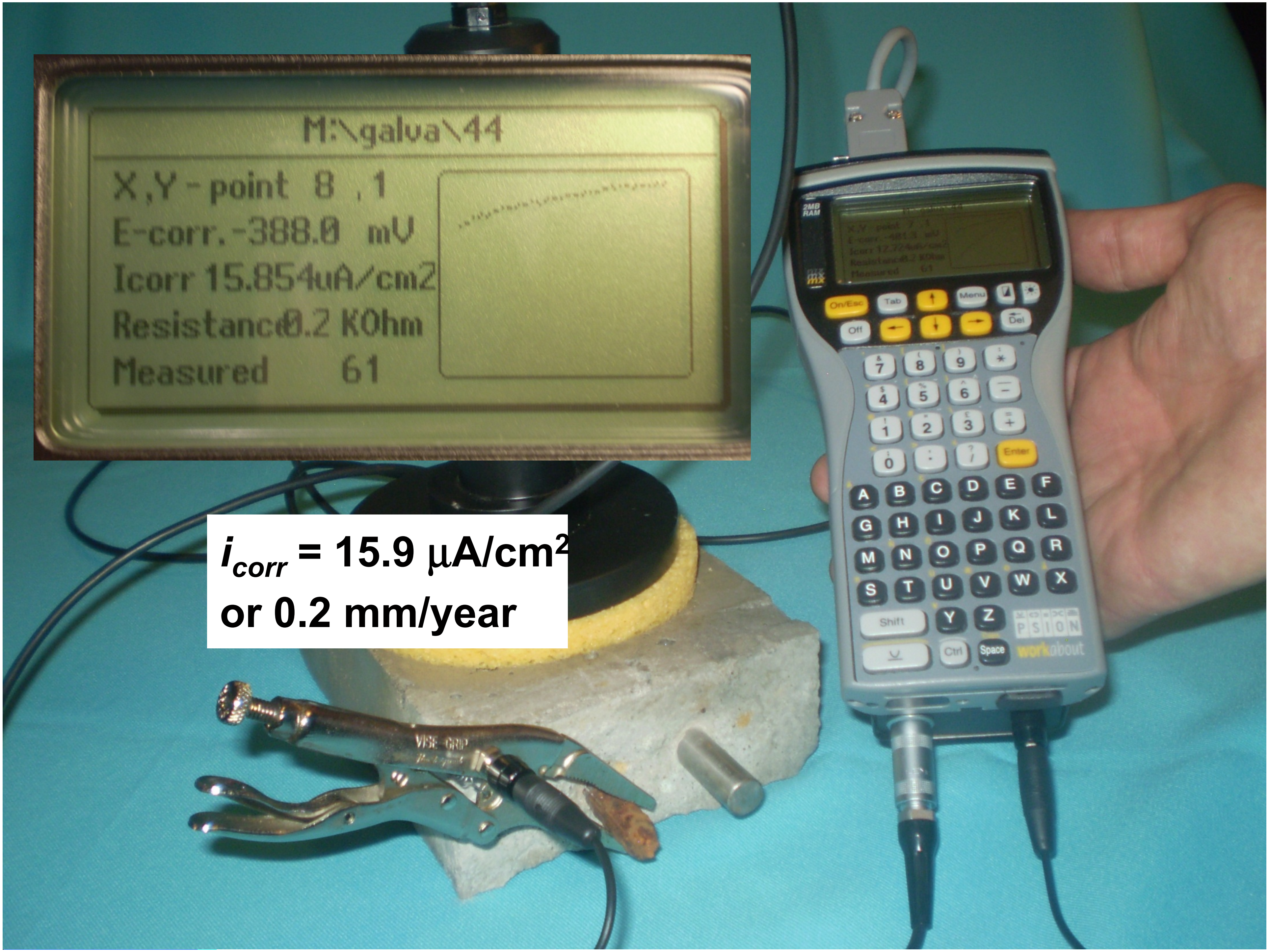
- Several commercial instruments are based on the pulsed method
  - GalvaPulse
  - RapidCor
- Do not give the same readings, but will give same relative order of corrosion activity

GalvaPulse

- Based on galvanic-pulse method
- Integrates into one unit:
    - Half-cell potential
    - Resistance (not resistivity)
    - Polarization resistance
- Software for data analysis and 3-D displays

GalvaPulse

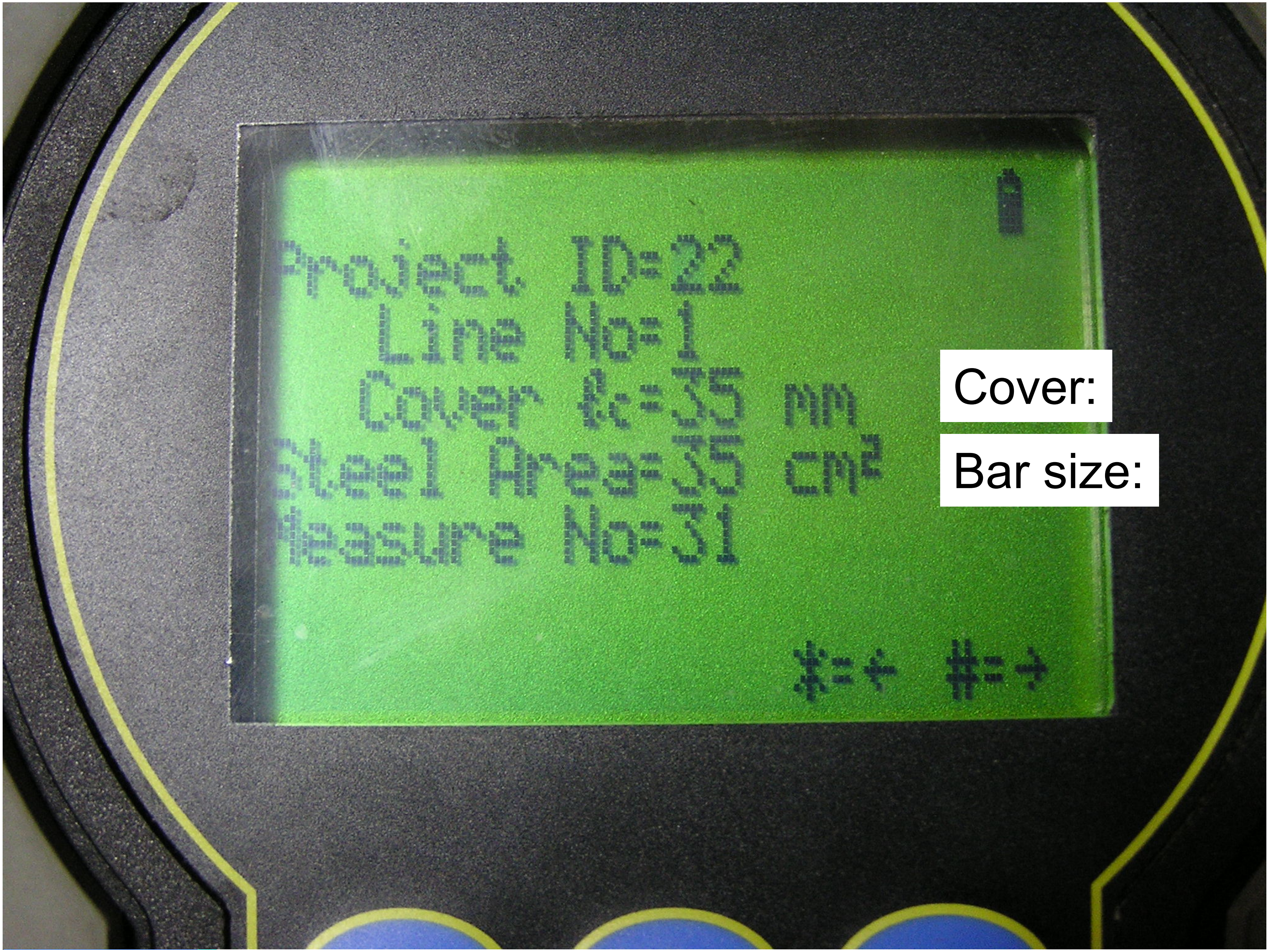

M:\galva\44
X,Y-point 6 ,1
E-corr.-70.81 mV
Icorr 0.4327uA/cm2
Resistanc0.3 KOhm
Measured 61
i_{corr} = 0.43 μA/cm²
or 0.005 mm/year
On/Esc
Tab
Menu
Off
Del
Enter
Shift
Ctrl
Space
PSION
workabout

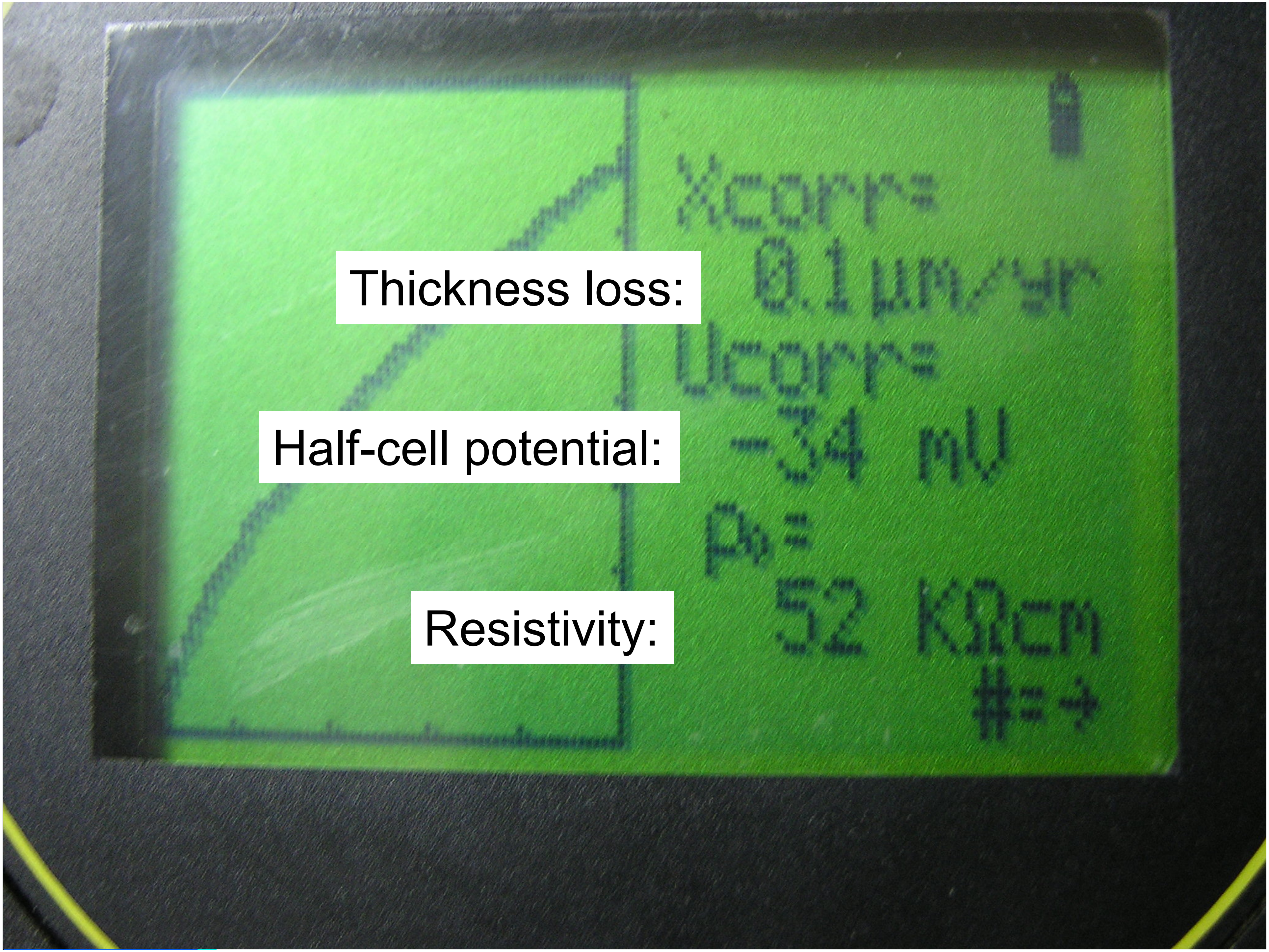

M:\galva\44
X,Y-point 8 ,1
E-corr.-388.0 mV
Icorr 15.854uA/cm2
Resistanc0.2 KOhm
Measured 61
i_{corr} = 15.9 μA/cm²
or 0.2 mm/year
PSION
workabout
VISE-GRIP

RapiCor

- Galvanic pulse method
- Rectangular probe with guard electrode
- Modulates polarization current based on corrosion activity
    - Higher current needed for higher corrosion rate
- Calculates concrete resistivity
    - Requires knowing cover thickness


RapiCor
RapiCor
Counter electrode
Reference electrode
Ag/AgCl
Guard electrode
On/Off


Project ID=22
Line No=1
Cover &c=35 mm
Steel Area=35 cm²
Measure No=31
*=← #=→
Cover:
Bar size:


Xcorr=
0.1µm/yr
Ucorr=
-34 mV
ρ₀=
52 KΩcm
#=→
Thickness loss:
Half-cell potential:
Resistivity:

Summary

- Introduction to tools for in-place evaluation of concrete and steel reinforcement
  - Uniformity
  - Strength
  - Internal defects
  - Corrosion assessment
- Principles of methods have been stressed
- Not a training course on proper use of instruments

Tests for Uniformity

- Locate anomalous areas for closer examination
- Rebound hammer
  - Indicator of surface condition
  - Affected by texture, moisture content, carbonation
- Pulse velocity
  - Overall condition of concrete between transducers
  - Does not provide depth information

In-Place Strength

- Strength of drilled cores is reference method
- Pullout test
  - Sample more points without excessive damage
  - Good correlation with compressive strength
  - Evaluates outer 25 mm
- Pull-off test
  - Evaluate substrate preparation before repair
  - Evaluate bond strength of repair
  - Failure location depends on weakest link

Internal Defects

- Stress wave methods are inherently powerful because of complete reflection at air interface
- Impact-echo method
  - Point method; simple data processing
- Impulse-response method
  - Measures flexural response; comparative
- Ultrasonic-echo
  - Computer intensive; rapid; 3-D imaging

Corrosion Assessment

- Half-cell potential
  - Likelihood of active corrosion
- Polarization resistance
  - Indicator of corrosion rate at time of testing
  - Assumptions made to arrive at corrosion current density

Training

- Different levels of expertise are required
  - Rebound hammer → impact-echo
- Training is essential for proper use of these methods
  - No national programs
  - Manufacturers and “on the job”
- Flaw detection methods require experience for proper interpretation
  - Verification with invasive probing
- Corrosion assessment requires a corrosion expert

?