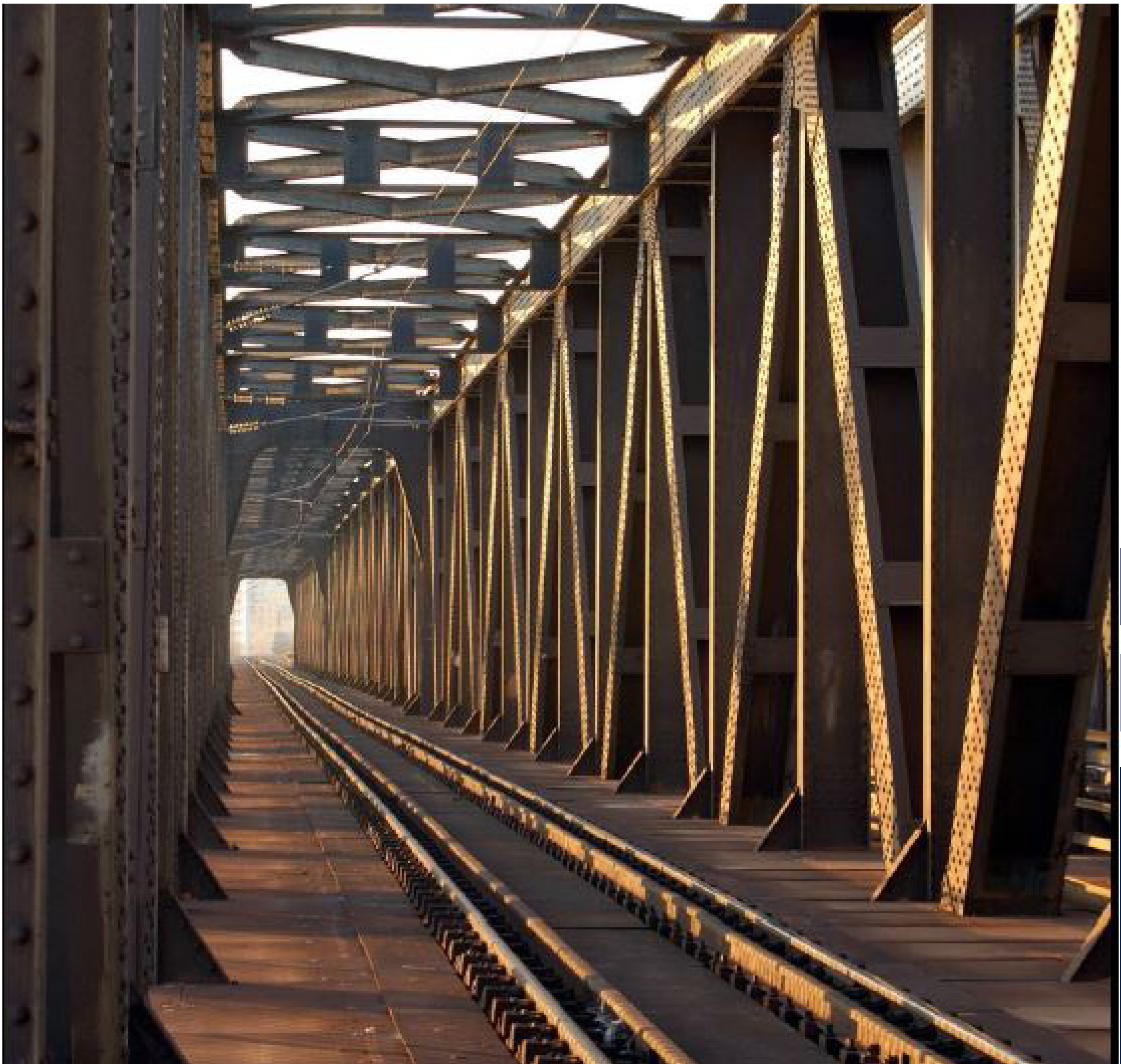
Diagnostics of Structures



Zoltán Orbán

Diagnostics of Structures

Pécs

2019

The Diagnostics of Structures course material was developed under the project EFOP 3.4.3-16-2016-00005 "Innovative university in a modern city: open-minded, value-driven and inclusive approach in a 21st century higher education model"

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SZÉCHENYI 2020

PÉCSI TUDOMÁNYEGYETEM
UNIVERSITY OF PÉCS

Zoltán Orbán

Diagnostics of Structures

Pécs

2019

A Diagnostics of Structures tananyag az EFOP-3.4.3-16-2016-00005 azonosító számú,
„Korszerű egyetem a modern városban: Értékközpontúság, nyitottság és befogadó szemlélet egy 21. századi felsőoktatási modellben" című projekt keretében valósul meg.

EFOP-3.4.3-16-2016-00005 Korszerű egyetem a modern városban:
Értékközpontúság, nyitottság és befogadó szemlélet
egy 21. századi felsőoktatási modellben

SZÉCHENYI 2020

MAGYARORSZÁG KORMÁNYA

Európai Unió
Európai Szociális Alap

BEFEKTETÉS A JÖVŐBE

DIAGNOSTICS OF STRUCTURES

LECTURE 01

Damages to concrete structures

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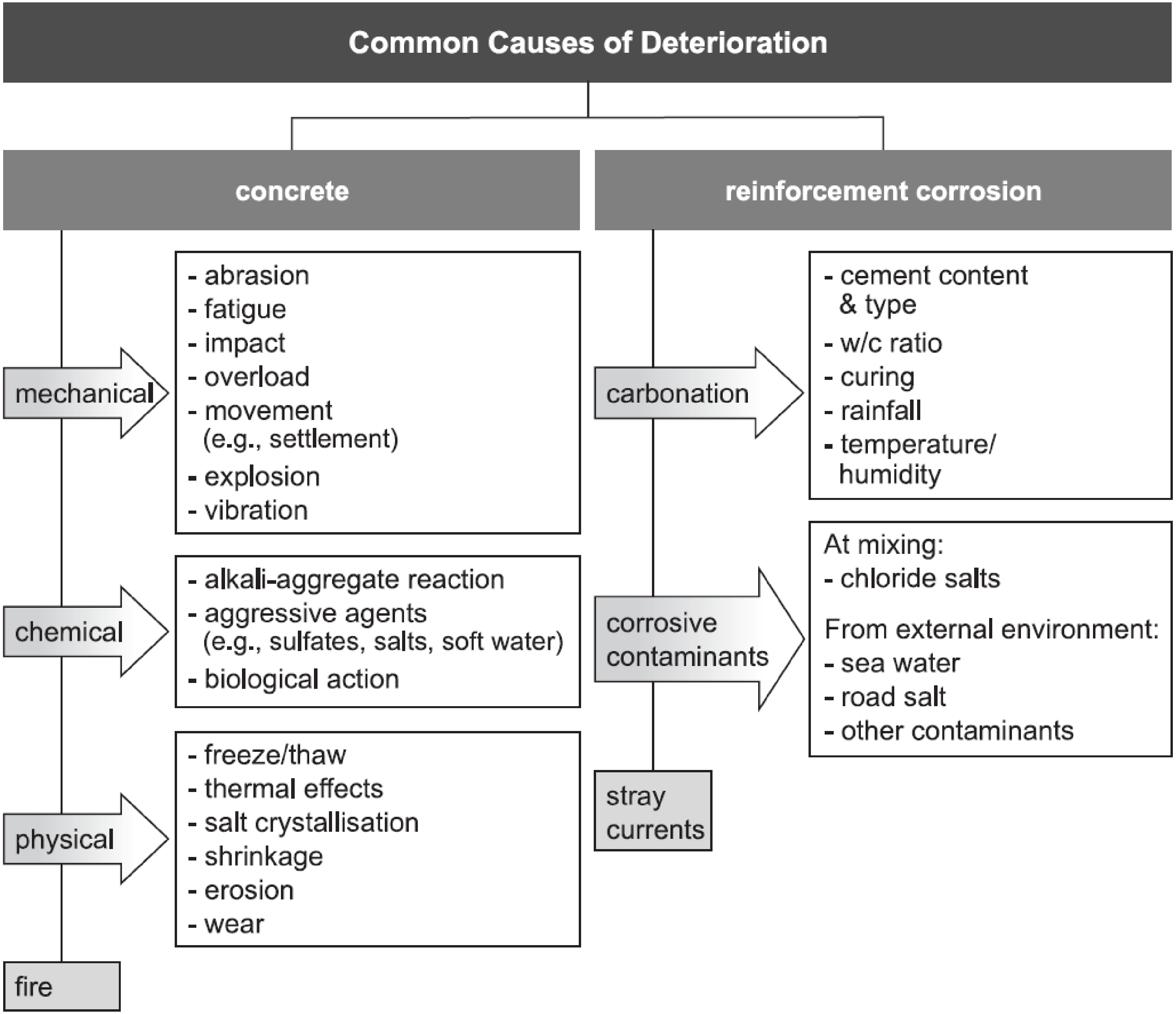
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

CAUSE(S) OF DAMAGE AND DETERIORATION

The purpose of the main assessment is:

- To identify the cause or causes of defects
- To establish the extent of defects
- To establish where the defects can be expected to spread to parts of the structure that are at present unaffected
- To assess the effect of defects on structural reliability
- To identify all locations where protection or repair may be needed

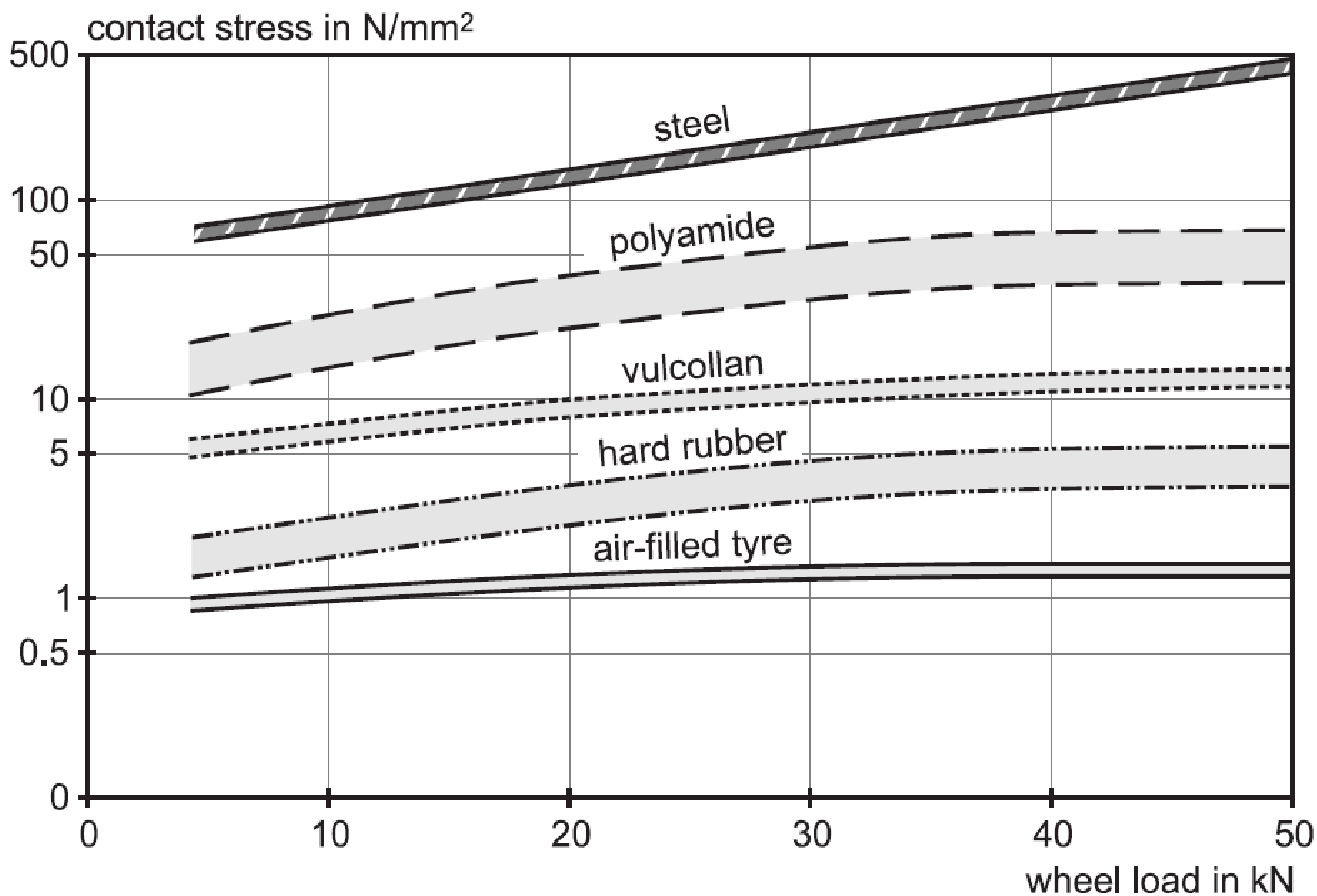

Common Causes of Deterioration
concrete
reinforcement corrosion
mechanical
- abrasion
- fatigue
- impact
- overload
- movement (e.g., settlement)
- explosion
- vibration
chemical
- alkali-aggregate reaction
- aggressive agents (e.g., sulfates, salts, soft water)
- biological action
physical
- freeze/thaw
- thermal effects
- salt crystallisation
- shrinkage
- erosion
- wear
fire
carbonation
- cement content & type
- w/c ratio
- curing
- rainfall
- temperature/ humidity
corrosive contaminants
At mixing:
- chloride salts
From external environment:
- sea water
- road salt
- other contaminants
stray currents

Damages to concrete

1. Mechanical attack

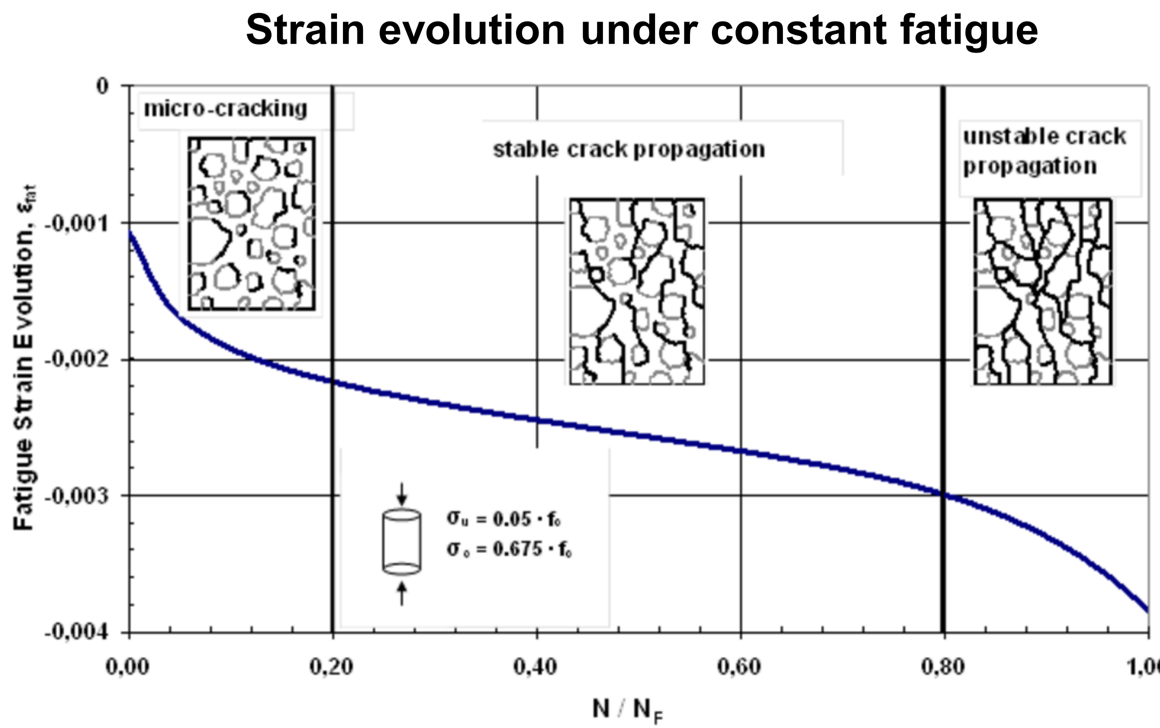
Induced by abrasion, fatigue of the material, impact overload, movement like settlement, explosion, vibration, pedestrians or vehicles

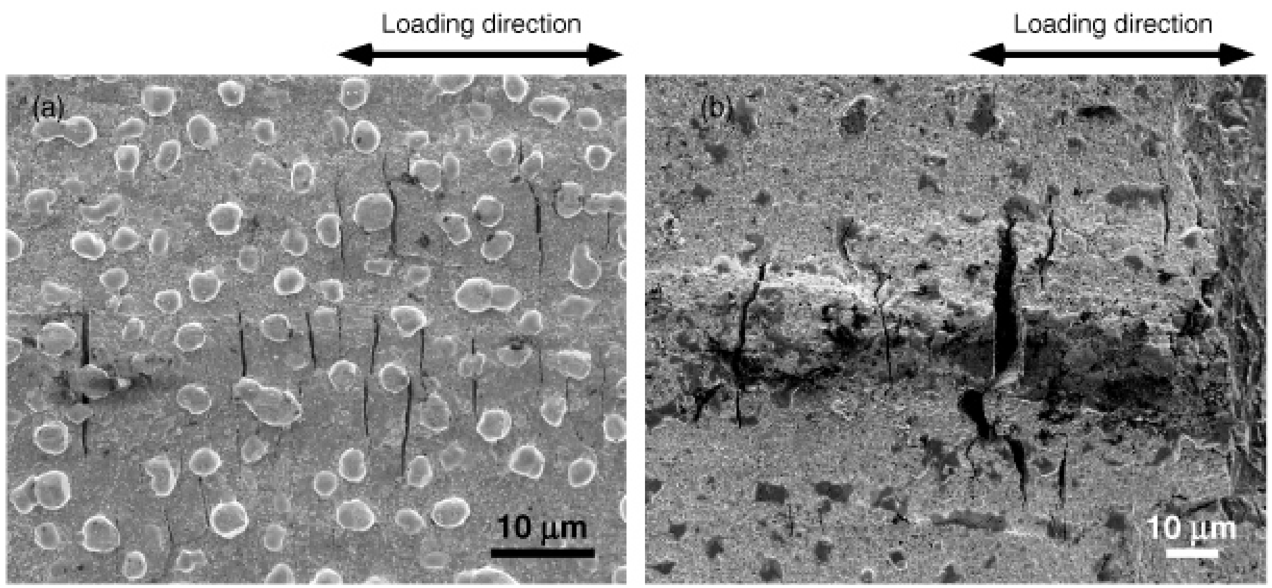

Mechanical damage of
concrete floor



Contact stresses to concrete floors induced by wheels with different types of tyres. (From Sasse, H.R., Schäfer, H.G., Bäätjer, G., Borg, G., et al., *Schriftenreihe des Deutschen Ausschusses für Stahlbeton* (1996), no. 467.)

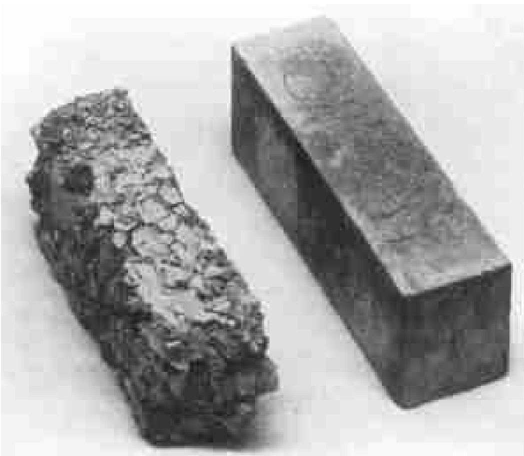
Fatigue damage in concrete

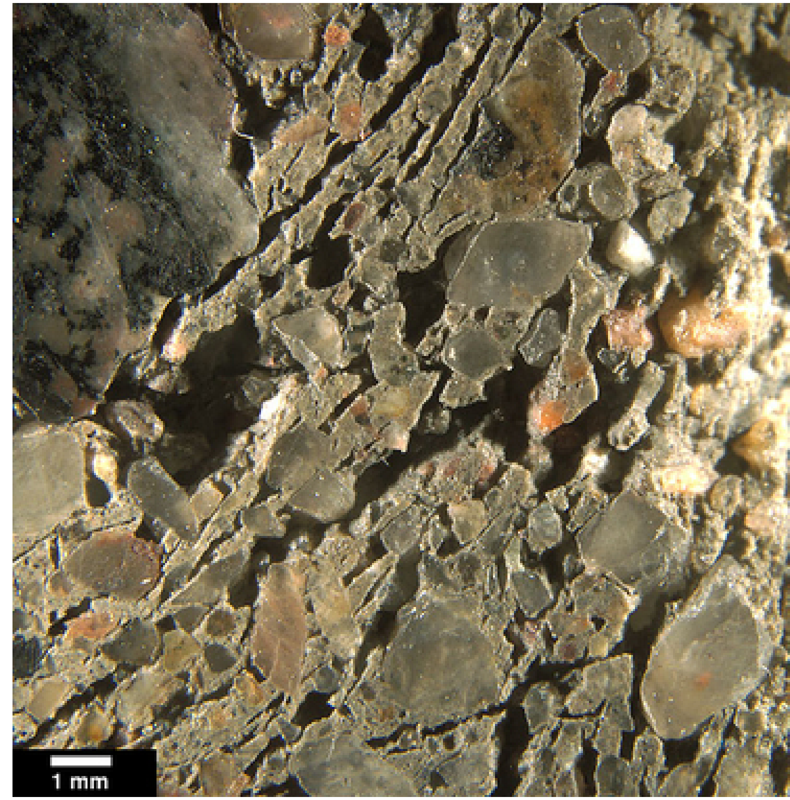




2. Physical attack (freeze-thaw, wear)

Freeze-thaw





Fire damage

3. Chemical attacks

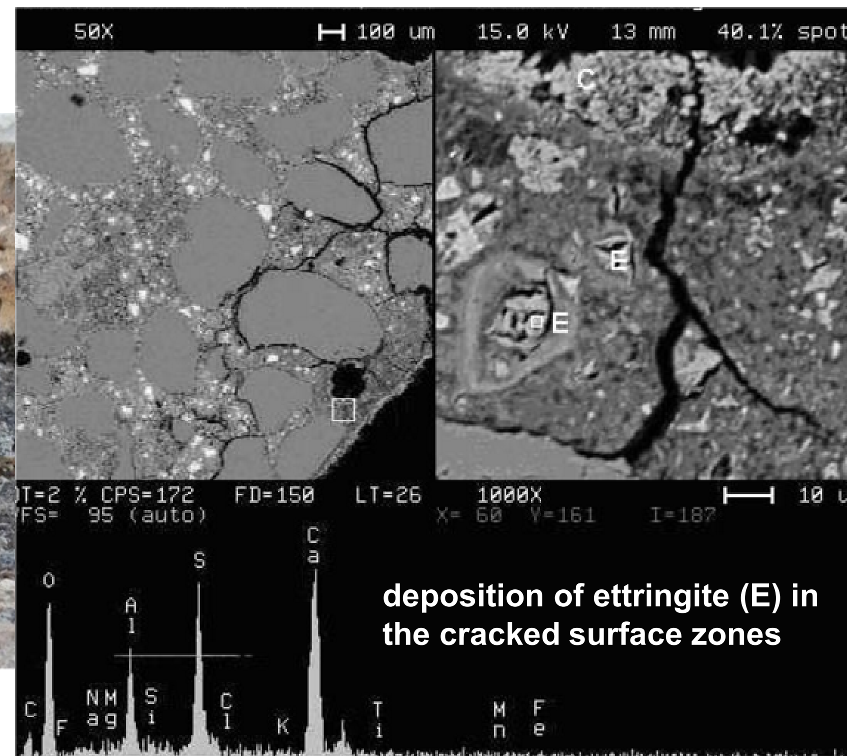
Dissolving attack

- Induced by acids, which dissolve components of the concrete forming soluble reaction products.
- Acids may be present in concrete structures of the chemical industry, in sewage water, or in special cases in natural water
- As a result, the concrete loses strength, beginning from the surface where the acid is acting.
- In the course of time the strength is fully lost and the material disappears, reducing the concrete cover and the thickness of the concrete element.
- The corrosion rate depends on the type and concentration of the acid as well as the quality of the concrete.

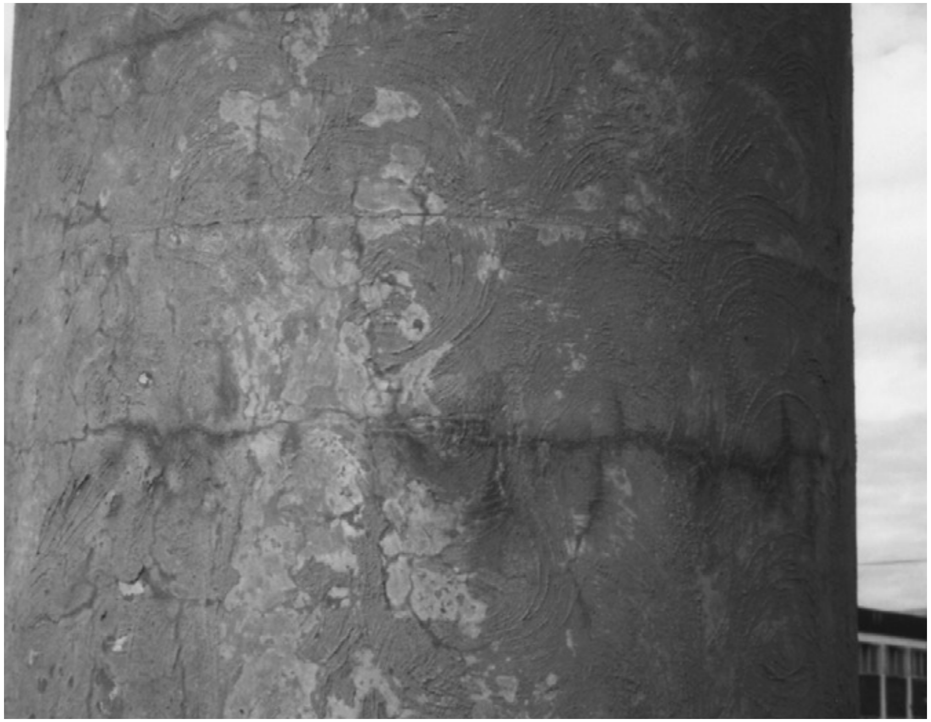
Expanding attack

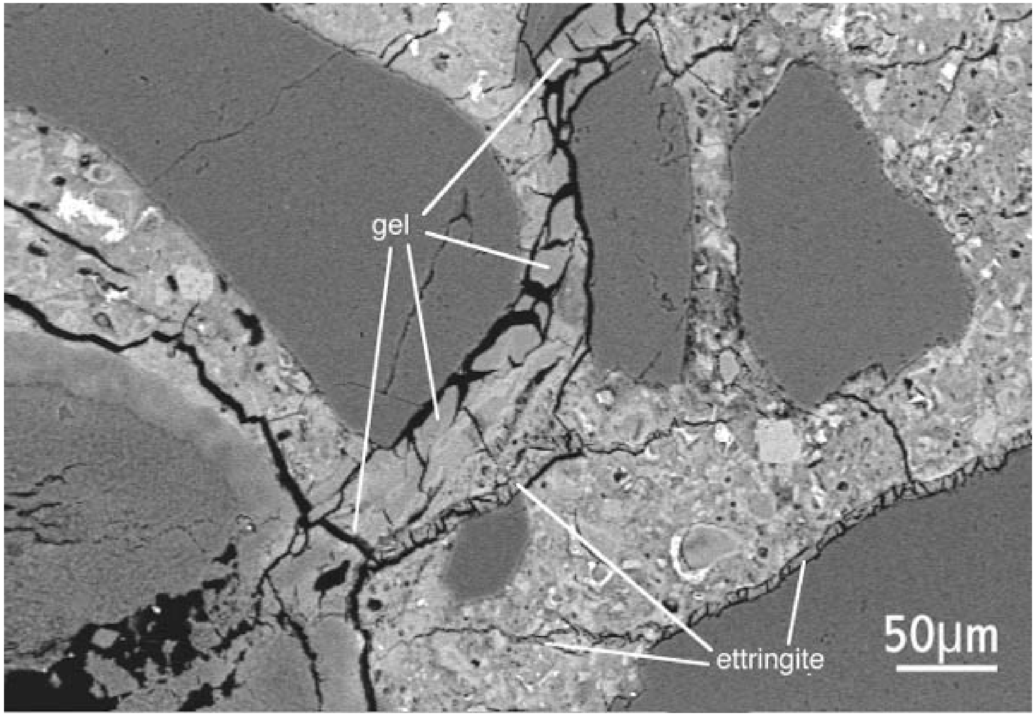
- Reactions are occurring within the concrete that form reaction products with a high volume.

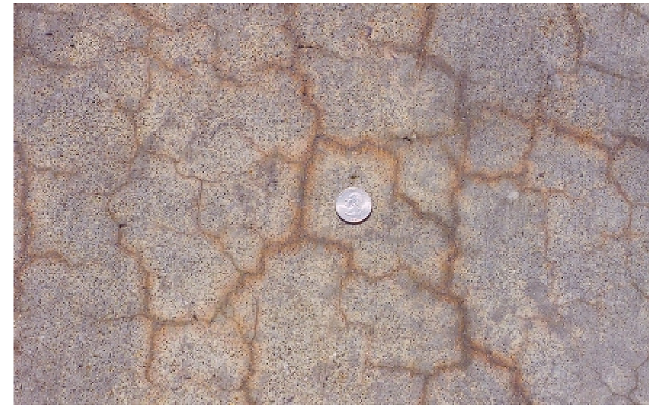
- Examples for this corrosion mechanism:
  - sulphate attack at foundations from soils or groundwater.
  - lime (CaO), magnesium (MgO), or magnesia salts
  - alkali-silica reaction (ASR)

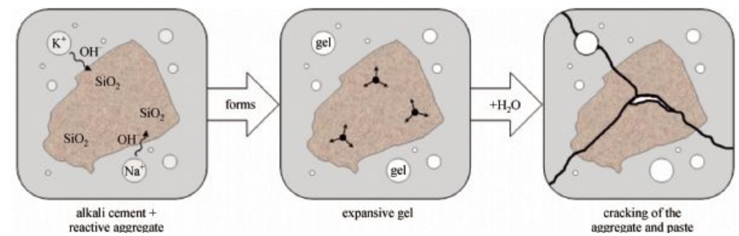


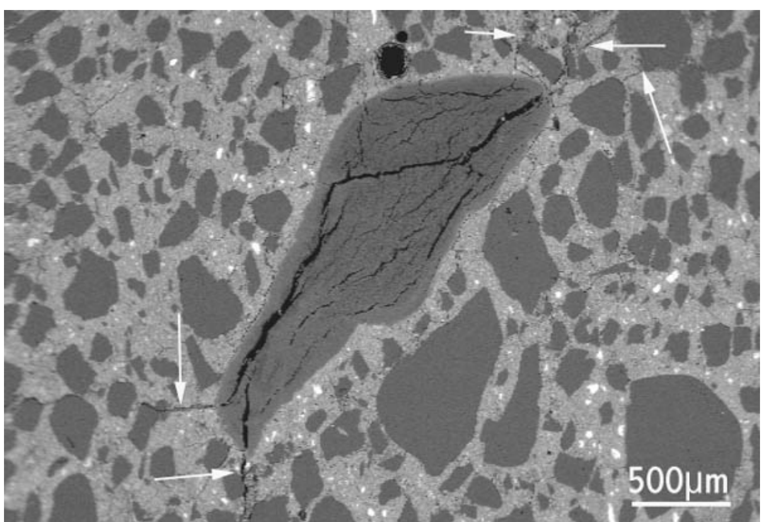
• **Alkali-silica reaction** (ASR) occurs when certain types of aggregates or sand have been used in concrete that are not stable in alkaline environments at high pH values. This reaction leads to the formation of products with a high volume, resulting in an inner pressure within the concrete.





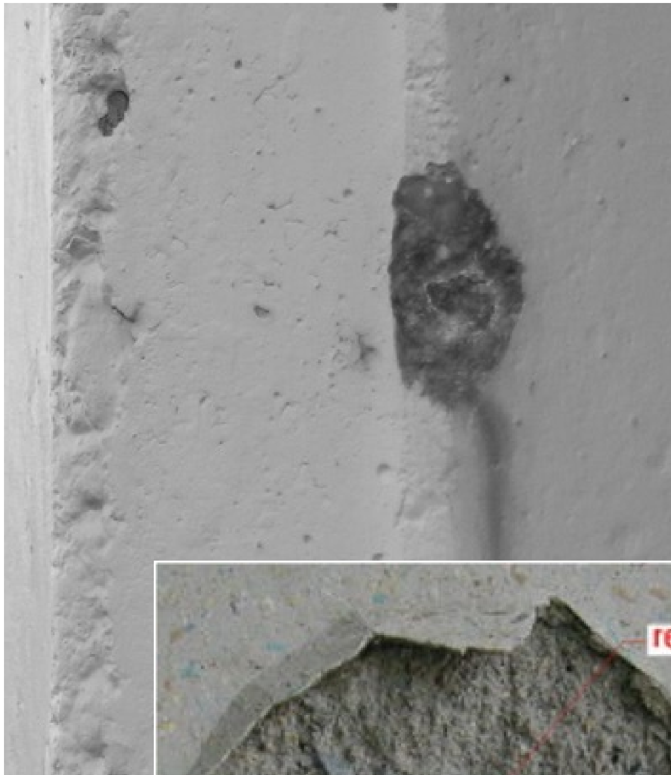






Alkali-silica reaction (ASR)

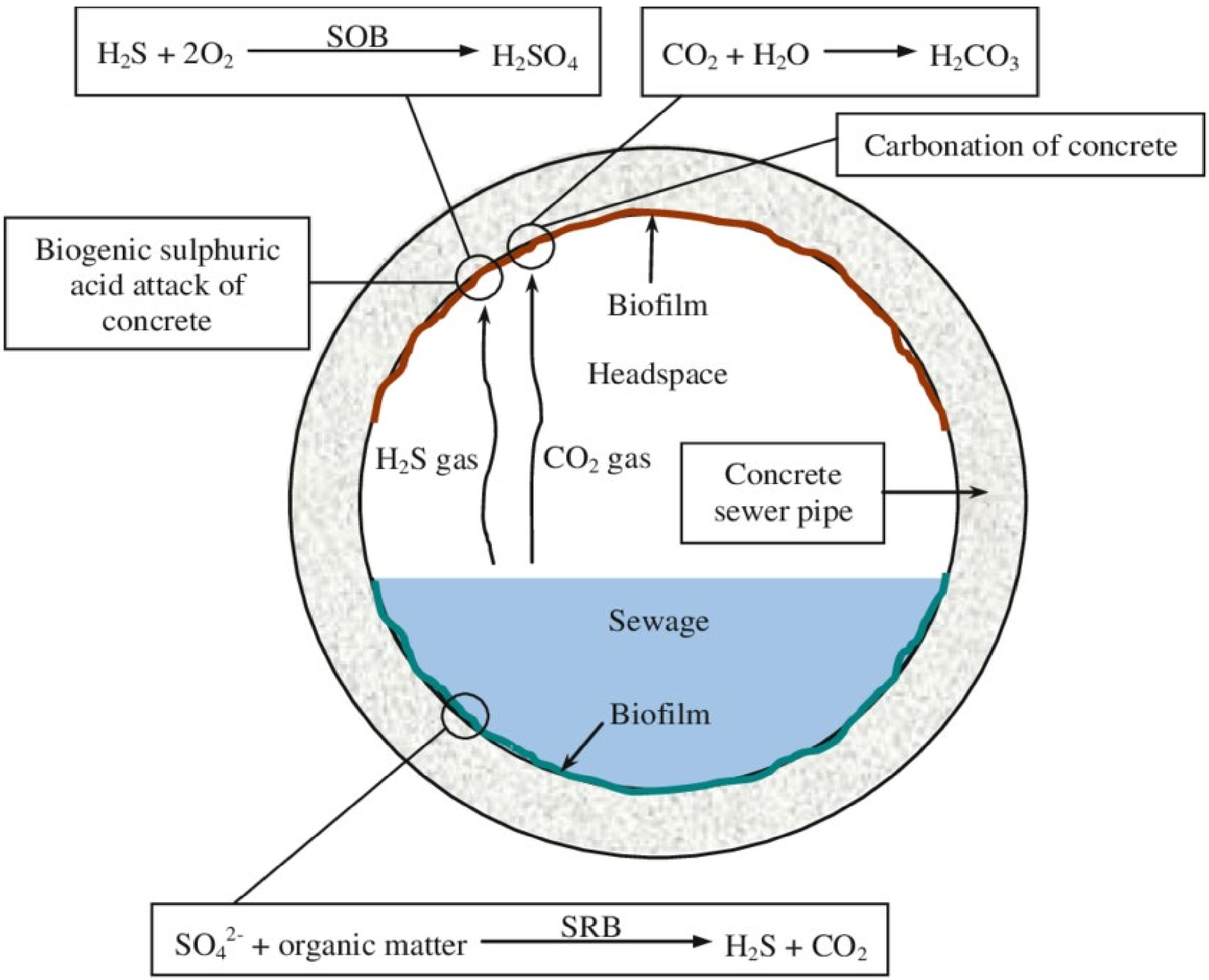
• Local **pop-outs** can occur, when aggregates contain critical amounts of sulphides, e.g., pyrite (FeS_2) or pyrrhotite (FeS), which can oxidise.



Biological acid attack

- Of the most aggressive types, often occurs in sewage treatment plants or sewage ducts, under anaerobic conditions.
- Microorganisms play an important part because they produce the sulphuric acid.
- The corrosion rates often are extremely high and in the range of 1 cm per year.

This biogenous sulphuric acid attack typically occurs in the upper areas of the duct above the sewage water level, where microorganisms produce a highly concentrated acid



Other biological attack

Damages to reinforcement in concrete

• Reinforcement corrosion can be induced by **carbonation**, corrosive contaminants like **chlorides**, or **stray currents**.

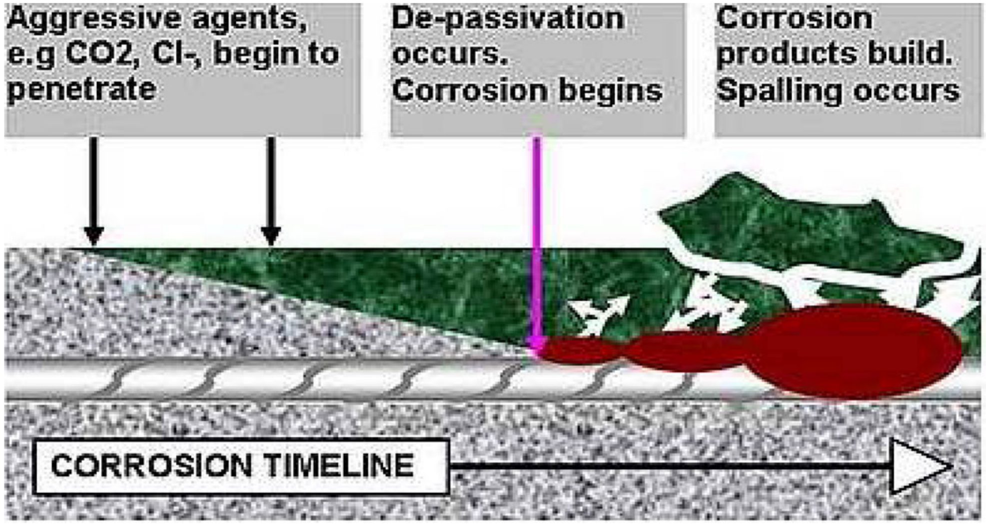
• Generally steel is protected in sound concrete by the alkalinity of the concrete with **pH values typically higher than 13**.

• The **passive layer on the steel surface** prevents the further dissolution of iron. This passivity occurs at pH values above about 9–10

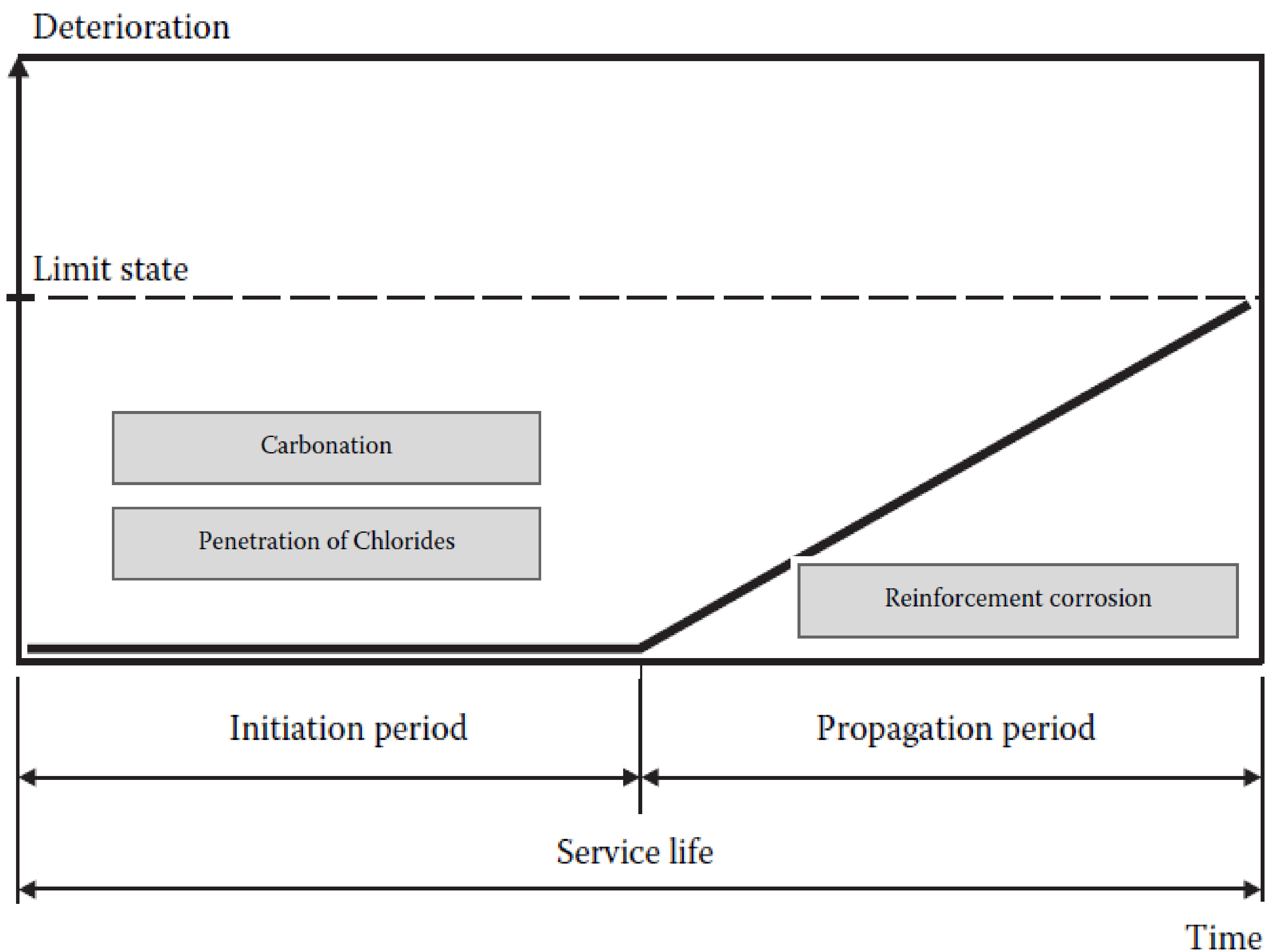
Damage to passive layer:

- Carbonation of the concrete, i.e., the reaction of the alkalis in the pore solution with CO_2 within the air, leads to a decrease of the initial pH value of >13 to values of <9.

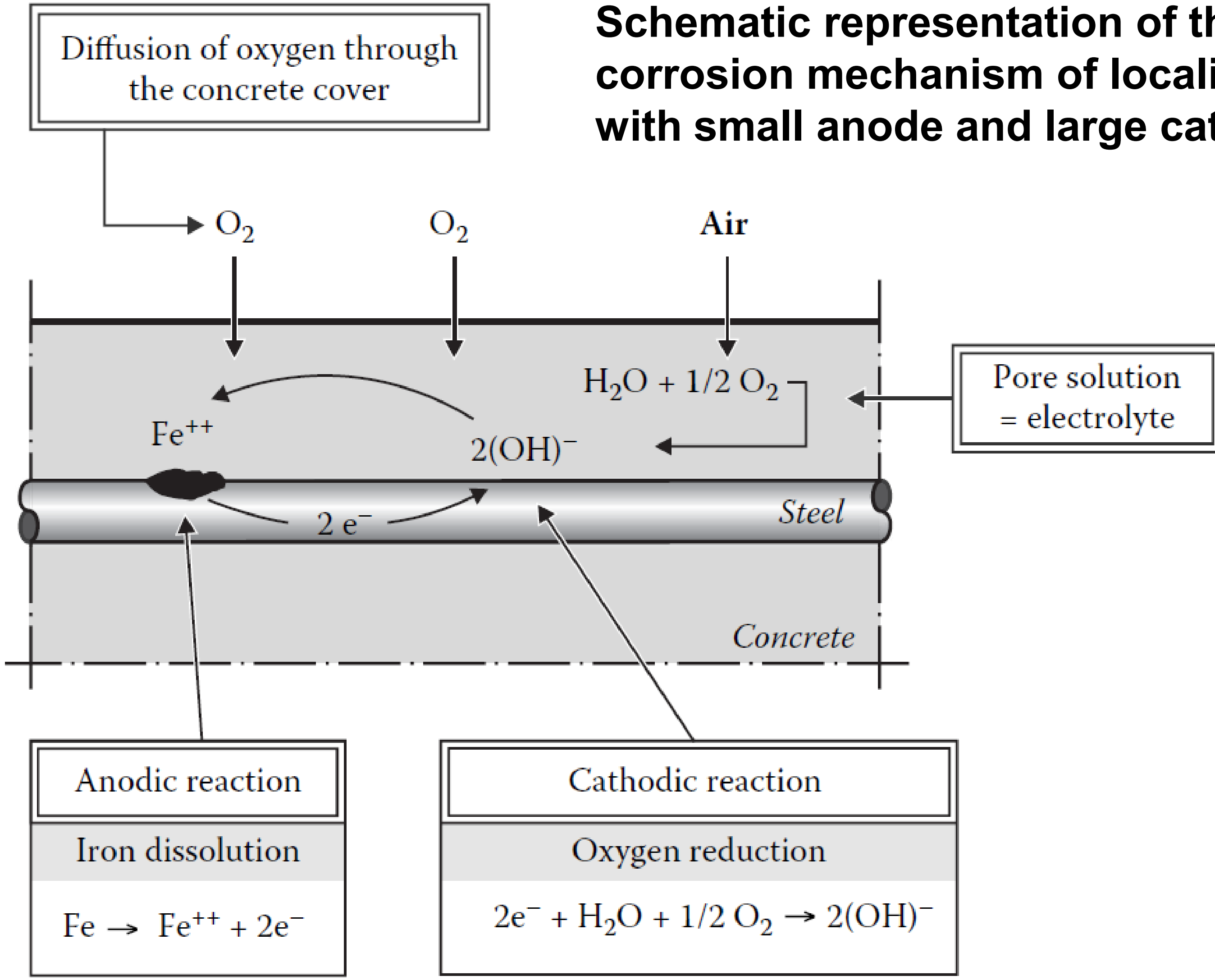
- Chloride ingress into the concrete can cause depassivation of the steel surface, where a critical chloride content is reached.



Schematic representation of the corrosion process of steel in concrete



Schematic representation of the electrochemical corrosion mechanism of localised depassivation with small anode and large cathodes



One requirement for electrochemical corrosion is the presence of an electrolyte at the steel surface. In the case of steel in concrete the electrolyte is given by the aqueous solution within the pore system of the concrete. The high pH value of this pore solution causes passivation of the steel.

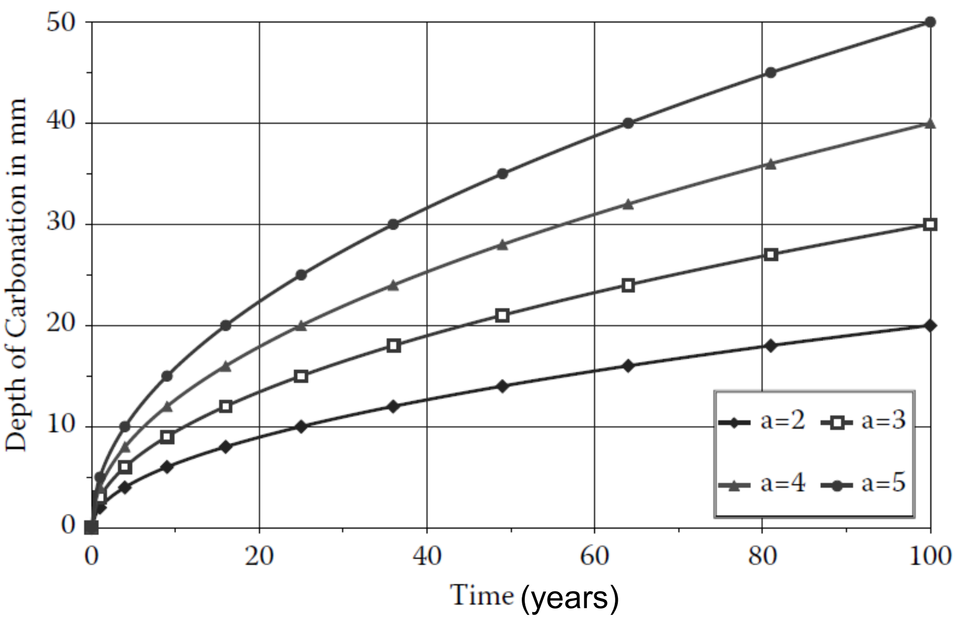
1. Corrosion induced by carbonation of the concrete

- It occurs when the carbonation front has reached the level of the reinforcement.

- The rate of carbonation depends on:
  - Moisture content of air
  - CO_2 concentration of air
  - The age and quality of concrete (or cement)
  - Water content of the concrete
  - Thickness of concrete cover

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

$$CO_2 + H_2O + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O$$

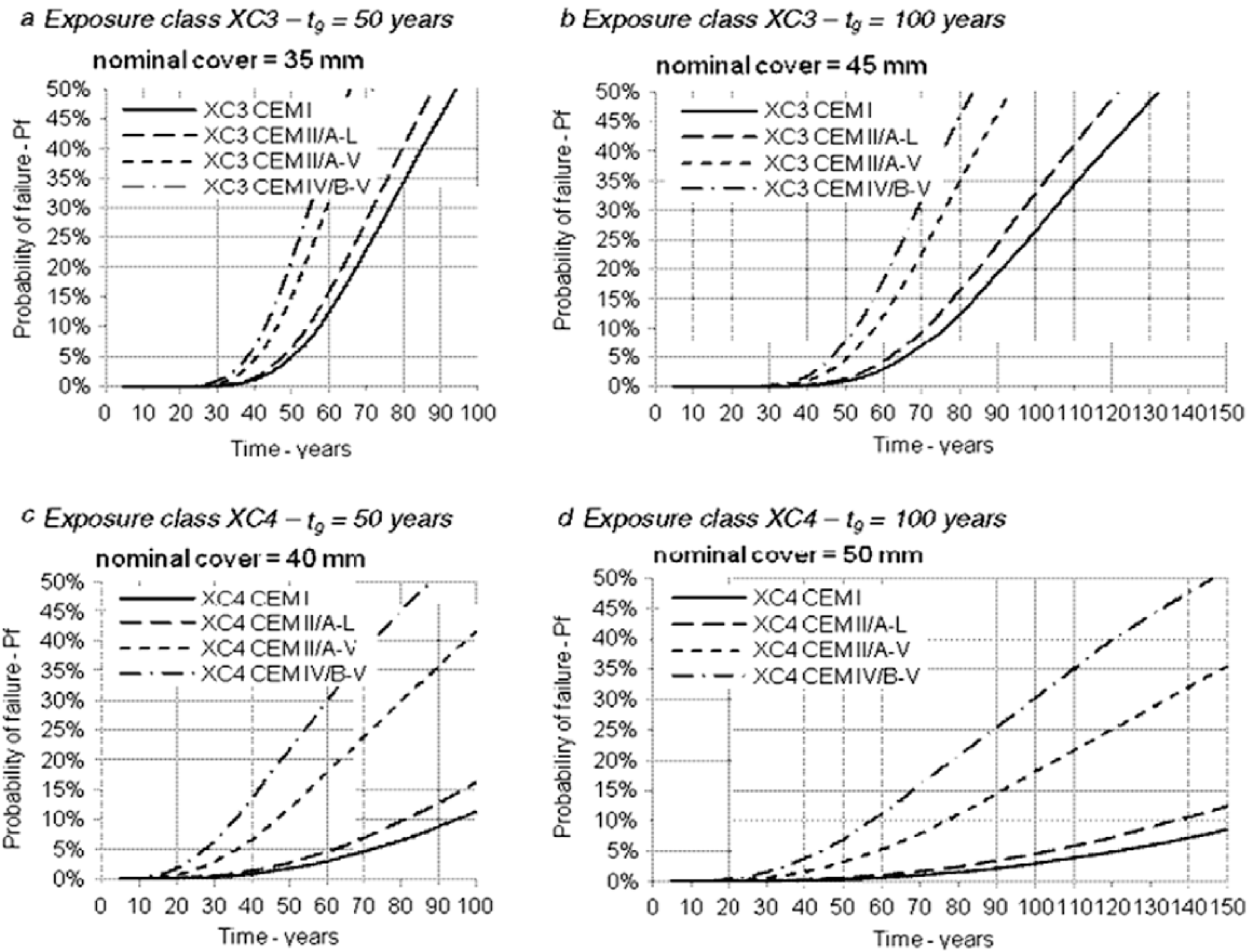


$$X_c(t) = a^* \sqrt{t}$$

where

$X_c(t)$ = Carbonation depth in mm
a = Constant in mm/$\sqrt{a}$
t = Time in a

The constant *a* includes the diffusion coefficient of the concrete for CO2. For usual concrete compositions it is in the range of 2–5 mm/$\sqrt{a}$, but for particularly good or bad quality (especially in old structures), it can be significantly lower or higher.



a Exposure class XC3 – t_g = 50 years
nominal cover = 35 mm
XC3 CEM I
XC3 CEM II/A-L
XC3 CEM II/A-V
XC3 CEM IV/B-V
Probability of failure - Pf
Time - years
b Exposure class XC3 – t_g = 100 years
nominal cover = 45 mm
XC3 CEM I
XC3 CEM II/A-L
XC3 CEM II/A-V
XC3 CEM IV/B-V
Probability of failure - Pf
Time - years
c Exposure class XC4 – t_g = 50 years
nominal cover = 40 mm
XC4 CEM I
XC4 CEM II/A-L
XC4 CEM II/A-V
XC4 CEM IV/B-V
Probability of failure - Pf
Time - years
d Exposure class XC4 – t_g = 100 years
nominal cover = 50 mm
XC4 CEM I
XC4 CEM II/A-L
XC4 CEM II/A-V
XC4 CEM IV/B-V
Probability of failure - Pf
Time - years

Carbonation induced corrosion

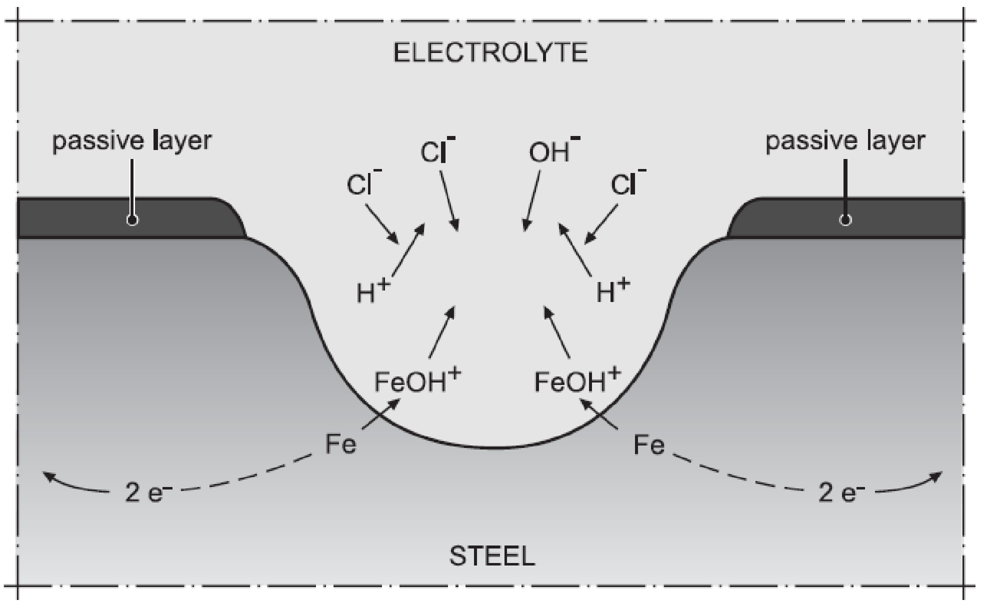
Carbonation induced corrosion

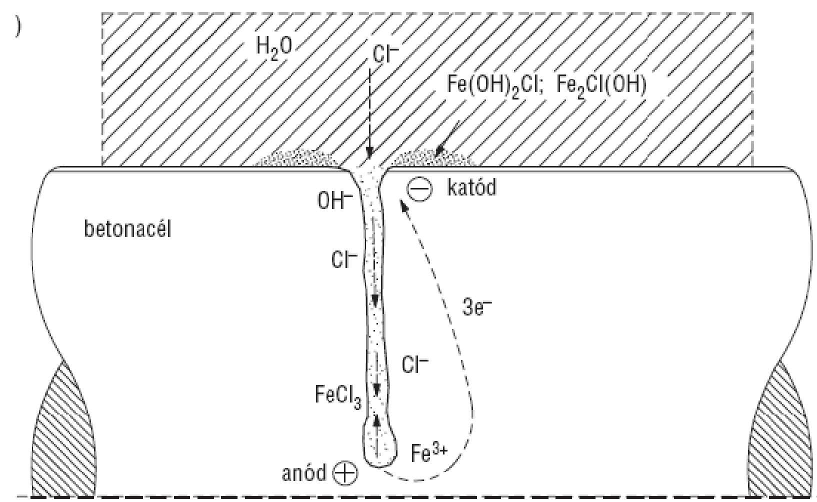

CO_2

Carbonation induced corrosion /advanced/

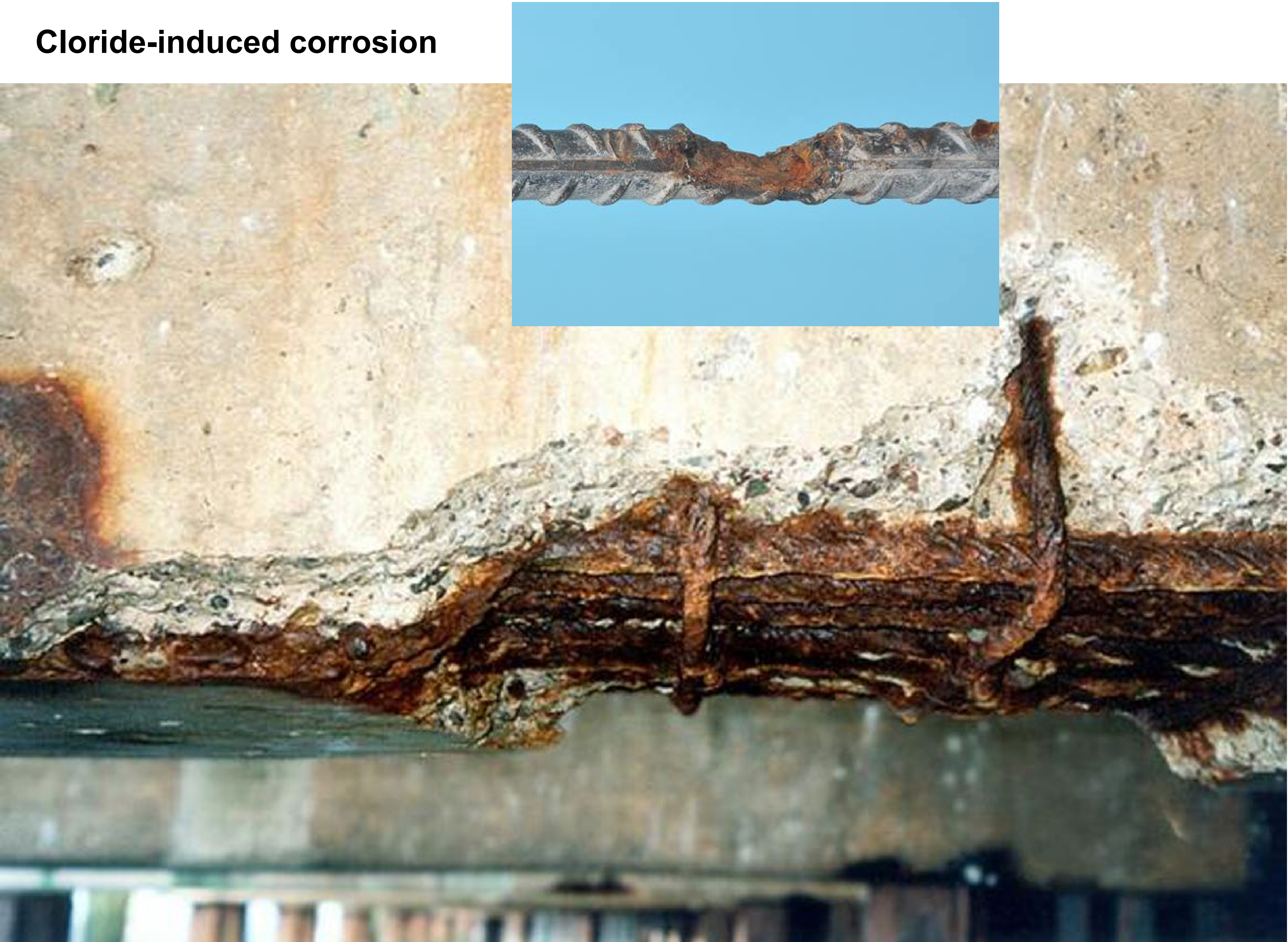
2. Corrosion induced by cloride

Chloride-induced corrosion of steel in concrete does not usually lead to a uniform loss in the cross section of the reinforcement like carbonation-induced corrosion, but to **localised corrosion spots (pitting corrosion)**. This is due to the fact that a more or less highly concentrated hydrochloric acid (HCl) emerges at the anodes, which causes high corrosion rates and stabilises the corrosion process.



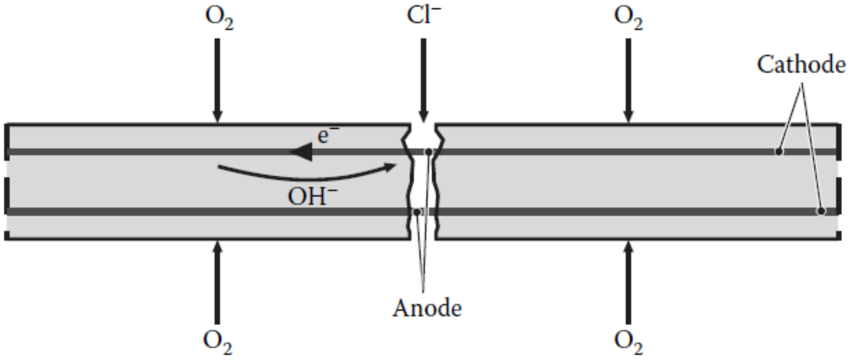


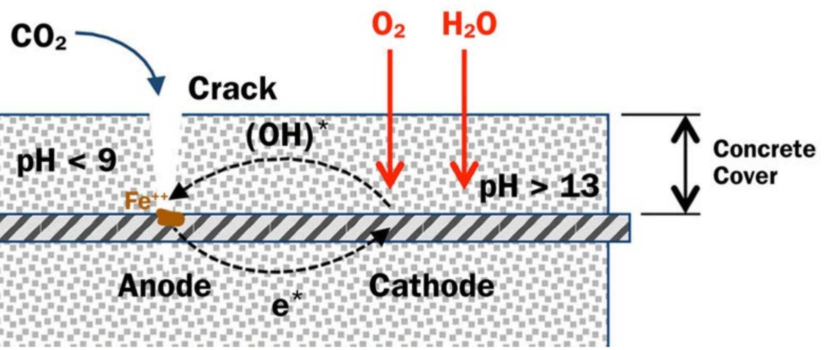
Cloride-induced corrosion



Corrosion mechanisms in cracks

In cracks aggressive substances like chlorides can directly penetrate into the concrete very quickly.
Reinforcement corrosion starts quickly and with high rates, especially when wide cracks reach down to the level of the reinforcement or cross the reinforcement.
The most unfavourable situations are when a crack runs through the whole cross section of a concrete structure.



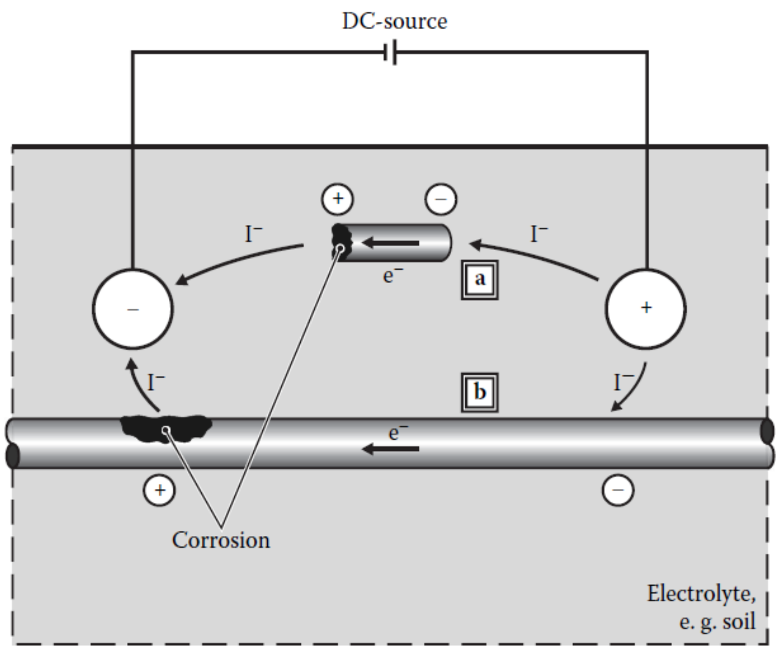


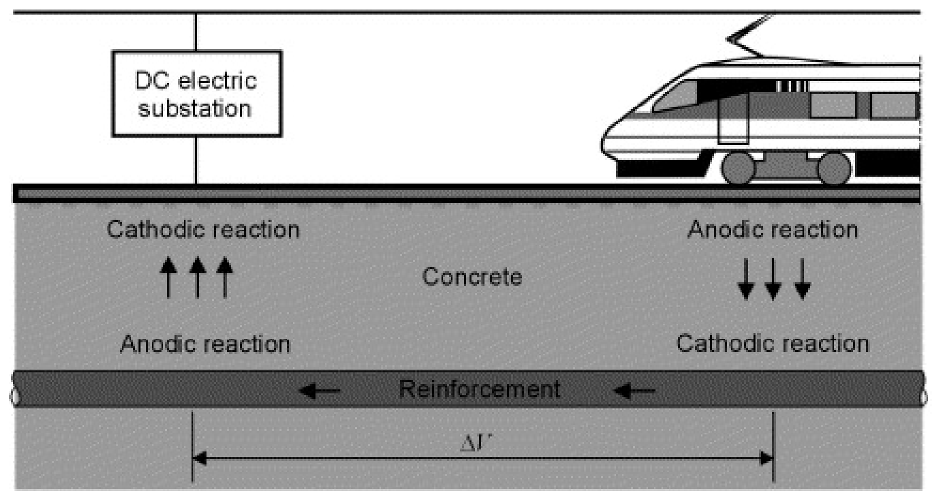
Leaching out of the concrete

Reinforcement corrosion can also be induced in the area of cracks or joints where water passes through over significant periods of time. This can lead to a local reduction of the pH value where the alkali ions are transported away with the water.

3. Corrosion induced by stray currents

This type of corrosion only occurs in very exceptional cases, where electrical current fields are active in the ground and the usual measures (grounding) to prevent stray current corrosion are missing or defective.





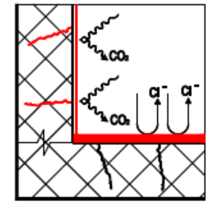
CONCRETE DEFECTS AND PRINCIPLE FOR REPAIR – Part 1

MECHANICAL ATTACK

Cause	Relevant principles for repair and protection
Impact	Principles 3,5
Overloading	Principles 3,4
Movement	Principles 3,4
Vibration, Earthquake, Explosion	Principles 3,4

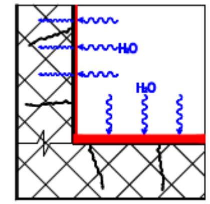
CHEMICAL ATTACK

Cause	Relevant principles for repair and protection
AAR Alkali aggregate reactions	Principles 1,2,3
Aggressive chemical Exposure	Principles 1,2,6
Bacterial or other biological action	Principles 1,2,6
Efflorescence / leaching	Principles 1,2



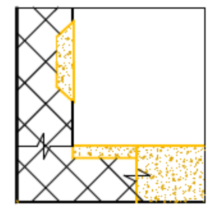
PRINCIPLE 1

Protection against ingress



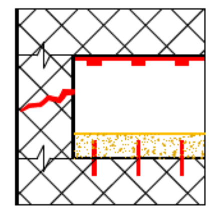
PRINCIPLE 2

Moisture control



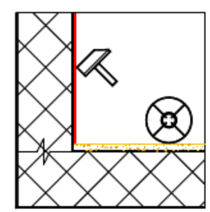
PRINCIPLE 3

Concrete restoration



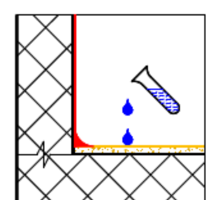
PRINCIPLE 4

Structural strengthening



PRINCIPLE 5

Increasing physical resistance



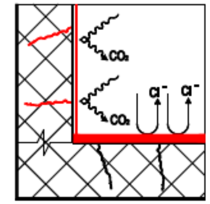
PRINCIPLE 6

Resistance to chemicals

CONCRETE DEFECTS AND PRINCIPLE FOR REPAIR – Part 2

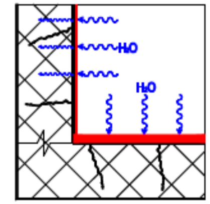
PHYSICAL ATTACK

Cause	Relevant principles for repair and protection
Freeze/thaw action	Principles 1,2,3,5
Thermal movement	Principles 1,3
Salt crystal expansion	Principles 1,2,3
Shrinkage	Principles 1,4
Erosion	Principles 3,5
Abrasion and wear	Principles 3,5



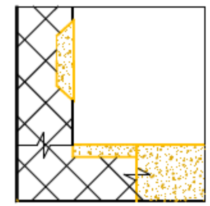
PRINCIPLE 1

Protection against ingress



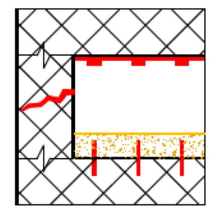
PRINCIPLE 2

Moisture control



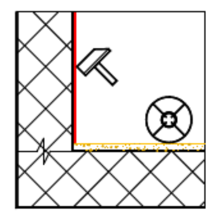
PRINCIPLE 3

Concrete restoration



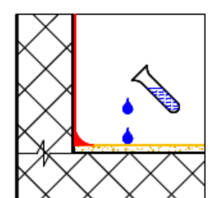
PRINCIPLE 4

Structural strengthening



PRINCIPLE 5

Increasing physical resistance



PRINCIPLE 6

Resistance to chemicals

CONCRETE DAMAGE DUE TO STEEL REINFORCEMENT CORROSION – PRINCIPLE FOR REPAIR – Part 1

CHEMICAL ATTACK

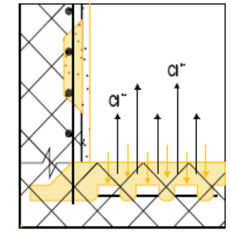
Cause	Relevant principles for repair and protection
Carbon dioxide (CO_2) inthe atmosphere reacting with calcium hydroxide in the concrete pore liquid. $CO_2 + Ca(OH)_2 \rightarrow CaCO_3 + H_2O$ Soluble and strongly alkaline pH 12 – 13 → almost insoluble and much less alkaline pH 9. Steel protected (passivation) → steel unprotected	Principles 1,2,3,7,8,11

CORROSIVE CONTAMINANTS E.G. CHLORIDES

Cause	Relevant principles for repair and protection
Chlorides accelerate the corrosion process and can also cause dangerous “pitting” corrosion. At above 0.2 – 0.4% concentration in the concrete chlorides can break down the passive oxide protective layer on the steel surface. Chlorides are typically from marine/salt water exposure and/or the use of de-icing salts.	Principles 1,2,3,7,8,9,11

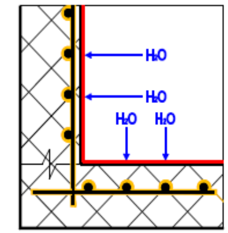
PRINCIPLE 7

Preserving or restoring passivity



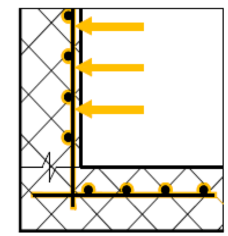
PRINCIPLE 8

Increasing resistivity



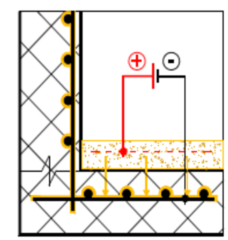
PRINCIPLE 9

Cathodic control



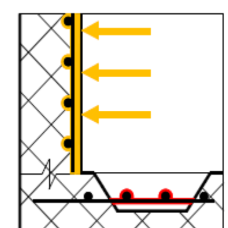
PRINCIPLE 10

Cathodic protection



PRINCIPLE 11

Control of anodic areas



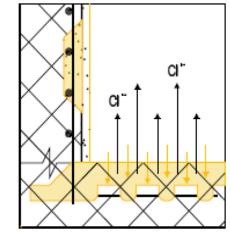
CONCRETE DAMAGE DUE TO STEEL REINFORCEMENT CORROSION – PRINCIPLE FOR REPAIR – Part 2

STRAY ELECTRICAL CURRENT

Cause	Relevant principles for repair and protection
Metals of different electropotential are connected to each other in the concrete and corrosion occurs. Corrosion can also be due to stray electrical currents from power supply and transmission networks.	No specific Repair Principles defined at this time. For repair of the concrete use Principles 2,3,10

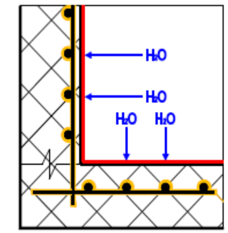
PRINCIPLE 7

Preserving or restoring passivity



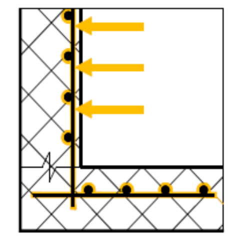
PRINCIPLE 8

Increasing resistivity



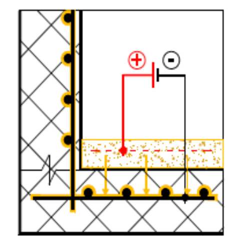
PRINCIPLE 9

Cathodic control



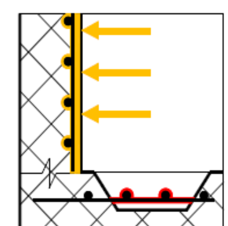
PRINCIPLE 10

Cathodic protection



PRINCIPLE 11

Control of anodic areas



DIAGNOSTICS OF STRUCTURES

LECTURE 02

Strength tests on concrete

Destructive Testing

Non-Destructive Testing

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Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Destructive Tests (DT)

Compressive Strength

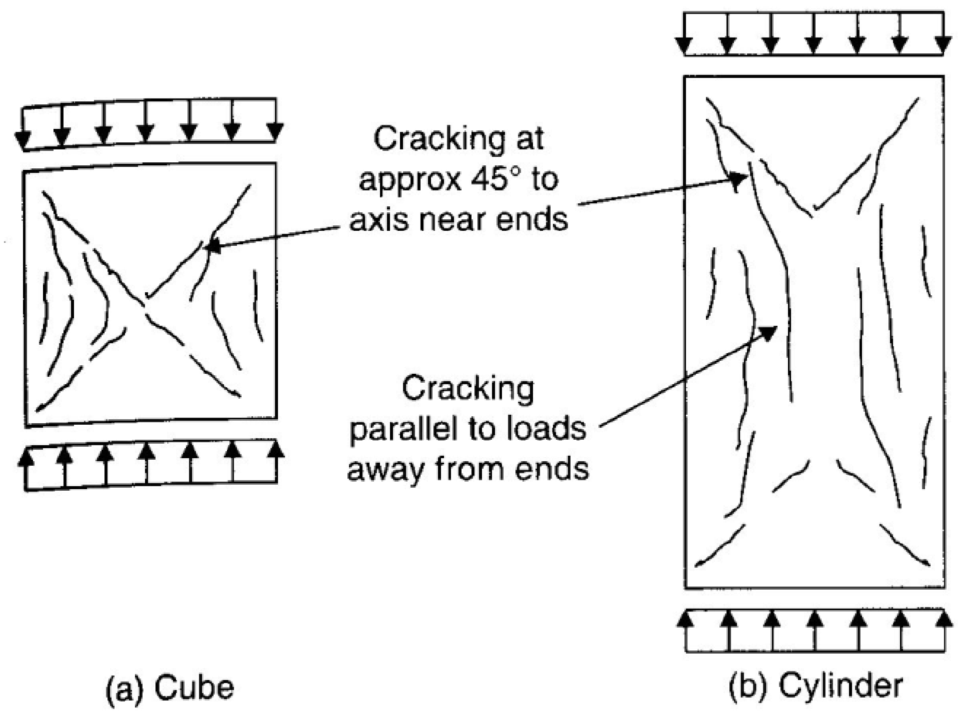
(mainly for newly built structures)

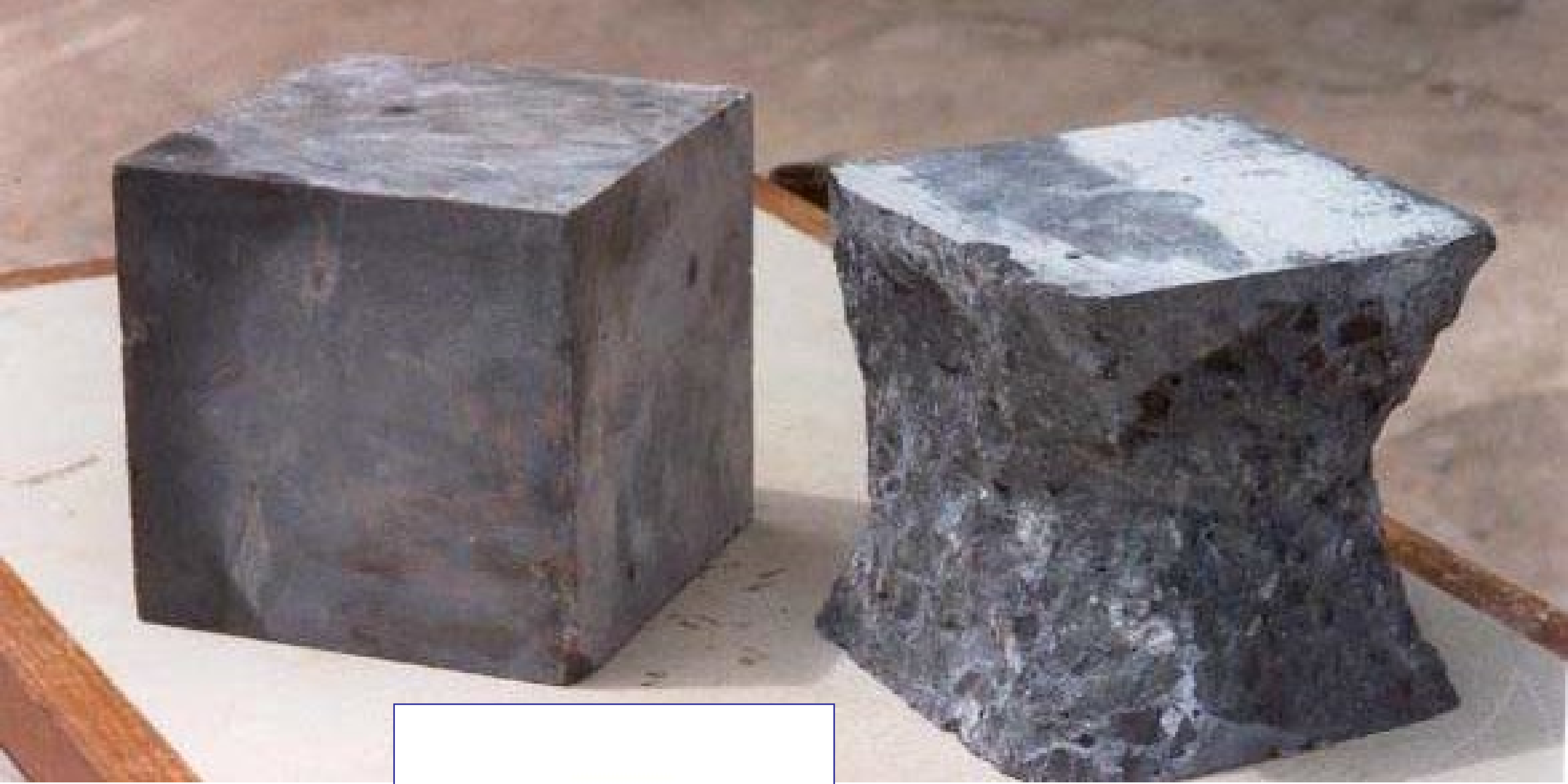
- **Cube test**

  Standard size: 150mm

- **Cylinder test**

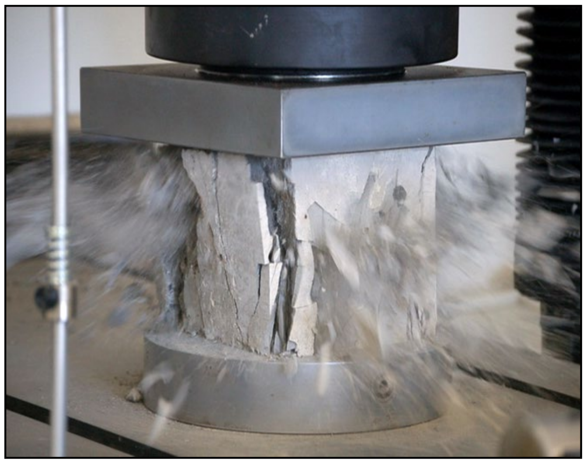
  Standard size:
  D=150mm
  H=300mm





The compressive strength should be tested at 28 days age of concrete (standard: MSZ EN 12390-3)

Storage prior to testing: underwater

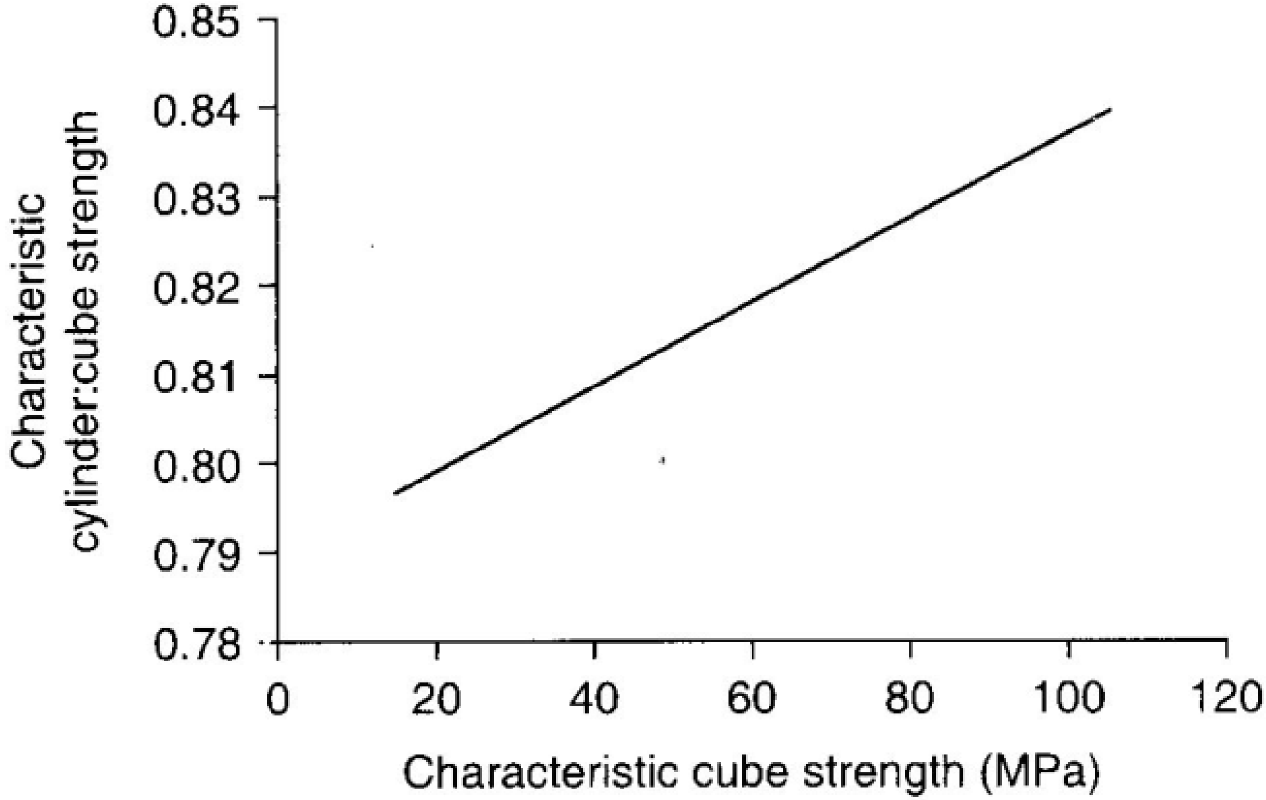


$$C16/20 \leftarrow f_{ck,cube}$$

$$f_{ck,cyl} \nearrow$$

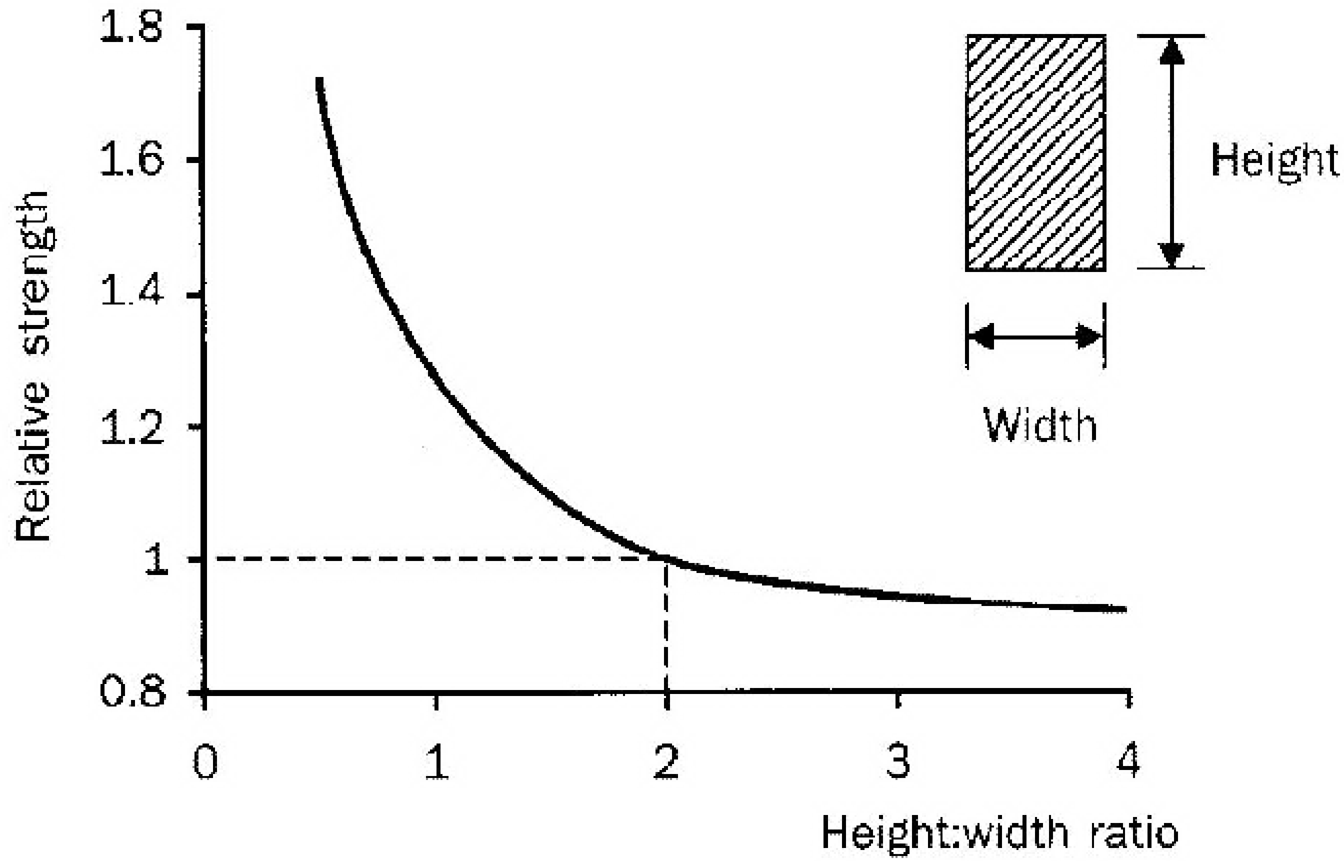
$f_{ck,cyl}$ – characteristic value of cylinder test (150x300mm)

$f_{ck,cube}$ – characteristic value of cube test (150x150x150 mm)



Variation of cylinder and cube strength ratio with strength of concrete

$$f_{cyl} = 0.85\ f_{cube} - 1{,}6\ \ (N/mm^2)$$



The relationship between height:width (diameter) ratio and strength of concrete in compression

Interpretation of characteristic strength

$$f_{ck} = f_{cm} - k \cdot t \cdot s$$

The stress below which only 5% of the test results fall

f_{ck}: characteristic compressive strength of concrete (N/mm^2)

f_{cm}: mean value of compressive strength of concrete (N/mm^2)

s: standard deviation of compressive strength (N/mm^2)

k: factor for failure rate (-), depends on the type of distribution

t: Student factor (-), takes account of the number of specimens

Mean value, f_{cm}	5	7	10	14	20	28	40	56
k	0,77	0,81	0,87	0,92	1,00	1,08	1,19	1,31

k=1,00 can be taken for normal concrete

Number of specimens	3	5	10	12	14	16	20	40	∞
Student factor (t)	2,28	1,97	1,79	1,77	1,75	1,73	1,71	1,64	1,48

Example 1

A set of concrete <u>cube</u> compressive test results is shown in the table

Calculate

a) the mean strength (f_{cm})

b) the standard deviation (s)

c) coefficient of variation (COV)

d) characteristic cube strength ($f_{ck,cube}$)

e) characteristic cylinder strength ($f_{ck,cyl}$)

f) concrete grade

n=40

DATA	
Cube No	f_c
1	36.64
2	40.96
3	27.42
4	24.10
5	41.44
6	34.94
7	25.32
8	41.14
9	37.36
10	31.64
11	41.42
12	37.53
13	23.34
14	36.43
15	31.81
16	33.65
17	33.88
18	38.19
19	24.79
20	24.81

DATA	
Cube No	f_c
21	23.47
22	34.29
23	32.09
24	24.89
25	25.67
26	33.78
27	38.60
28	37.23
29	31.31
30	25.39
31	26.39
32	42.99
33	32.69
34	38.16
35	36.49
36	42.87
37	41.54
38	28.60
39	37.37
40	30.22

a) the mean strength: $f_{cm} = f_{ci} / n =$ 33.3 N/mm²

b) the standard deviation:

$$s = \left[\frac{\sum (f_{ci} - f_{cm})^2}{n-1} \right]^{\frac{1}{2}} = \left[\frac{n \sum (f_{ci})^2 - \left(\sum f_{cm}\right)^2}{n-1} \right]^{\frac{1}{2}}$$

= 6.18 N/mm²

c) coefficient of variation (COV):

$c = s / f_{cm}$ = 0.18 (18%)

(***k*** $\cdot t \cdot s$)

d) characteristic cube strength: $f_{ck,cube} = f_{cm} - 1{,}14 \cdot 1{,}64 \cdot s$ = 21.75 N/mm²

e) characteristic cylinder strength: $f_{ck,cyl} = 0.85\, f_{ck,cube} - 1{,}6$ = 16.89 N/mm²

f) concrete grade: C16/20

Concrete grade	C16/20	C20/25	C30/37	C35/45	C40/50	C45/55	C50/60	C55/67	C60/75	C70/85	C80/95	C90/105
f_{ck} [N/mm²]	16	20	30	35	40	45	50	55	60	70	80	90
$f_{ck,cube}$ [N/mm²]	20	25	37	45	50	55	60	67	75	85	95	105

n=20

a) the mean strength: $f_{cm} = f_{ci} / n =$ 33.3 N/mm²

b) the standard deviation:

$$s = \left[\frac{\sum (f_{ci} - f_{cm})^2}{n-1} \right]^{\frac{1}{2}} = \left[\frac{n \sum (f_{ci})^2 - \left(\sum f_{cm}\right)^2}{n-1} \right]^{\frac{1}{2}}$$

= 6.35 N/mm²

c) coefficient of variation (COV):

$c = s / f_{cm}$ = 0.19 (19%)

($k \cdot t \cdot s$)

d) characteristic cube strength: $f_{ck,cube} = f_{cm} - 1{,}14 \cdot 1{,}71 \cdot s$

= 20.92 N/mm²

e) characteristic cylinder strength: $f_{ck,cyl} = 0.85\, f_{ck,cube} - 1{,}6$

= 16.18 N/mm²

f) concrete grade: C16/20

DATA	
Cube No	f_c
1	36.64
2	40.96
3	27.42
4	24.10
5	41.44
6	34.94
7	25.32
8	41.14
9	37.36
10	31.64
11	41.42
12	37.53
13	23.34
14	36.43
15	31.81
16	33.65
17	33.88
18	38.19
19	24.79
20	24.81

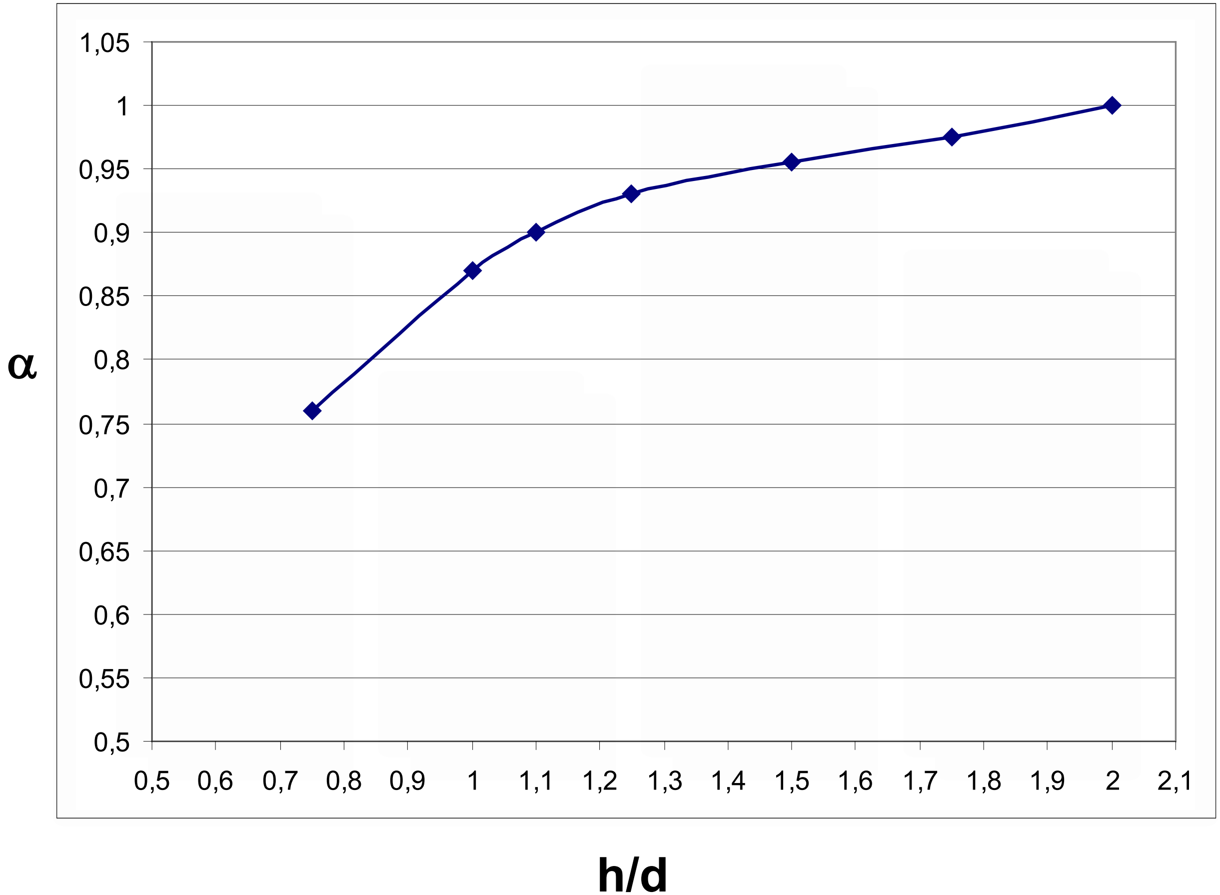
Próbatest száma (n)	3	5	10	12	14	16	20	40	∞
Student tényező (t)	2,28	1,97	1,79	1,77	1,75	1,73	1,71	1,64	1,48

Compressive test on drill cores

- The compressive strength of drill cores can be determined in an uniaxial compression test.
- The number of specimens taken out of an existing structure should always be minimised.
- The diameter of a single drill core should to be at least three times the size of the maximum aggregate size


3


Correction factor (α) for specimen h/d ratio



h/d	α_{mi}
2	1
1,75	0,975
1,5	0,955
1,25	0,93
1,1	0,9
1	0,87
0,75	0,76

h: height of specimen

d: diameter of specimen

N≥15

$$f_{ck,is} = f_{m(n),is} - k_2 \cdot s \text{ or } f_{ck,is} = f_{is,lowest} + 4$$

where

$f_{ck,is}$ = Characteristic compressive strength of the concrete.
$f_{m(n),is}$ = Arithmetic mean of n test results of the compressive strength of the concrete.
$f_{is,lowest}$ = Lowest test result of the compressive strength of the concrete.
k_2 = Defined in national standards. If they don't exist, k_2 = 1.48 is assumed.
s = The standard deviation of the test results or 2 N/mm². The greatest value is to be used.

N is between 3 and 14

$$f_{ck,is} = f_{m(n),is} - k \text{ or } f_{ck,is} = f_{is,lowest} + 4$$

The range of k for a small number n of test results is defined as follows:

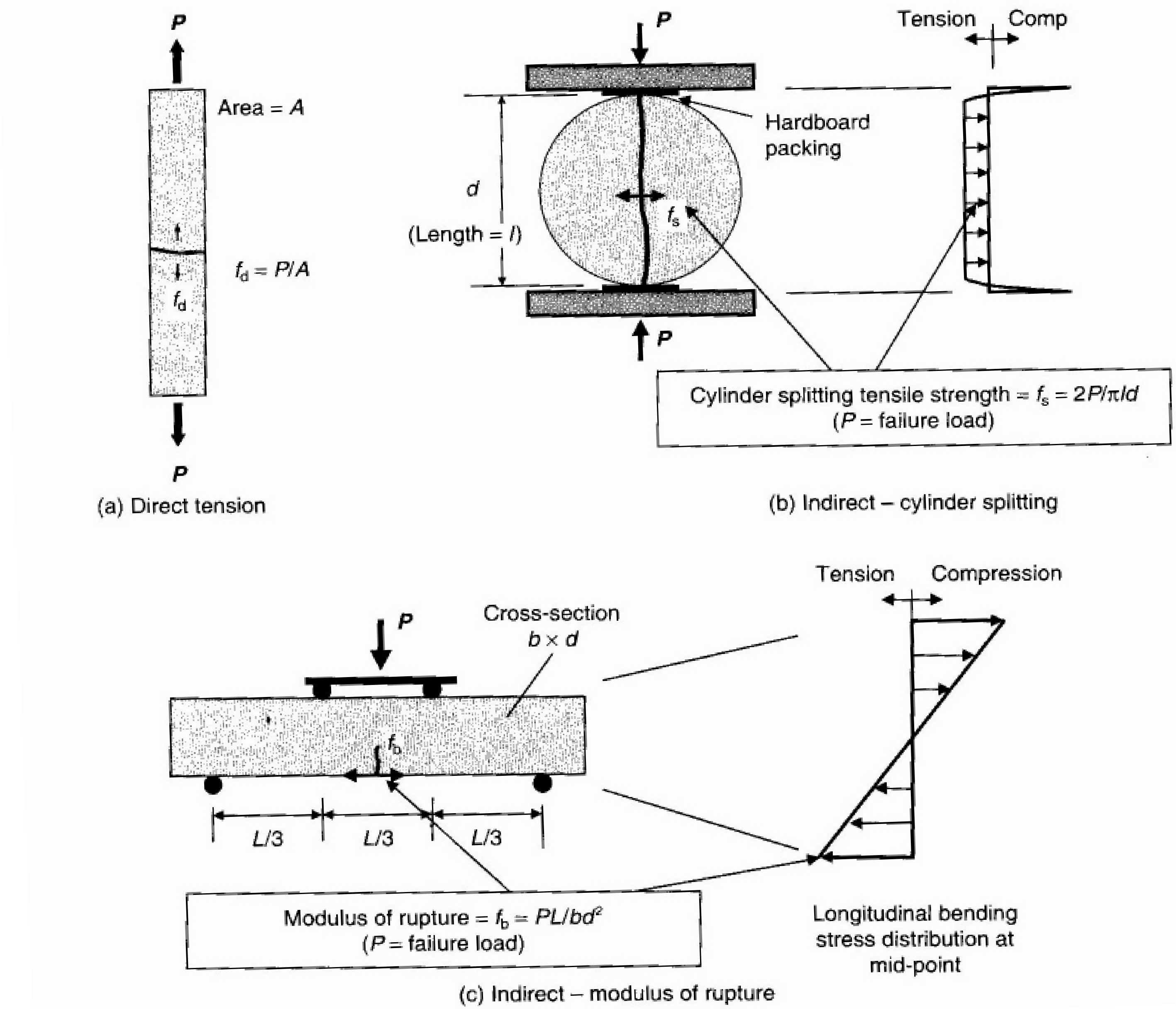
n	k
10–14	5
7–9	6
3–6	7

EN 13791:2008

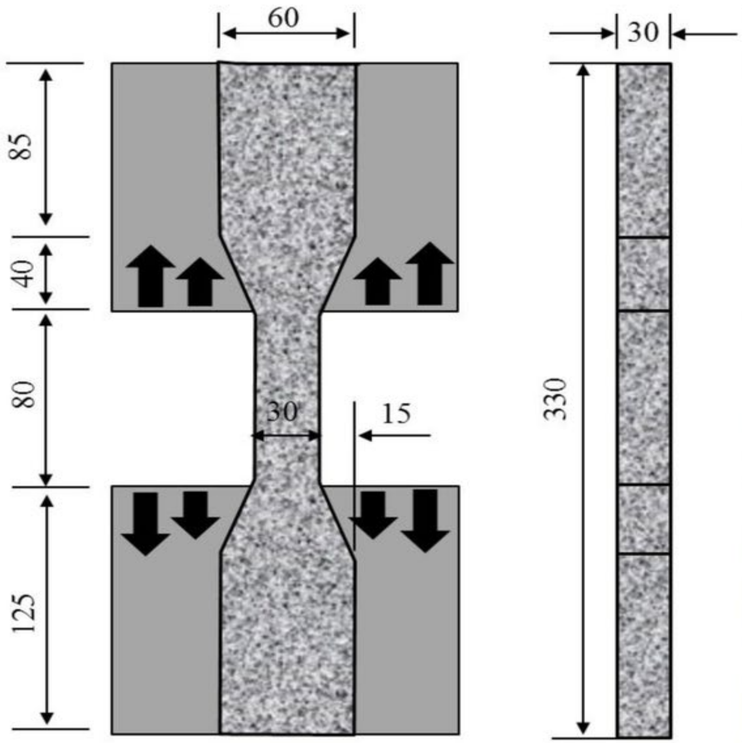
Class of compressive strength according to (DIN) EN 206-1	*Ratio of the compressive strength of concrete to the characteristic compressive strength of standardised samples*	*Characteristic minimum compressive strength of concrete* N/mm^2	
		$f_{ck,is,cylinder}$	$f_{ck,is,cube}$
C8/10	0.85	7	9
C12/15	0.85	10	13
C16/20	0.85	14	17
C20/25	0.85	17	21
C25/30	0.85	21	26
C30/37	0.85	26	31
C35/45	0.85	30	38
C40/50	0.85	34	43
C45/55	0.85	38	47
C50/60	0.85	43	51
C55/67	0.85	47	57
C60/75	0.85	51	64
C70/85	0.85	60	72
C80/95	0.85	68	81
C90/105	0.85	77	89
C100/115	0.85	85	98

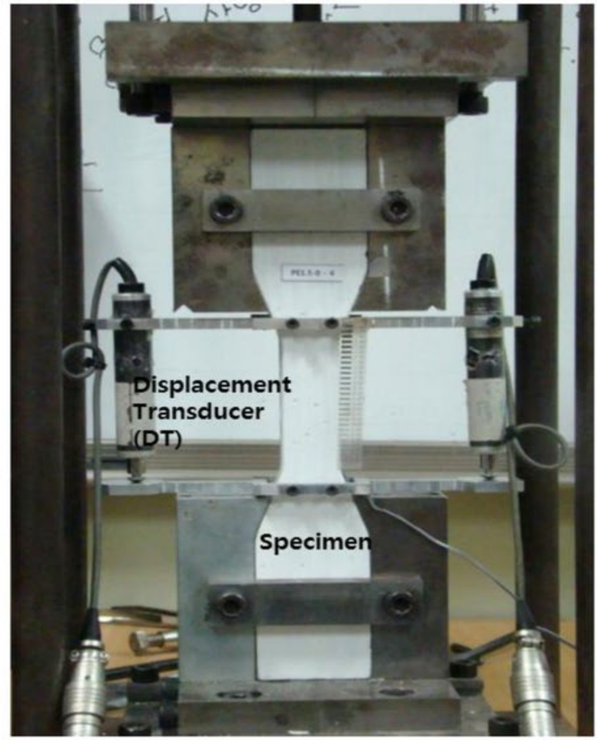
Tensile Strength

Tensile testing methods of concrete



Direct tensile test



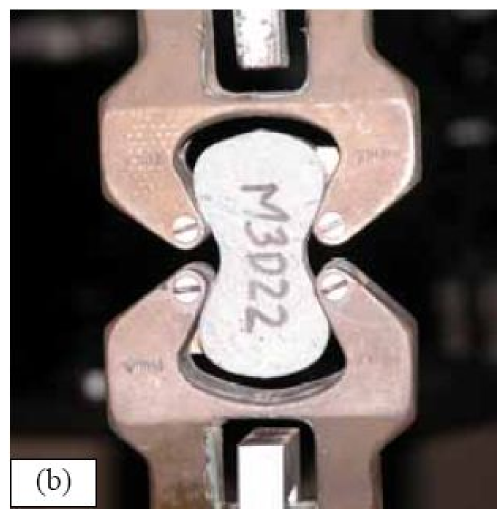


Only rarely applied

$$f_d = P/A$$

A: cross-sectional area

P: failure load



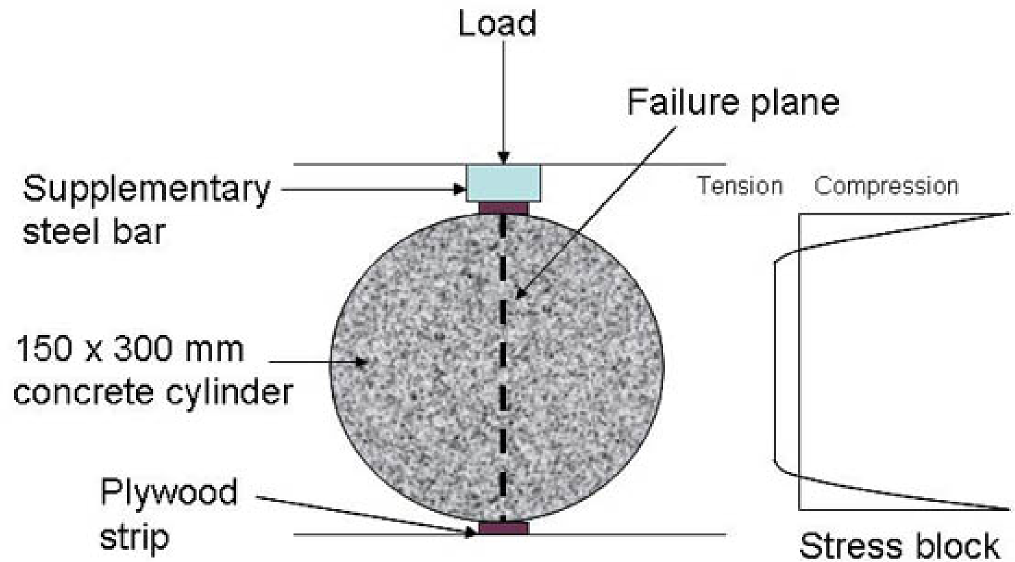
Cylinder splitting test /indirect/

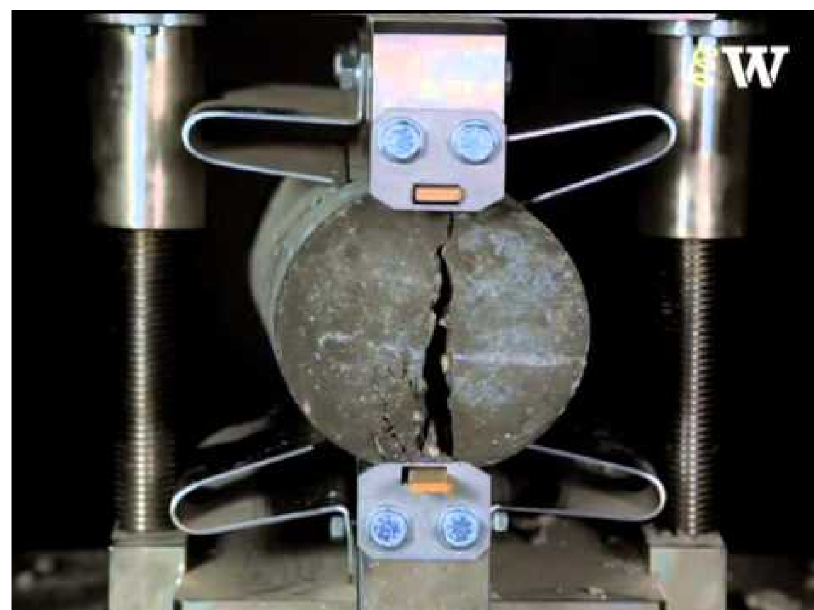
$$f_s = 2P/\pi l d$$

D=100, 150mm

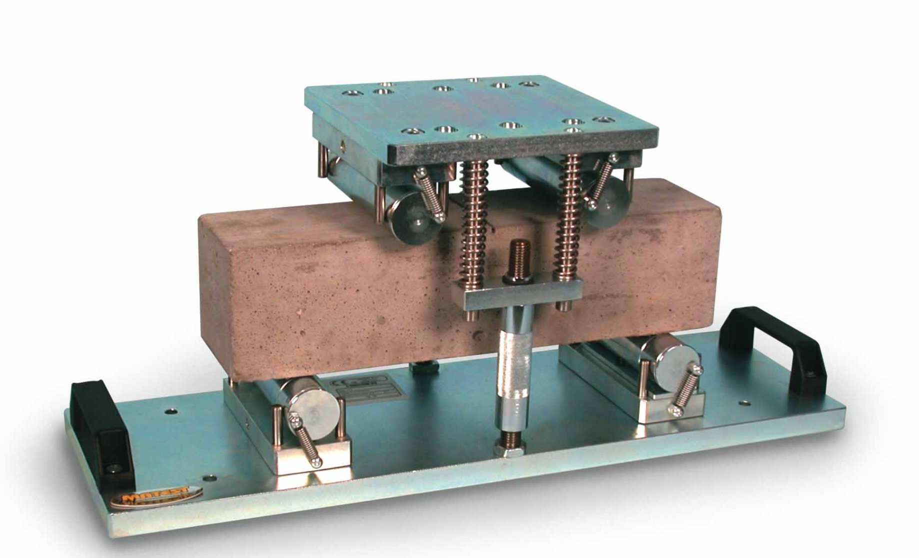
l=200, 300mm

P: failure load





Flexural test /indirect/



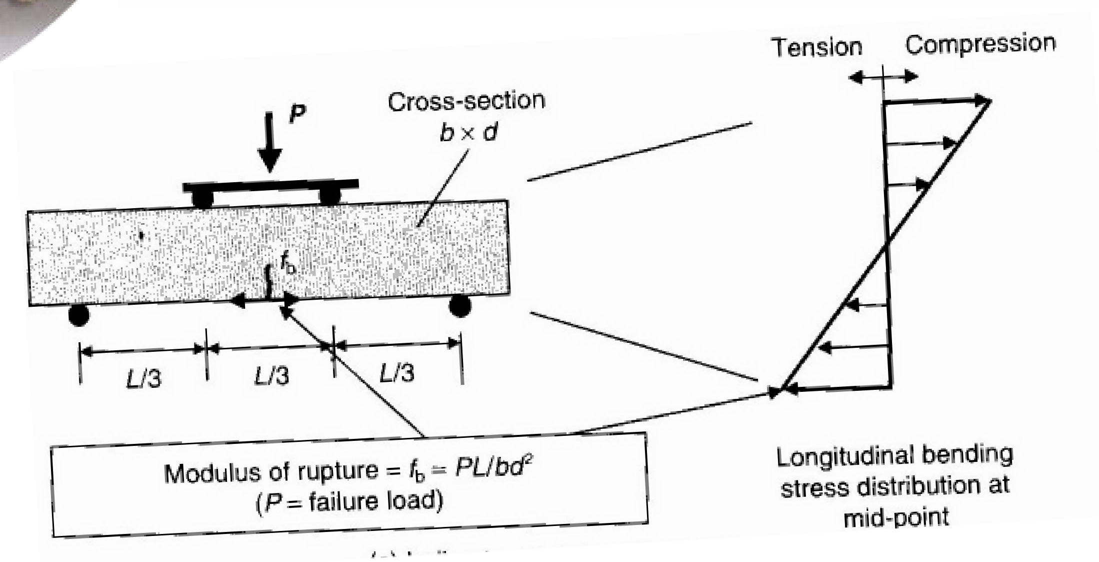
$$f_b = PL/bd^2$$

L= 600mm

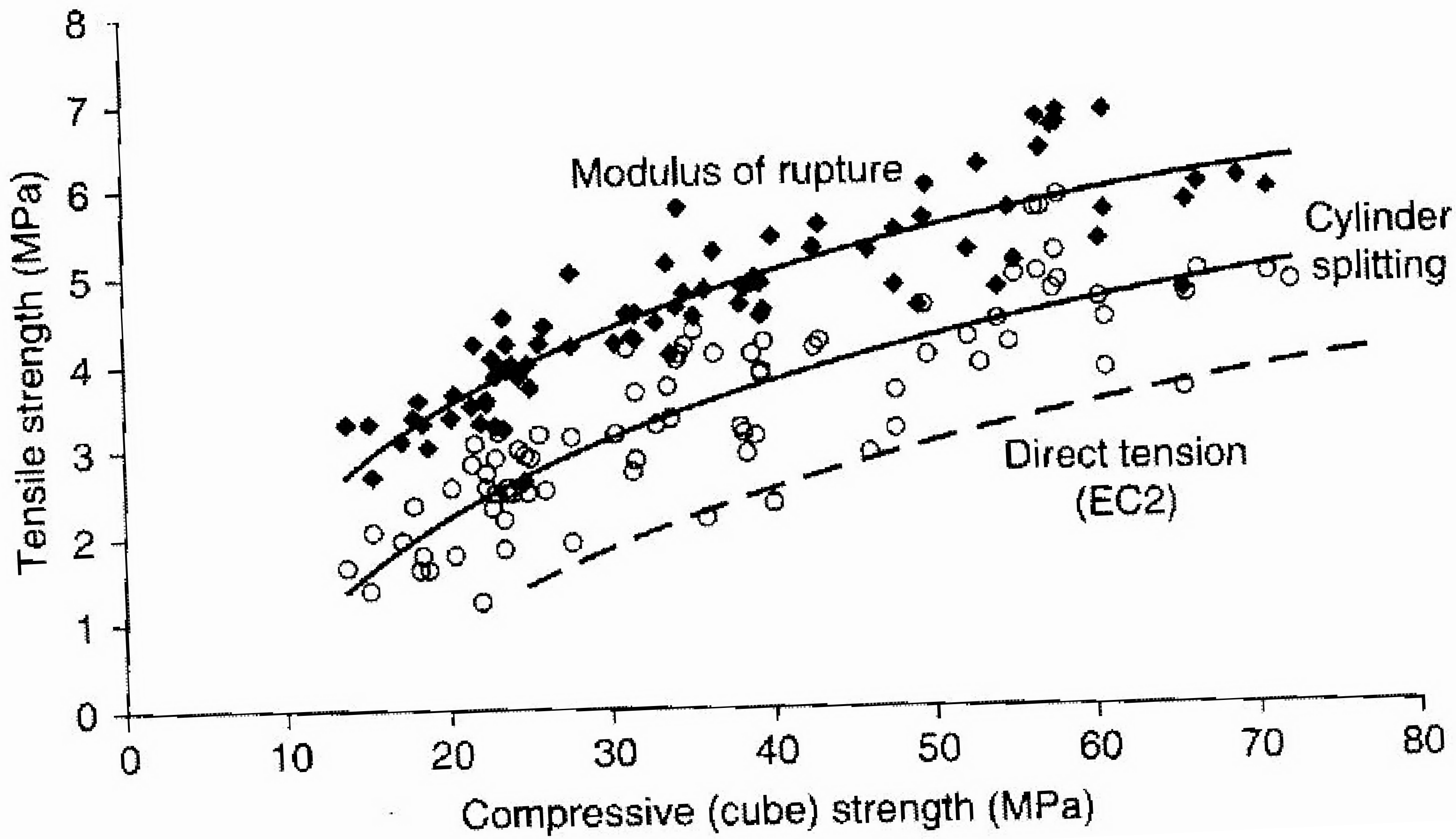
b,d: sizes of cross-section

b ≈ d ≈ 100 or 150mm

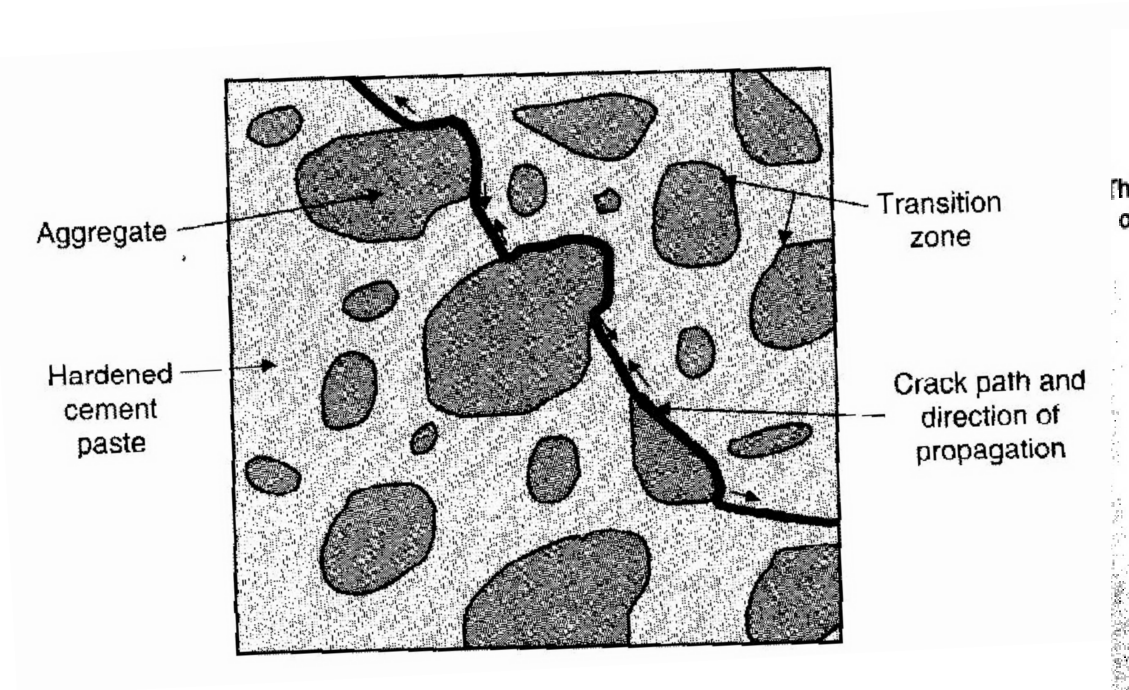
P: failure load

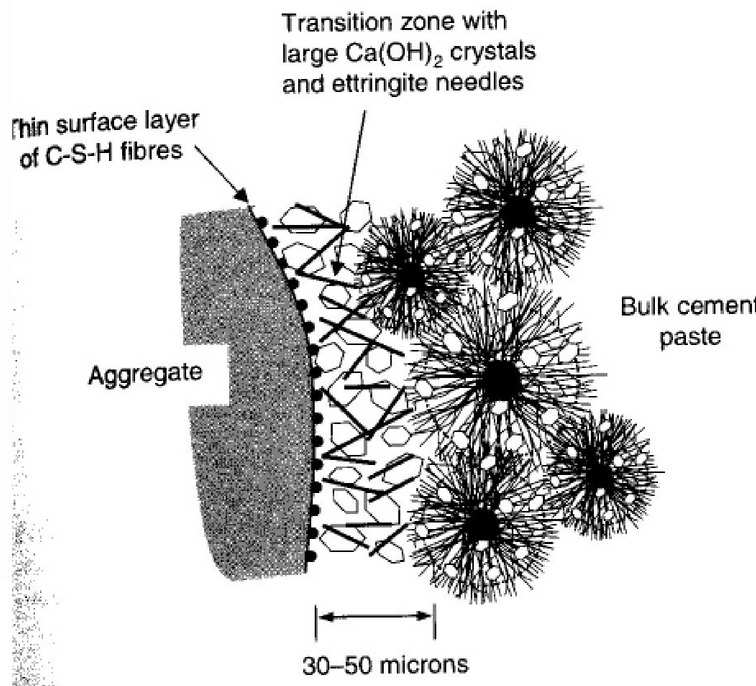


Relationship between strength parameters

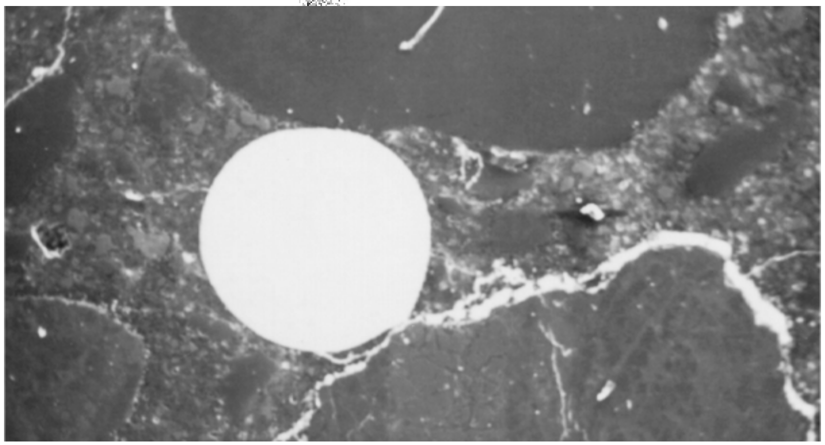


Factors influencing strength of concrete

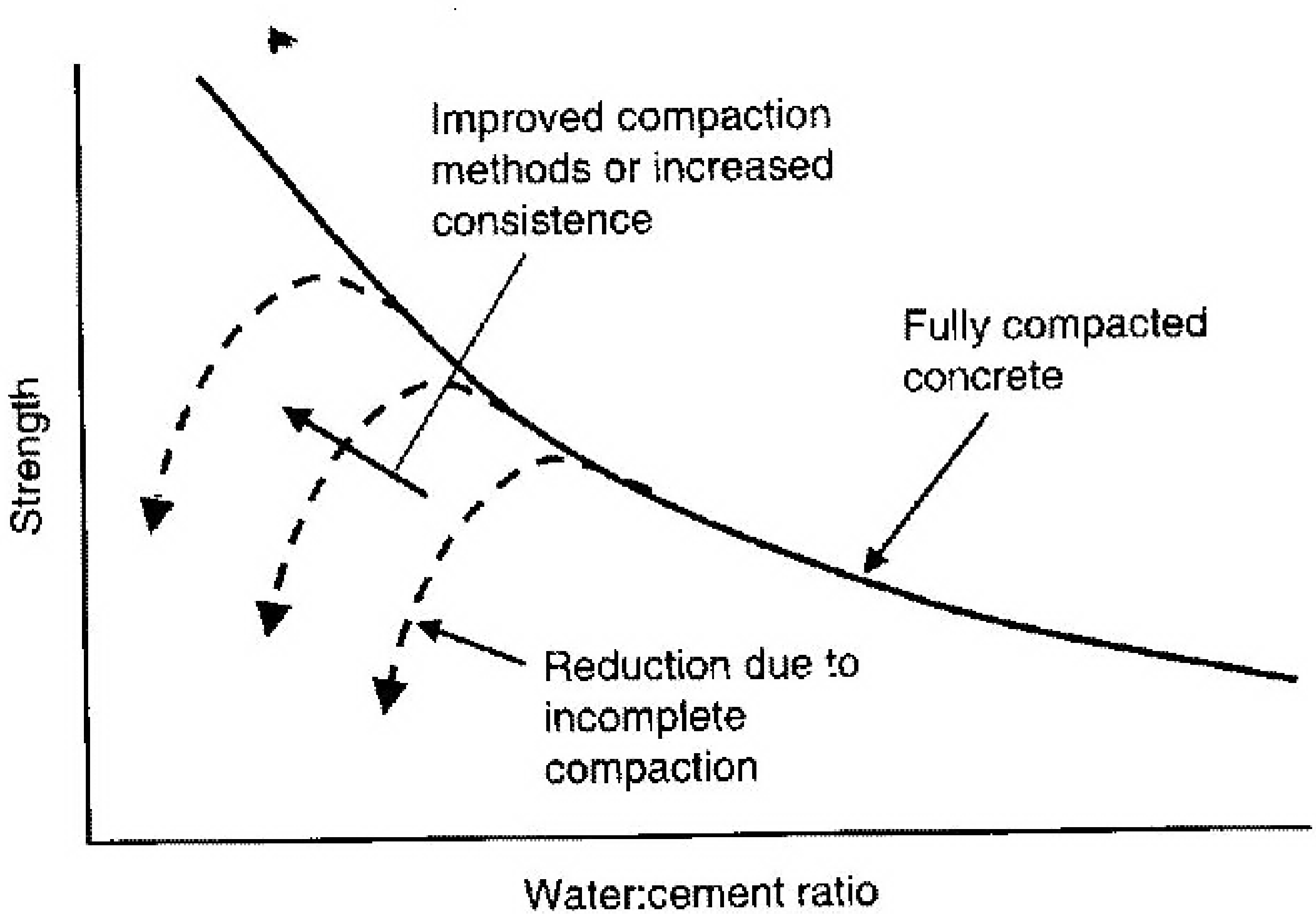


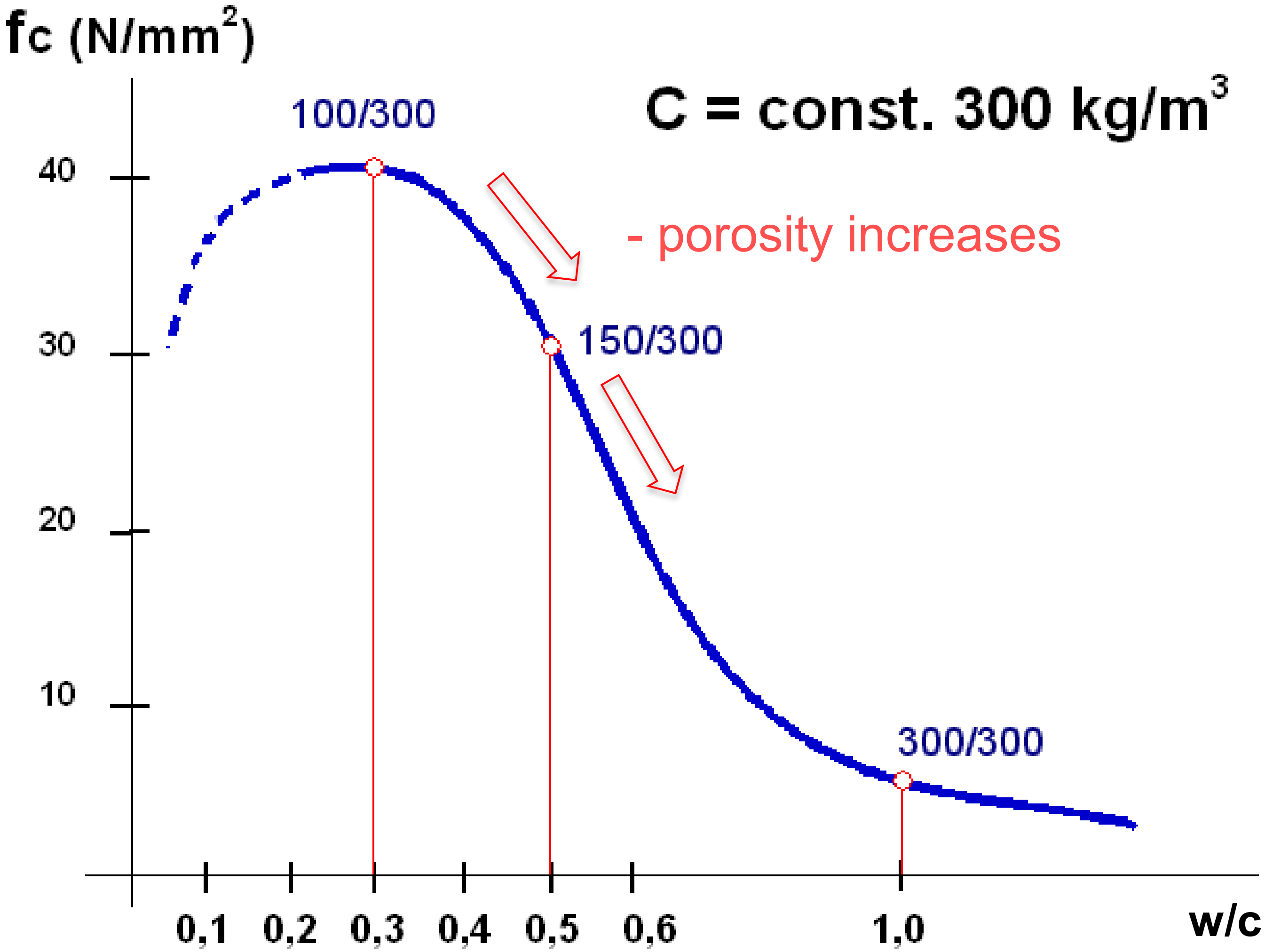


Cracking pattern



Water to cement ratio (w/c)





Effect of w/c on comptressive strength

Age of concrete

Degree of hydration increases with age.

The speed of hydration depends on type of cement.

Temperature

Temperature should be controlled at early age.

Humidity

Concrete stored in humid (wet) environment will achieve higher strength

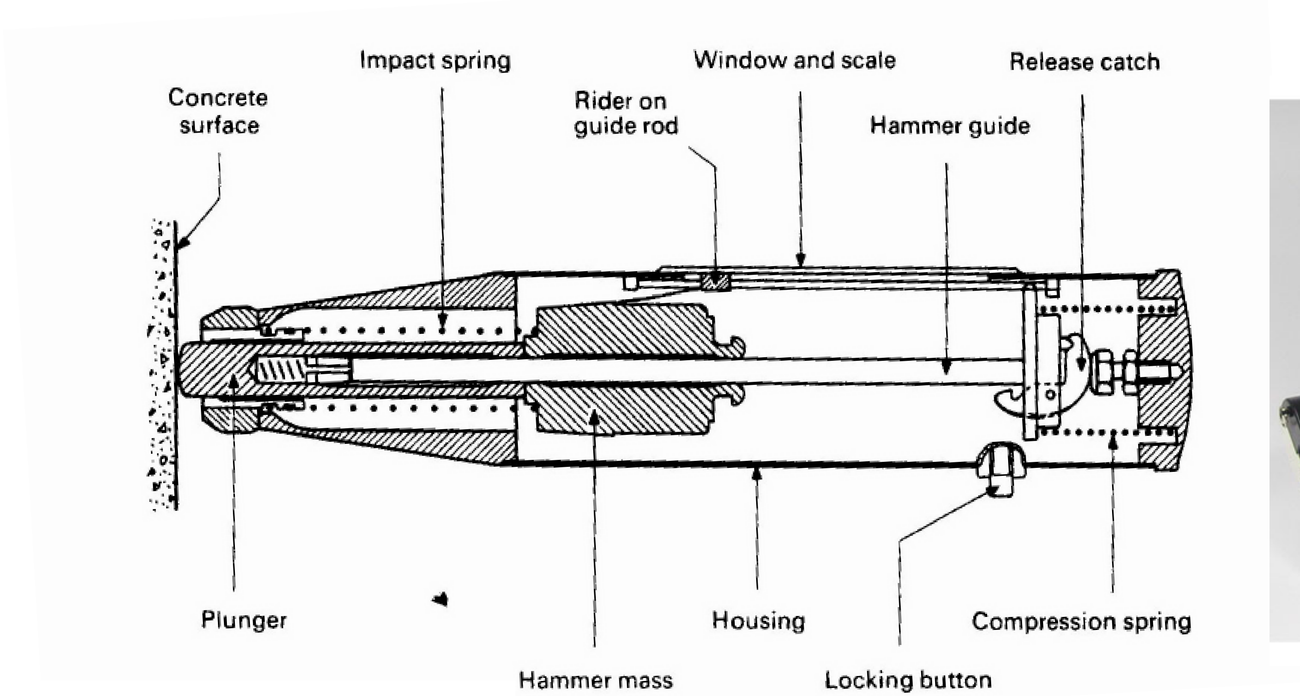
Aggregate properties, size and volume concentration

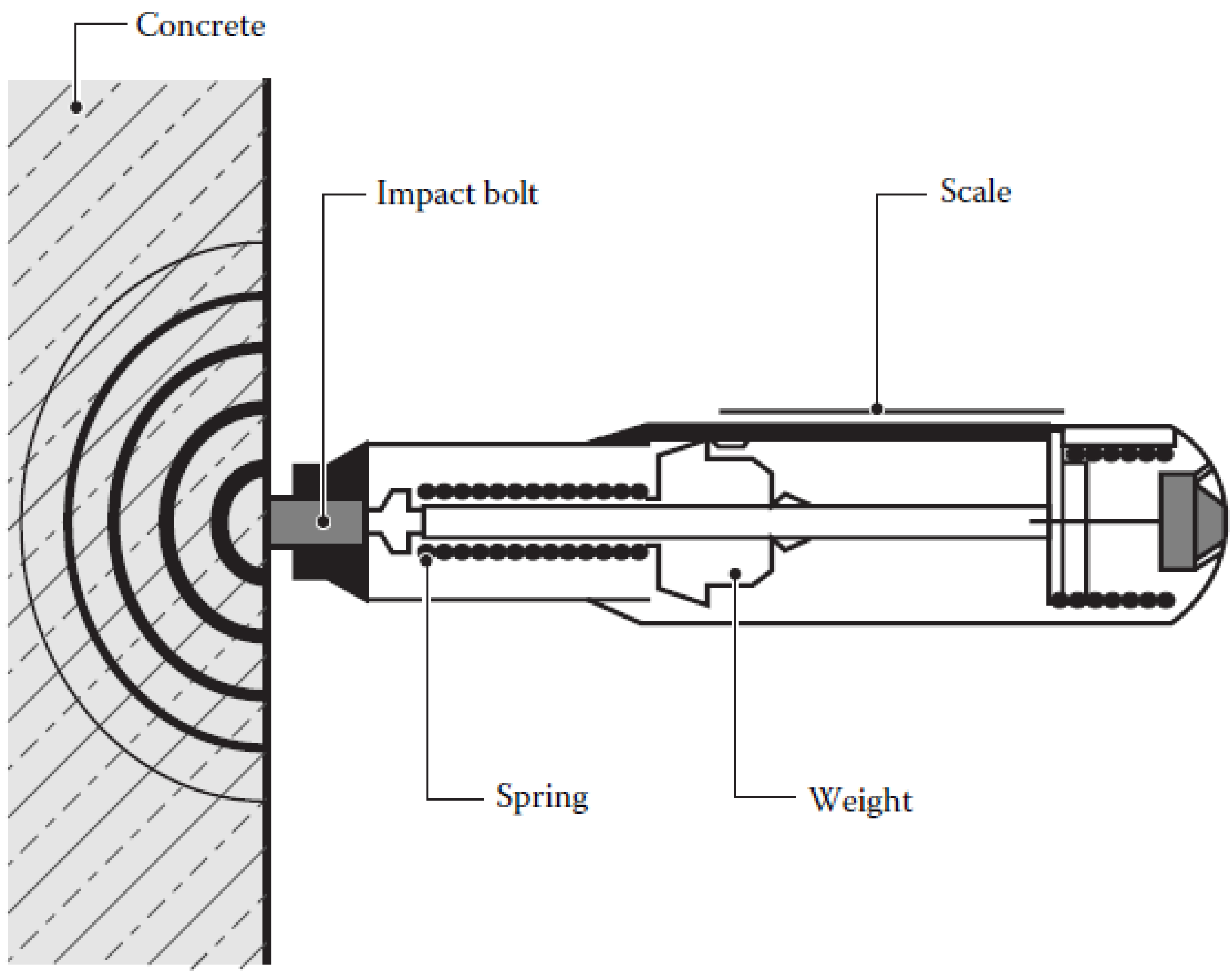
Aggregate strength becomes more significant for HSC.

Crushed rock aggregates usually provide higher strength.

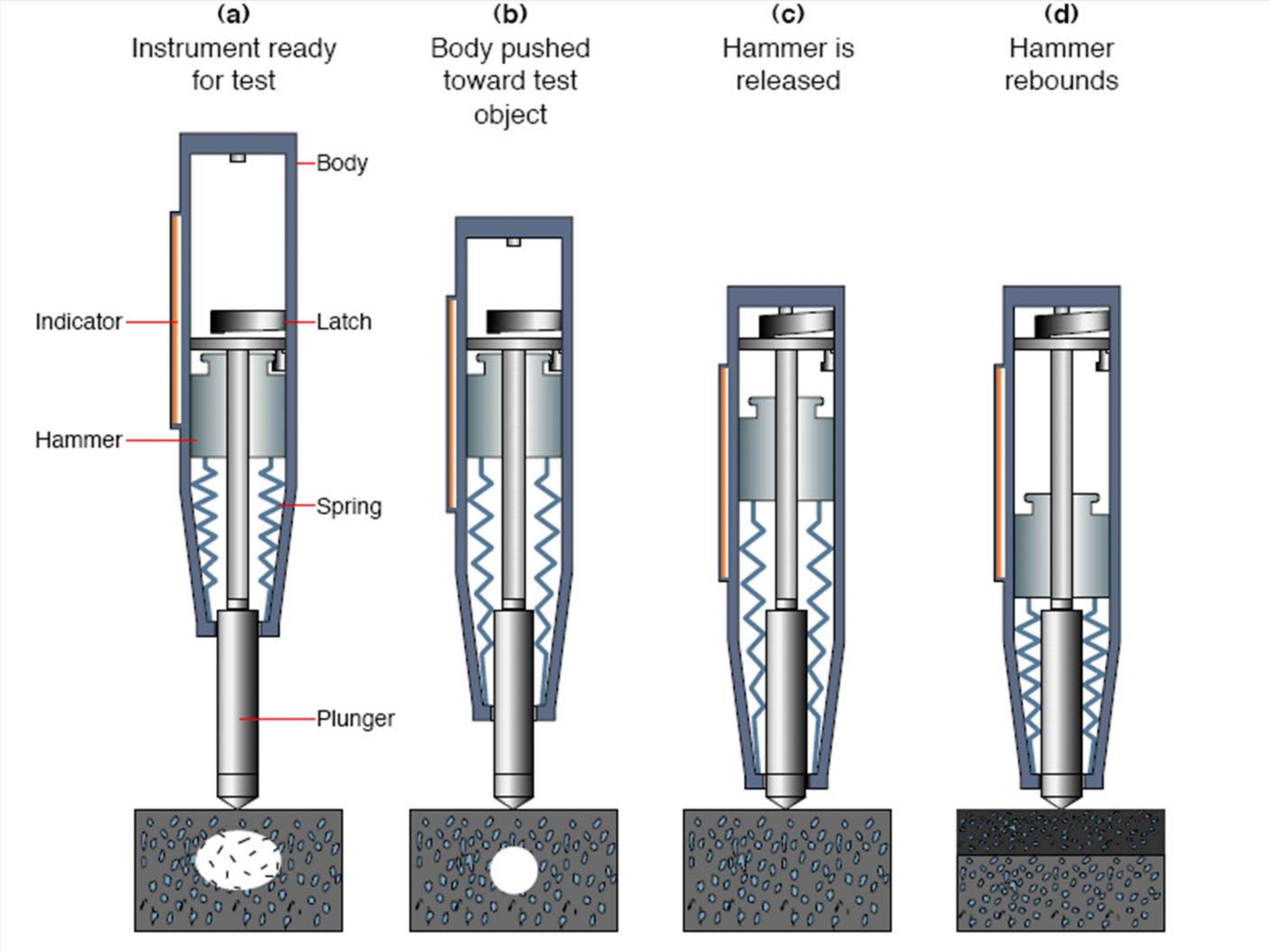
Non-Destructive Strength Tests /NDT/

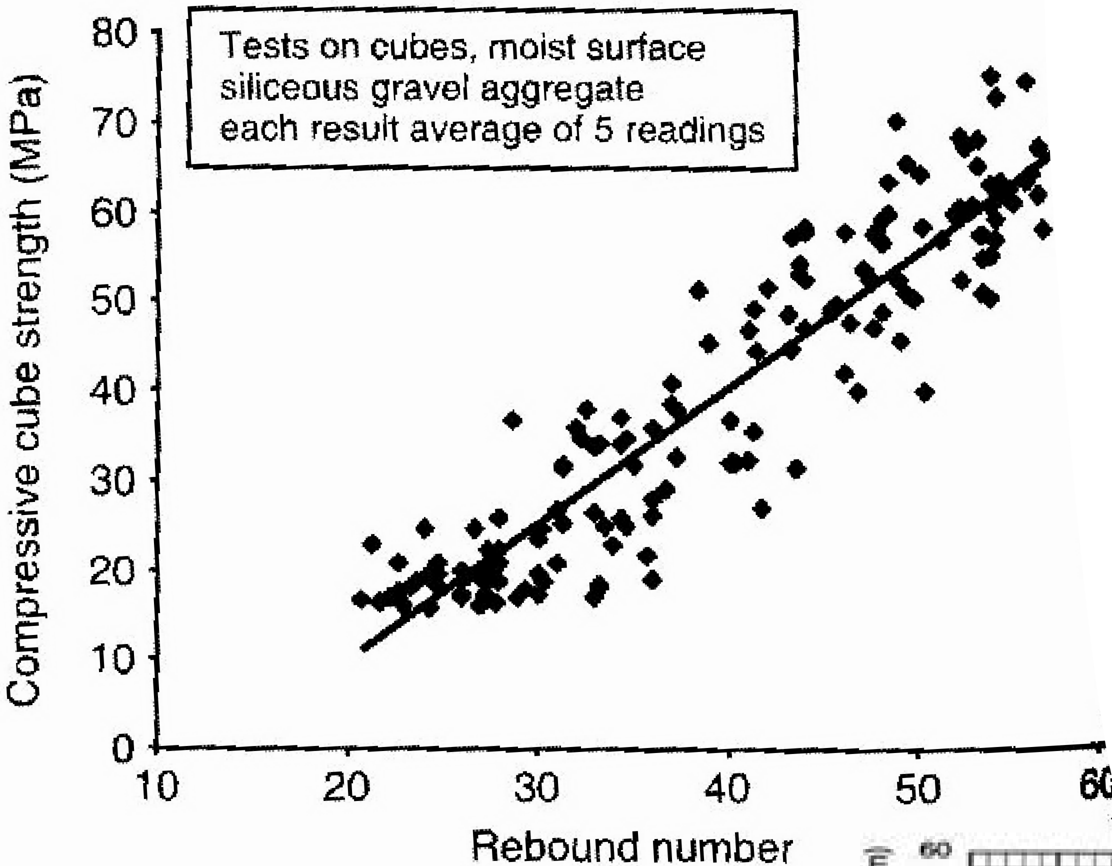
Surface Hardness – rebound (Schmidt) hammer test

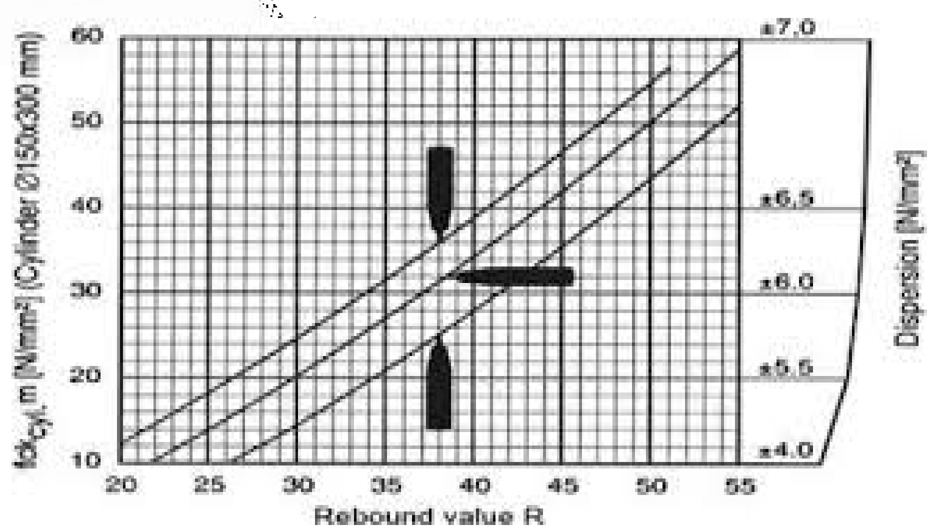




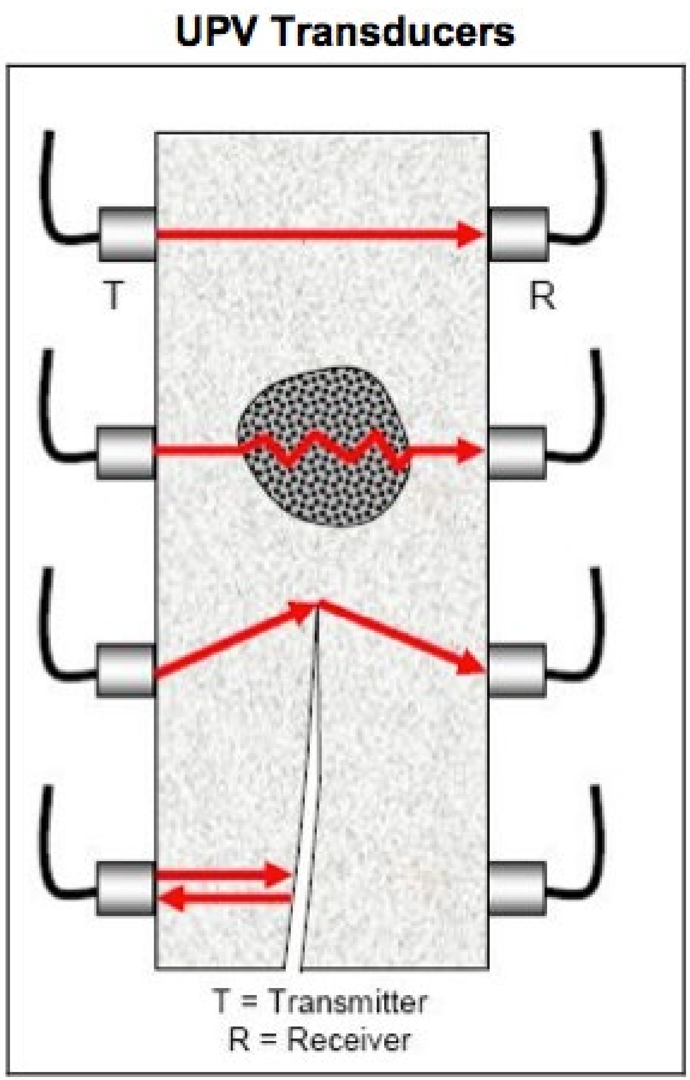
Generally the minimum thickness of the building part has to be 100 mm, and the testing area has to be at least 300 × 300 mm². Each area has to be tested with nine single strikes. The median value then represents the rebound value for this specific test area.

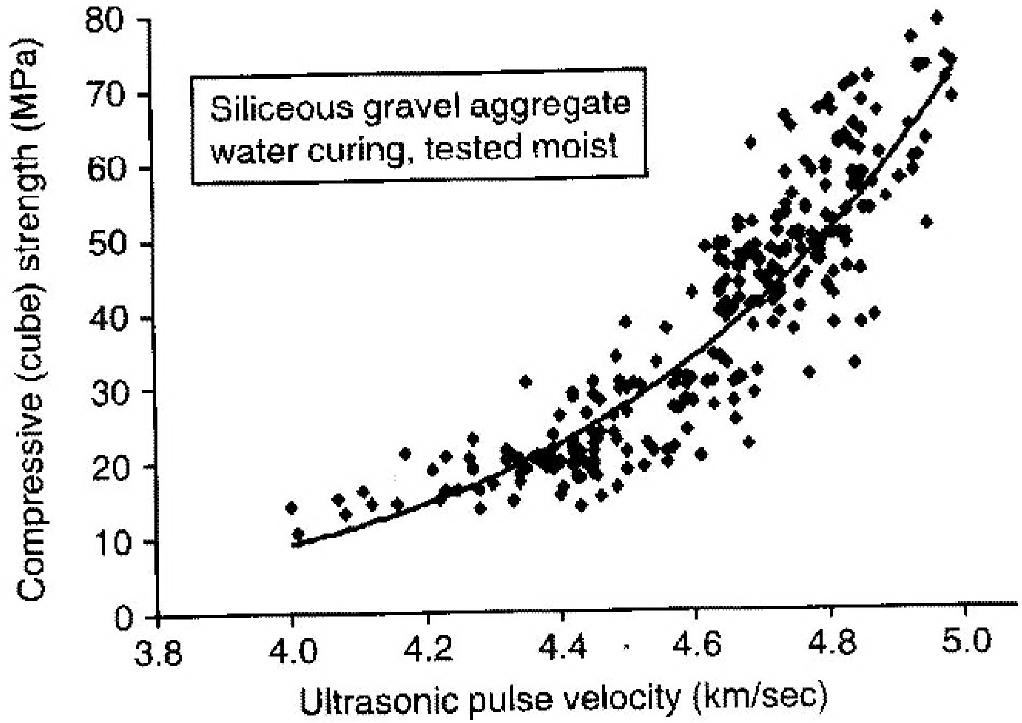

(a)
Instrument ready for test
(b)
Body pushed toward test object
(c)
Hammer is released
(d)
Hammer rebounds
Body
Indicator
Latch
Hammer
Spring
Plunger


Tests on cubes, moist surface
siliceous gravel aggregate
each result average of 5 readings
Compressive cube strength (MPa)
0
10
20
30
40
50
60
70
80
10
20
30
40
50
60
Rebound number


fck,cyl, m [N/mm²] (Cylinder Ø150x300 mm)
10
20
30
40
50
60
20
25
30
35
40
45
50
55
Rebound value R
±7.0
±6.5
±6.0
±5.5
±4.0
Dispersion [N/mm²]

Ultrasound Pulse Velocity (UPV) test





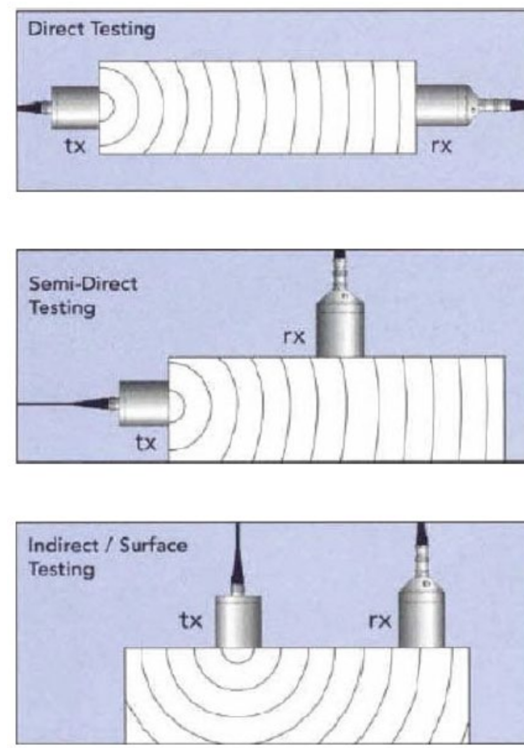
• An electrical pulse generator (peak voltage from 150 V to 1000 V) and amplifier for the wave,
• Transmitter transducer (mostly piezoelectric sometimes without contact).
• Receiver transducer (only one or several on a line to be precise on the distance value)


NDT
JAMES INSTRUMENTS
Non Destructive Test Equipment

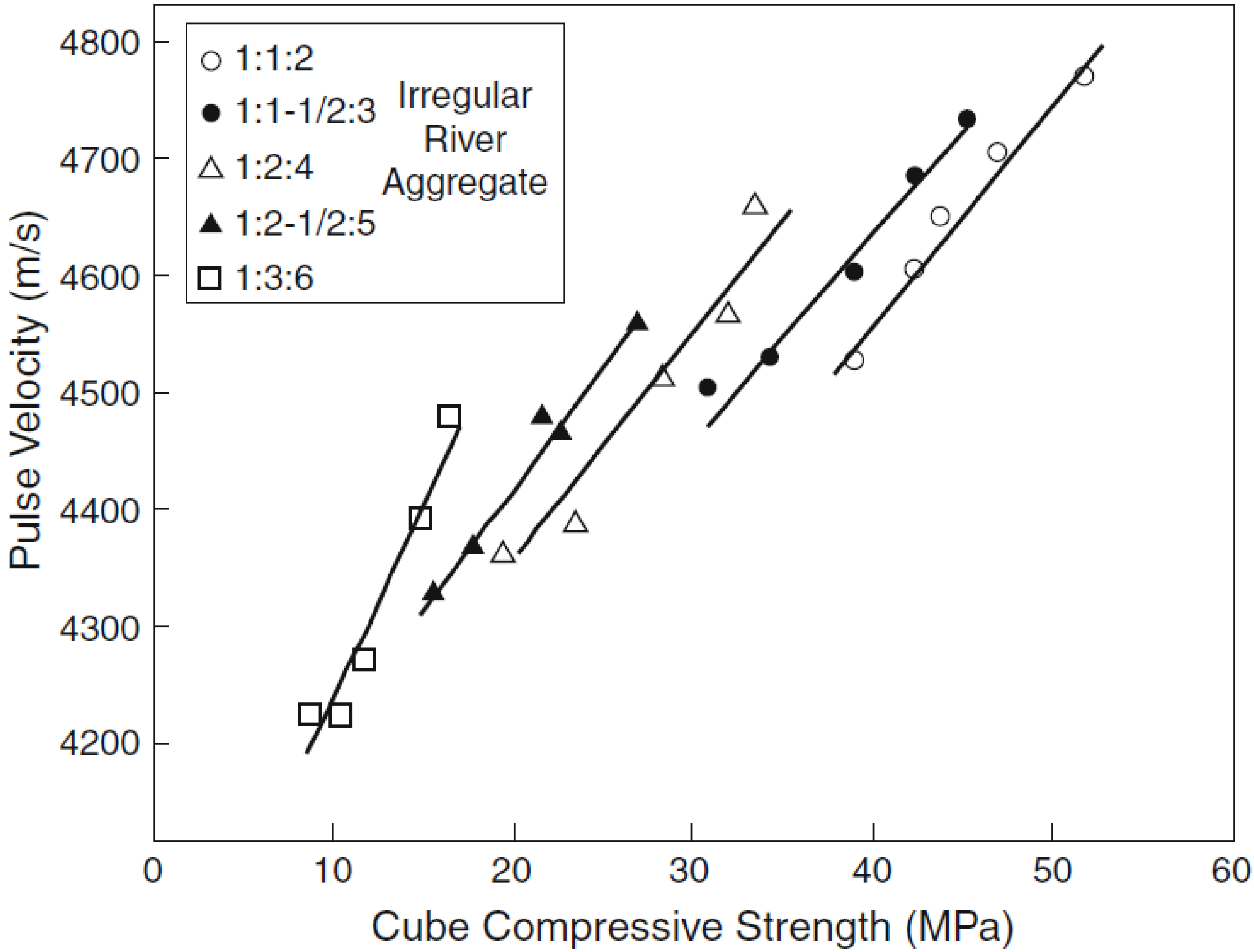
To estimate the material properties, the relationships between elastic constants and the velocity of respectively ultrasonic pressure wave (VL) and shear wave (VT) are derived from equations in an isotropic elastic medium of infinite dimensions:

$$V_L = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad V_T = \sqrt{\frac{E_d}{2\rho(1+\nu)}}$$

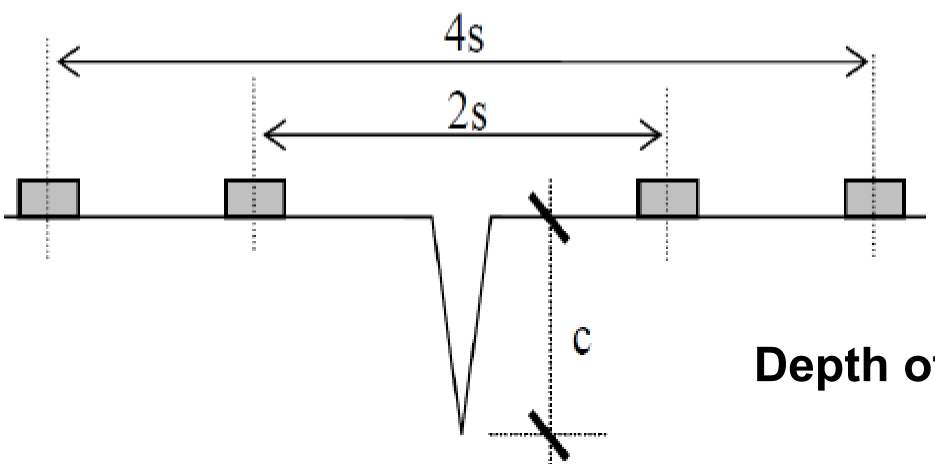
E_d = the dynamic elastic modulus (MPa)
ν = the dynamic Poisson's ratio.
ρ = the density (kg/m^3).
V_L = the pressure (longitudinal) wave velocity (km/s).
V_T = the shear wave (transversal) velocity (km/s).



Concrete condition	P-wave velocity (100 kHz)
Damaged	velocity < 3000 m/s
Sound	velocity > 4500 m/s



Effect of aggregate to cement ratio on the relationship between pulse velocity and compressive strength (after [Naik et al., 2004]

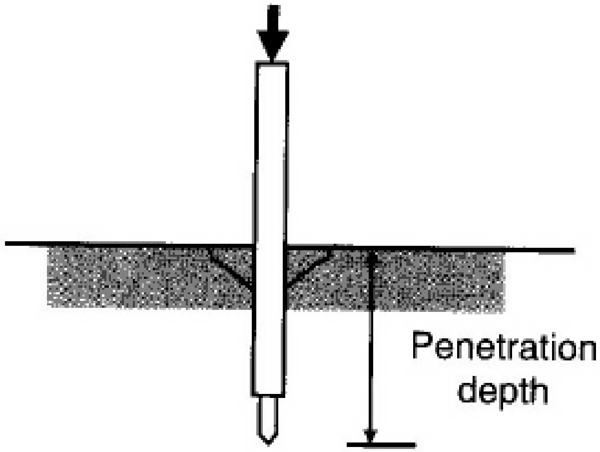


Depth of cracks

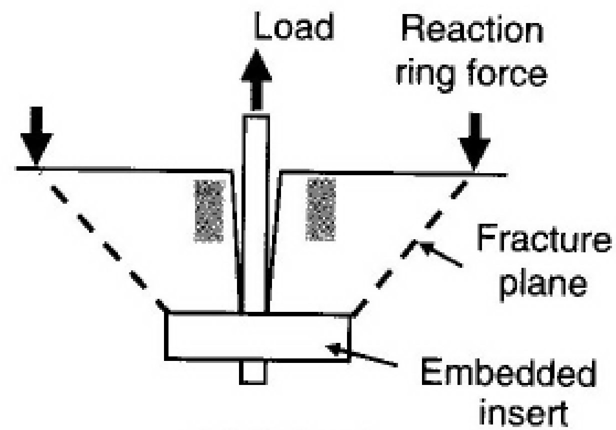
$$c = \sqrt{\frac{\left[4 - \left(\frac{t_2}{t_1}\right)^2\right] \cdot s^2}{\left(\frac{t_2}{t_1}\right)^2 - 1}}$$

Other tests

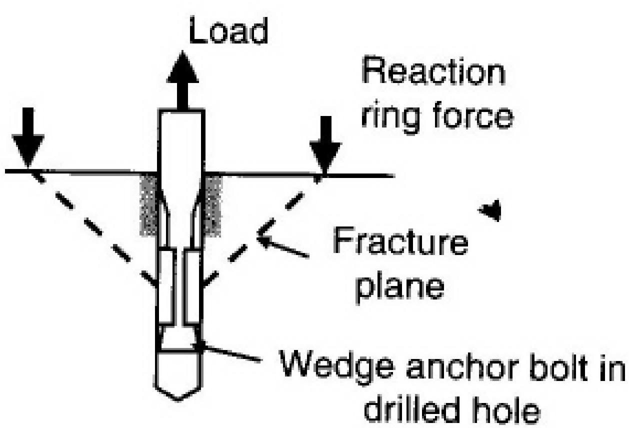
(semi-destructive)



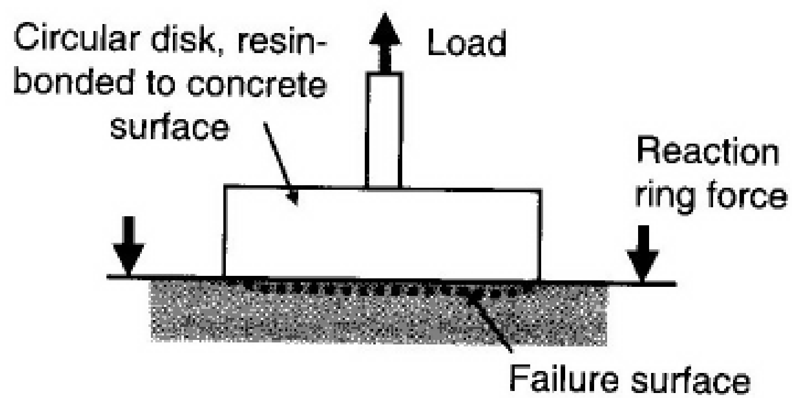
(a) Penetration resistance



(b) Pull-out

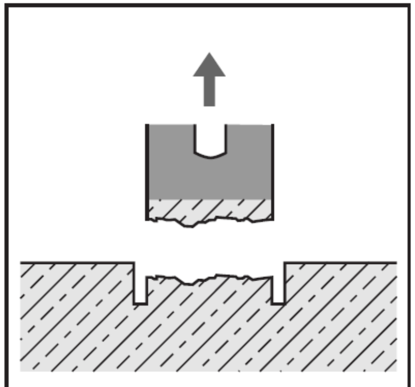


(c) Internal fracture

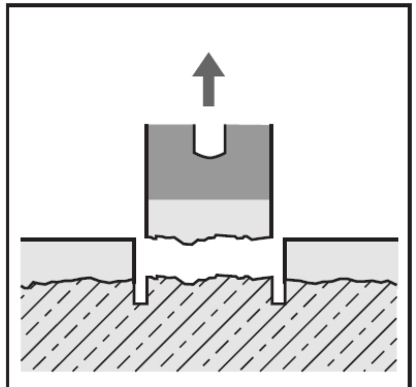


(d) Pull-off

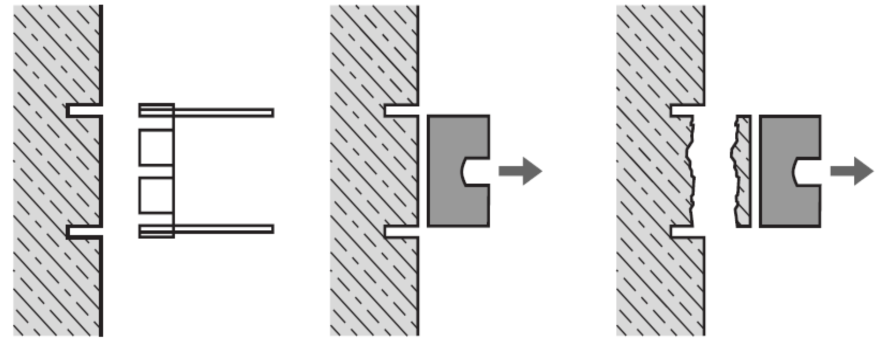
Surface strength



Determination
of the surface strength



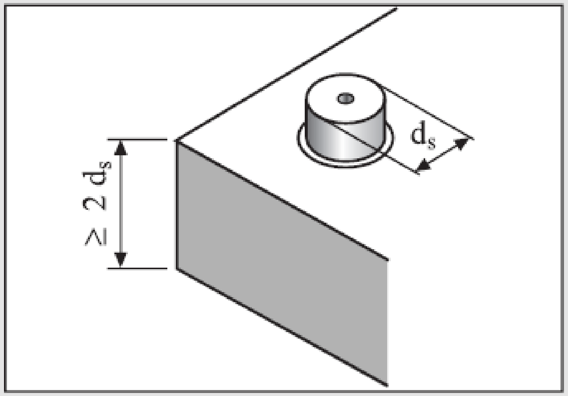
Determination
of the adhesion strength



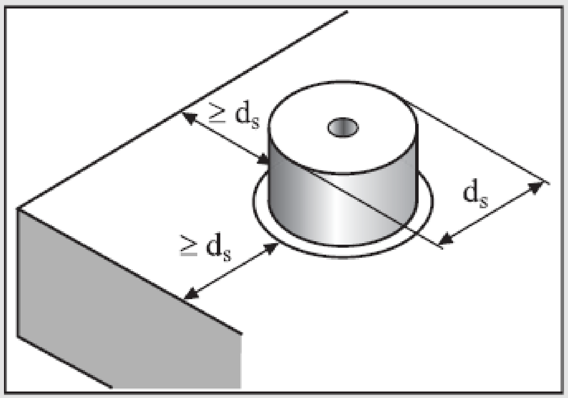
Steps

- Drilling of a cylindrical nut with a diameter of 50 mm and a depth of at least 10 mm into the substrate
- Applying a steel die with a reactive adhesive, e.g., (sand-filled) epoxy resin
- Cleaning of the nut so that no adhesive is in the groove and falsifies the result
- Adapting of the test rig to the steel die and performing an uniaxial tension test with a load rate of 100 N/s (concrete surfaces or stiff surface coatings) or 300 N/s (elastic surface coatings)
- Calculating of the tensile strength as well as judging the type of rupture in percentiles of the entire cross section of the die

Dyna Pull-off tester

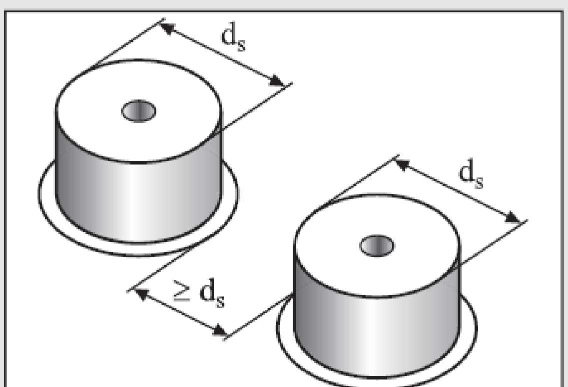


Depth of specimen or building member $\geq 2 \cdot d_s$



Distance of groove from edge of specimen $\geq d_s$

(if no groove is present
→ distance $\geq 1.5 \cdot d_s$)



Distance between each test area ^{3} d_s

(if no groove is present
→ distance $\geq 1.5 \cdot d_s$)

DIAGNOSTICS OF STRUCTURES

LECTURE 03

Reliability assessment of existing concrete structures based on non-destructive test data – Part1

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DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Related Terms

Reliability: ability of a structure or structural member to **fulfil the specified requirements**, during the working life, for which it has been designed.

- Reliability is often expressed in terms of probability.
- Reliability covers **safety, serviceability, and durability** (ISO 2394)

Structural safety: ability (of a structure or structural member) **to avoid exceedance of ultimate limit states**, including the effects of specified accidental phenomena, with a specified level of reliability, during a specified period of time (ISO 2394).

Assessment: a set of activities performed in order **to verify the reliability of an existing structure** for future use.

Steps of Assessment

1. **Specification of the assessment objectives**

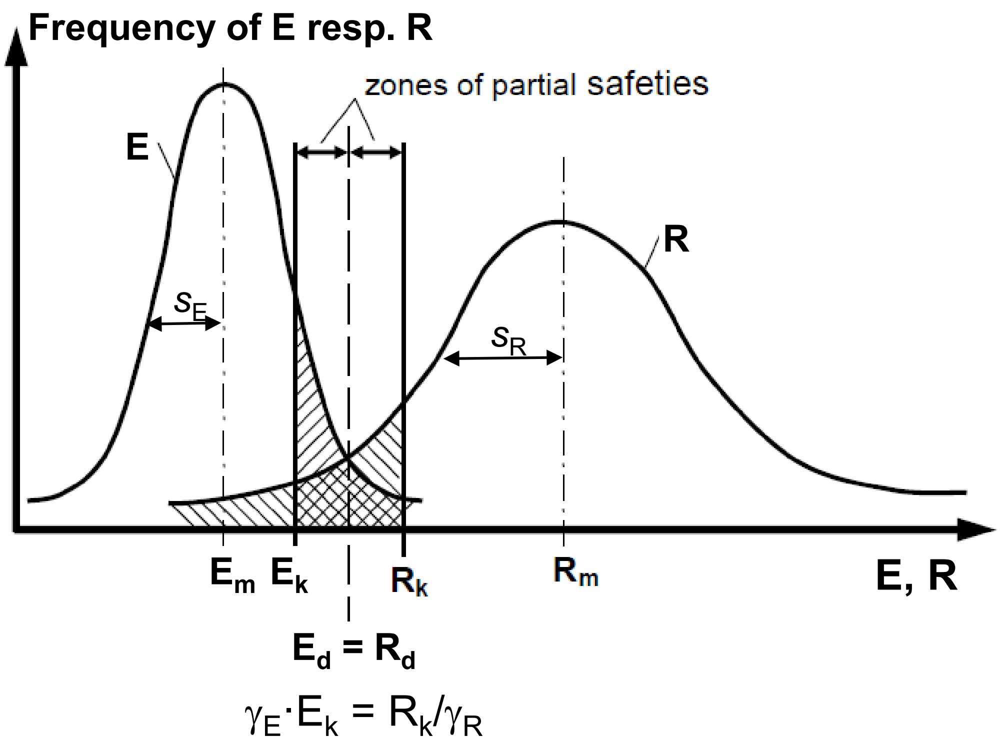
2. **Preliminary assessment**
   - study of available documentation;
   - preliminary inspection;
   - decision on immediate actions;
   - recommendation for detailed assessment;

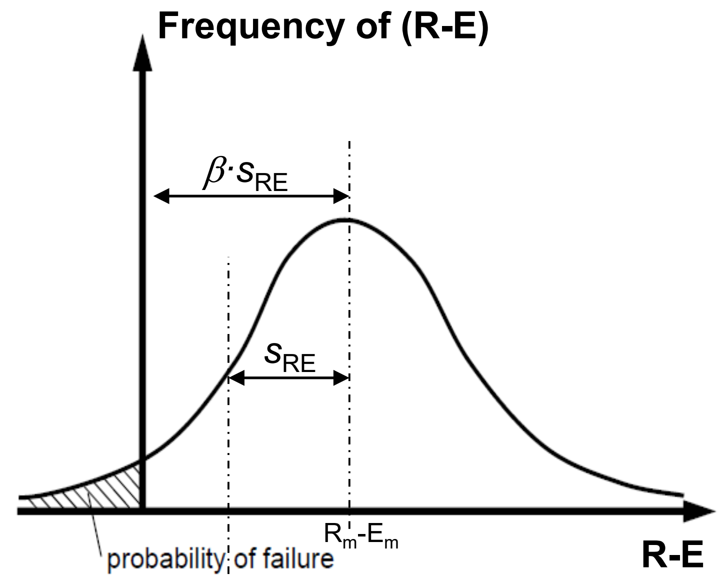
3. **Detailed assessment**
   - detailed documentary search;
   - detailed inspection;
   - material testing and determination of actions;
   - determination of structural properties;
   - structural analysis;
   - verification of structural reliability;

4. **Report including proposal for intervention**

Interpretation of Reliability

When R – E becomes < 0 ⇒ failure of the structure





(p_f)

$$\beta_{RE} = \frac{R_m - E_m}{s_{RE}}$$

$$s_{RE} = \sqrt{s_R^2 + s_E^2}$$

Reliability: M=1-p_f β= - $\Phi^{-1}(p_f)$ reliability index

Target reliability levels defined in ISO 2394 (for new structures)

$\beta = \beta_{opt}$ (based on the optimisation of overall cost)

Limit states	Target reliability index β	Reference period
Serviceability		
Reversible	0,0	Intended remaining working life
Irreversible	1,5	Intended remaining working life
Fatigue		
Inspectable	2,3	Intended remaining working life
Not inspectable	3,1	Intended remaining working life
Ultimate		
Very low consequences of failure	2,3	L_S years[a]
Low consequence of failure	3,1	L_S years[a]
Medium consequence of failure	3,8	L_S years[a]
High consequence of failure	4,3	L_S years[a]

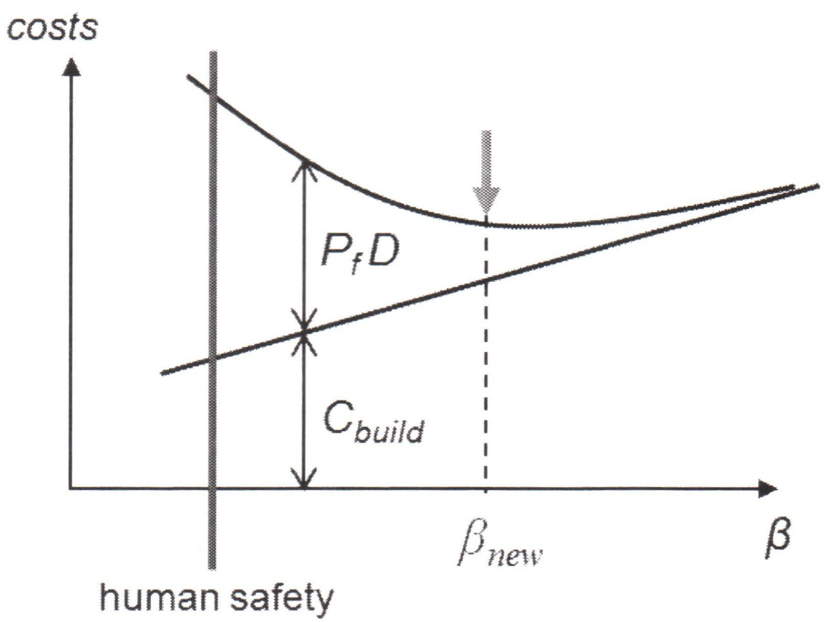
[a] L_S is a minimum standard period for safety (e.g. 50 years).

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,3	2,3	3,1	3,7	4,2	4,7	5,2

Target reliability levels for existing structures

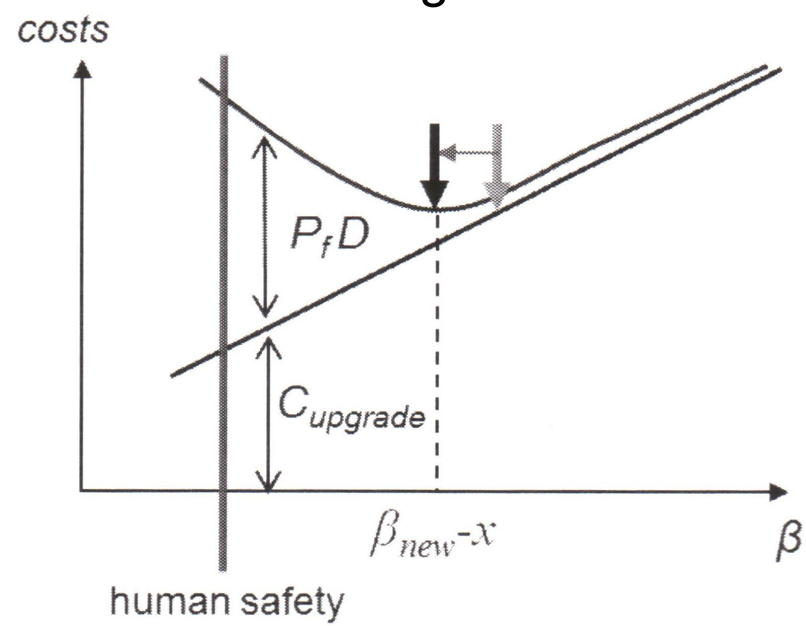
The optimum target reliability level for existing structures can be different from values defined for newly built stuctures

new structure



β_0=2,3

existing structure



β_0=2,3

Tests for Assessment

- Structural behaviour should be analysed using models that describe actual situation and state of the structure.

- Analysis is based on variables (input parameters)

  - Material characteristics
  - Structural characteristics
  - Deterioration processes
  - Effects

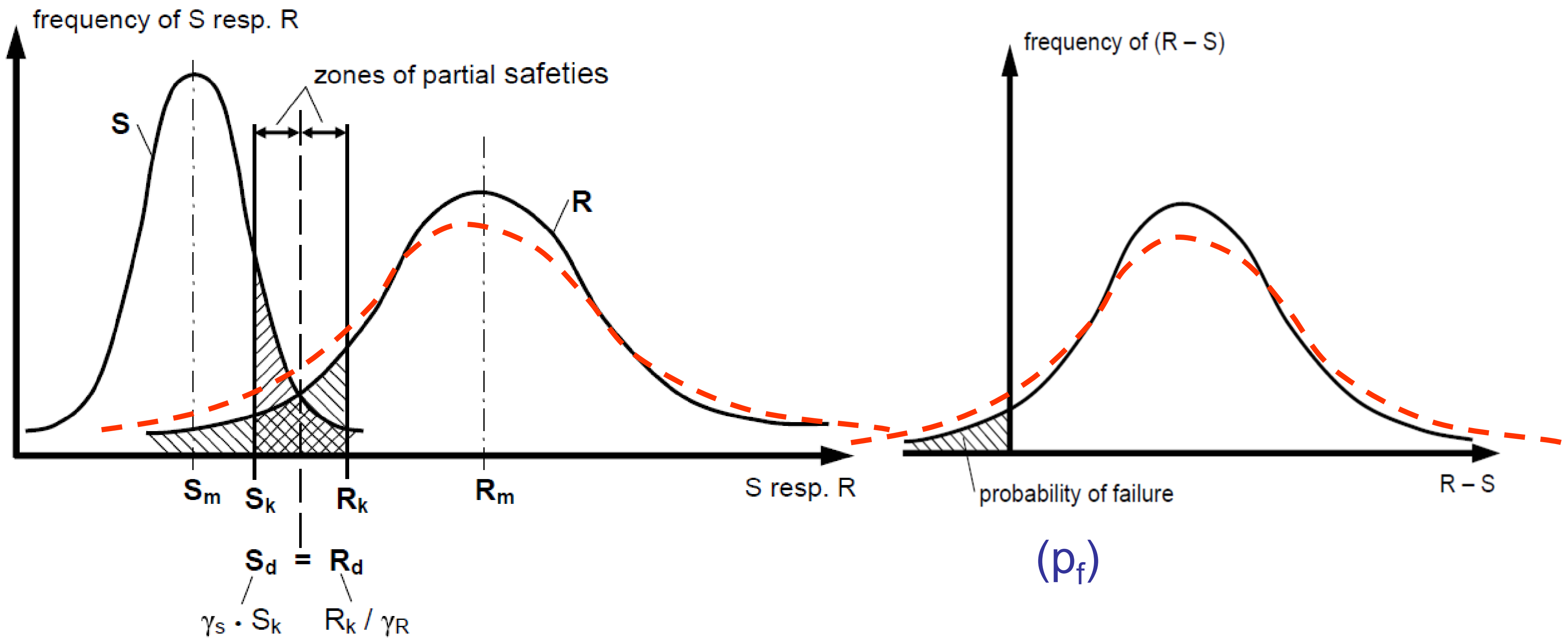
UNCERTAINTY!

- Tests should verify in place material condition, damage state, position and geometry of elements, and other important structural characteristics.

Handling Uncertainty

The uncertainty associated with the validity and accuracy of the models should be considered during assessment of existing structures.

Larger uncertainty results in larger probability of failure



Handling Uncertainty

Sources of uncertainty

- **Inherent random variability (e.g. action parameters)**
- **Uncertainty due to inadequate knowledge (e.g. structural model)**
- **Statistical uncertainty (e.g. material parameters)**

Uncertainties can normally be decreased by increasing test and observational efforts

The use of inspection & test data to update assessment

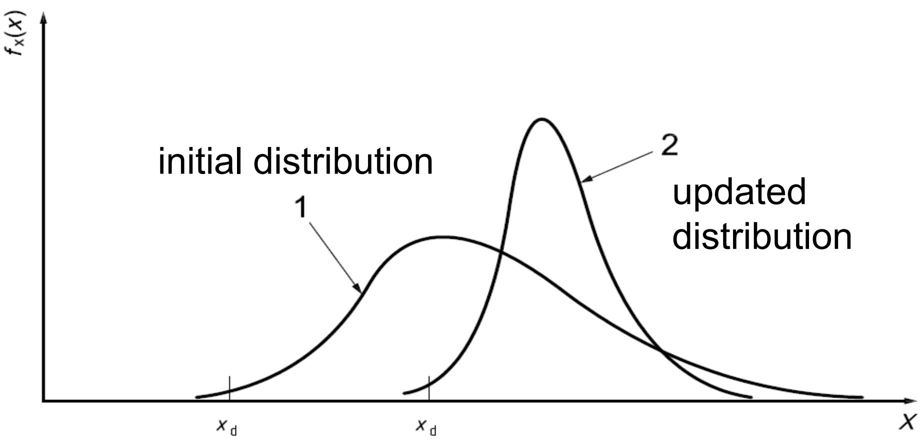
Using results of an investigation (qualitative inspection, quantitative inspection, proof loading) the properties and reliability estimates of the structure may be updated.

(1) Updating of the structural failure probability:
(by additional information from investigation)

$$\mathrm{P}(F|I) = \frac{\mathrm{P}(F \cap I)}{\mathrm{P}(I)}$$

P probability,
F local or global failure,
I inspection information,
$\cap$ intersection of two events.

(2) Updating of the probability distributions of basic variables (X_i):



$$x_\mathrm{d} = \mu\left(1 - \alpha\beta V\right)$$

x_d updated design value for X,
μ **updated mean value,**
α probabilistic influence coefficient,
β target reliability index,
V **updated coefficient of variation.**

DIAGNOSTICS OF STRUCTURES

LECTURE 04

Reliability assessment of existing concrete structures based on non-destructive test data – Part2

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STRUCTURAL
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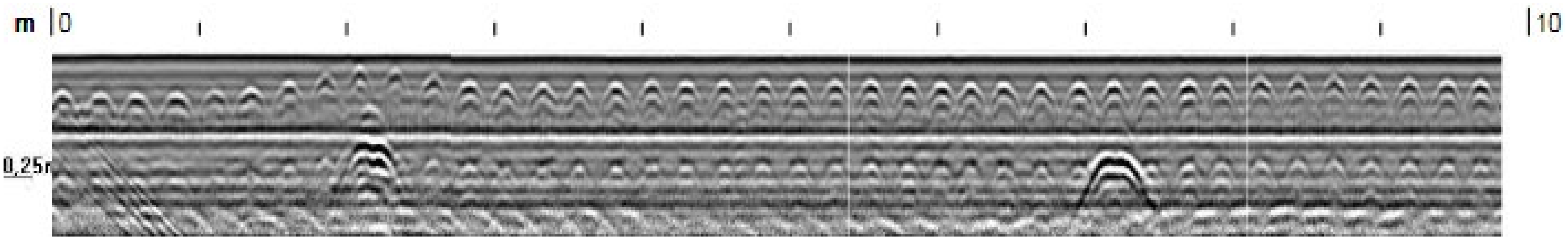
NDT methods for concrete structures

Tested parameter	(Some) Possible methods
Concrete quality, cracks, defects, voids	Visual inspection, Acoustic emission (AE), Impact echo, Impulse response, Ultrasonic, Radiography, Endoscopy
Compressive strength, surface hardness, adhesion	Rebound hammer, Ultrasonic pulse velocity (UPV), CAPO test, Microcoring, Pull off test
Corrosion rate, corrosion progress	Linear polarization resistance (LPR), Half-cell potential, X-Ray diffraction and atomic absorption, Galvanostatic pulse method
Carbonation depth, pH of concrete	Phenolphthalein indicator test, PH measurements on drill powder
Flaw detection, delamination	Vibration based damage identification (VBDI), Impact echo, Ground-Penetrating radar (GPR), endoscopy
Concrete cover, rebar diameter and location	Cover meter, Magnetic rebar locator, GPR
Structural dimensions	Impact echo, GPR, endoscopy

Requirements for NDT

- **to be able to detect defects** (roots of the problem, severity level, evolution)
  The mechanical properties of tomorrow depends on the deterioration process of today

- **to be able to build a hierarchy regarding a given property** (e.g. mapping stiffness, changes in dimensions…)**, between areas in a given structure or between structures**



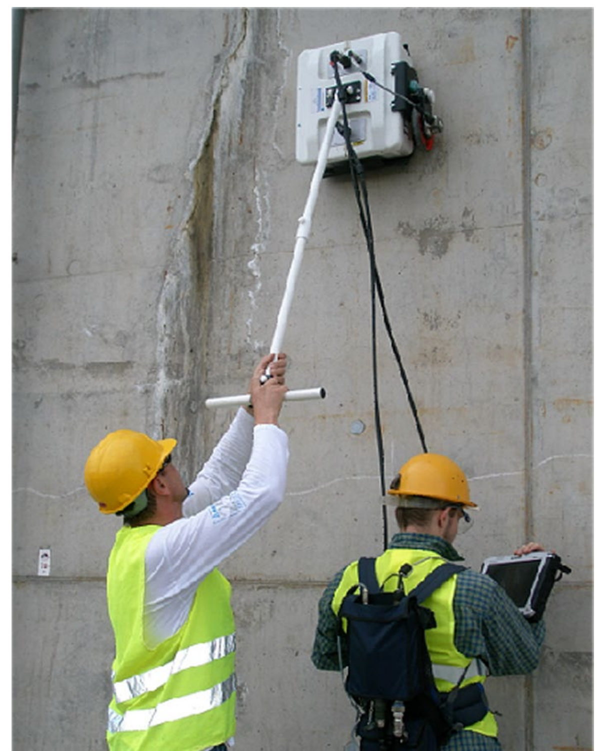
- **being able to quantify properties, e.g. comparing them with reference values** (e.g. expected strength or planned dimension).

Destructive tests vs. Non-Destructive Test methods

- **Provide direct information**
- **Only local information**

  (material as well as the damage level can be spatially variable)

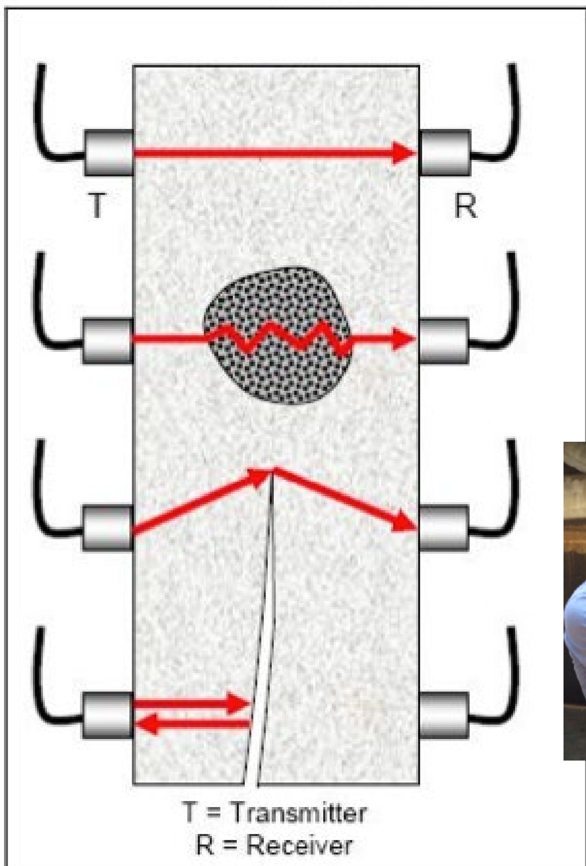
- **Provide indirect information**
- **Global information on the condition of the structure**

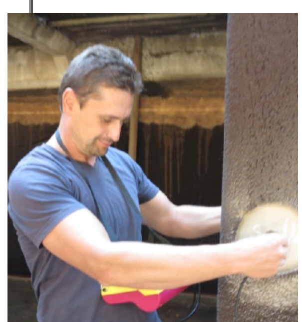


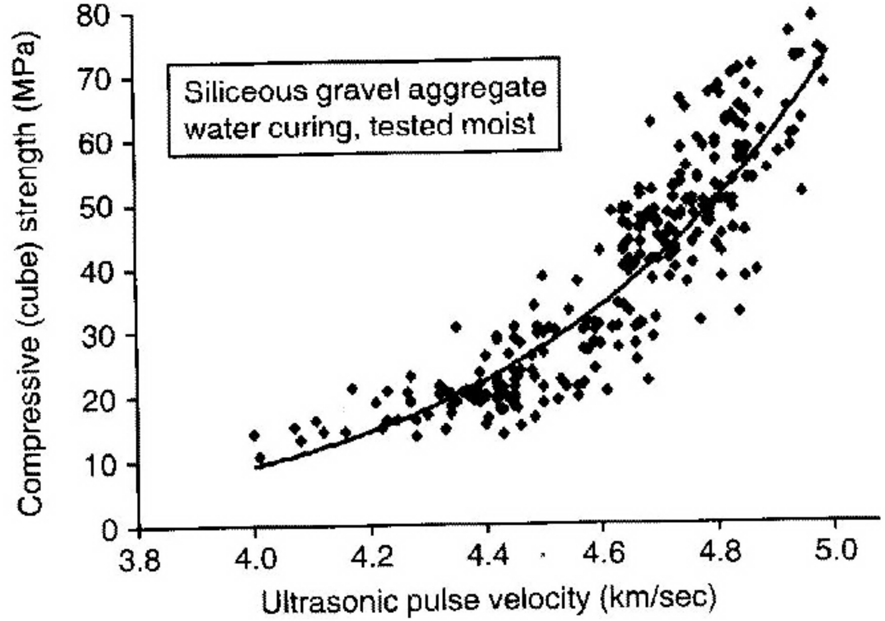
Non-Destructive Evaluation of strength properties

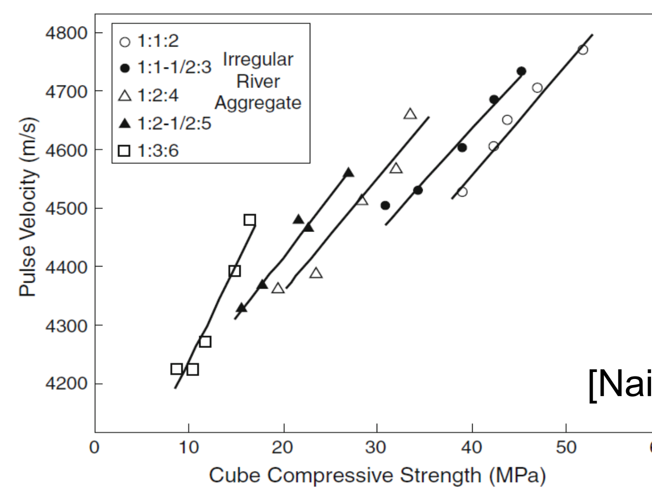
- **Ultrasonic Pulse Velocity**

UPV Transducers





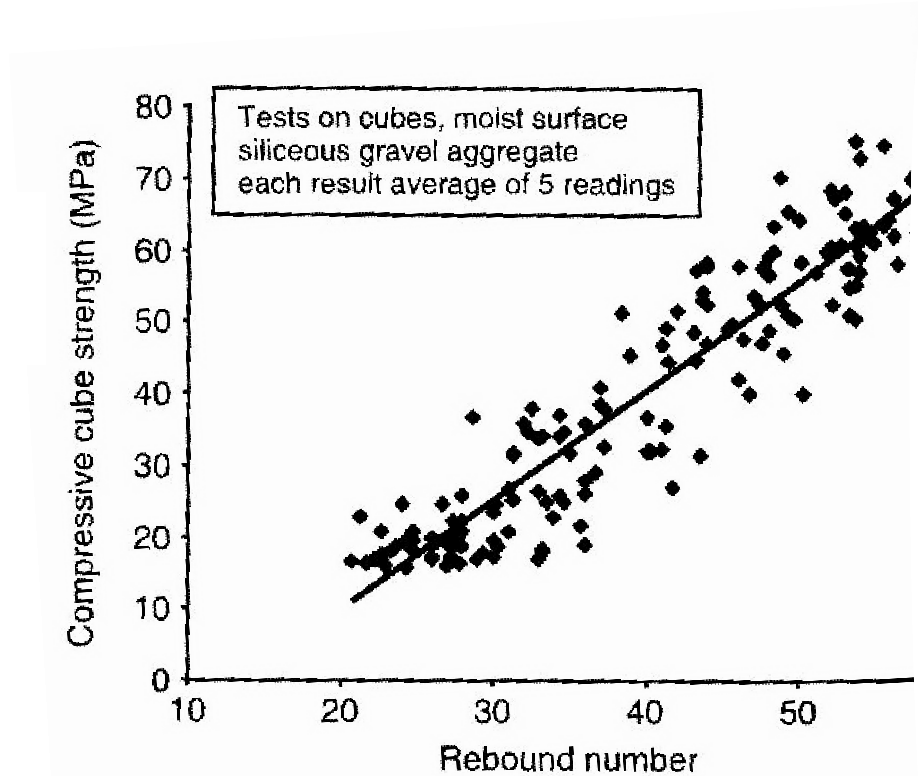


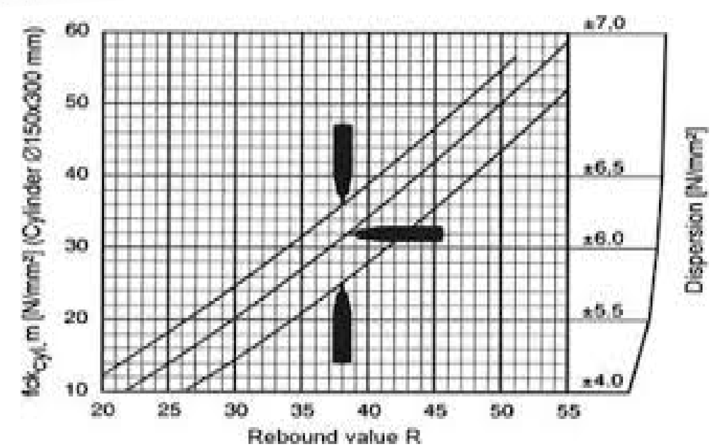


[Naik et al., 2004]

Non-Destructive Evaluation of strength properties

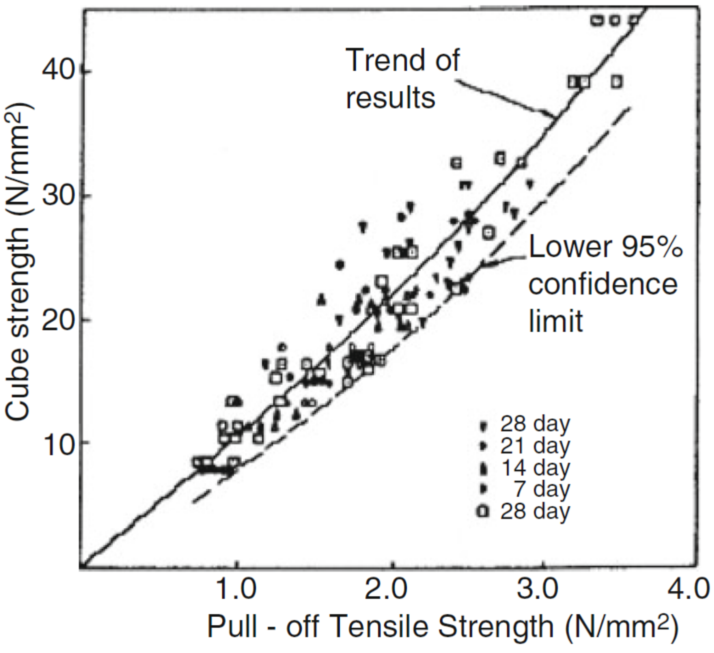
- **Rebound hammer**





Non-Destructive Evaluation of strength properties

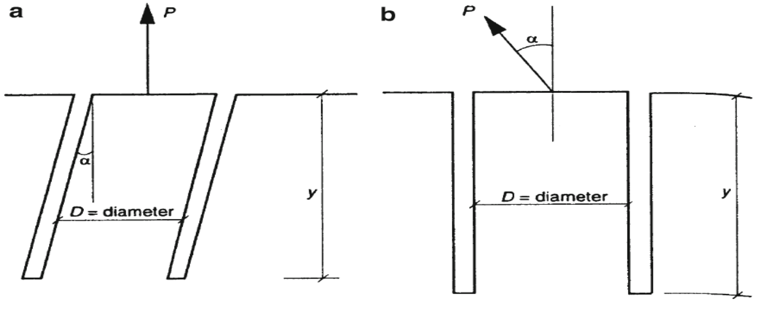
- **Pull-off tester (semi-destructive)**

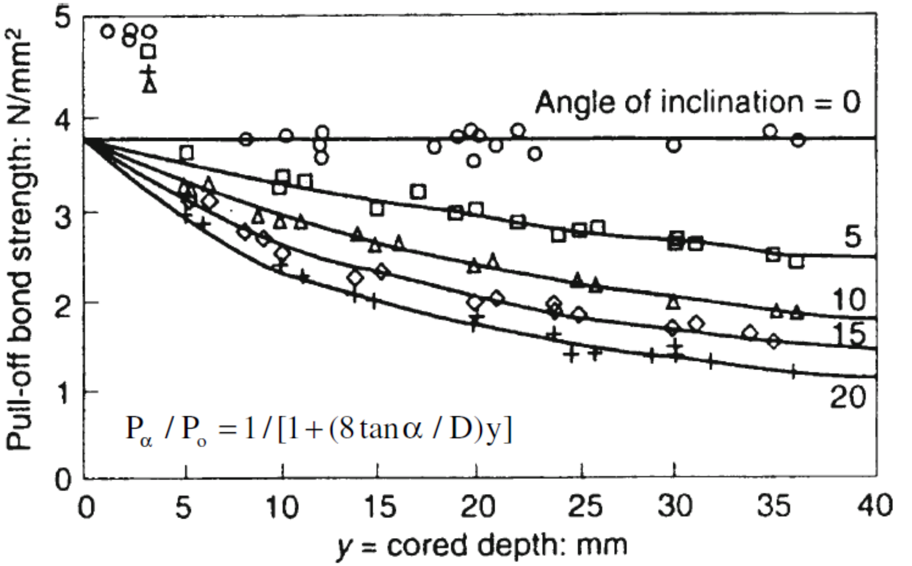


- Effect of the modulus of concrete

- Effect of the depth of partial coring

- Effect of the core perpendicularity





Combination of test methods

Benefit:

The combination of techniques can improve the accuracy of estimation of properties or help reduce time to reach an answer.

• Type [A]: comparison of results to confirm measurements and recorded variations

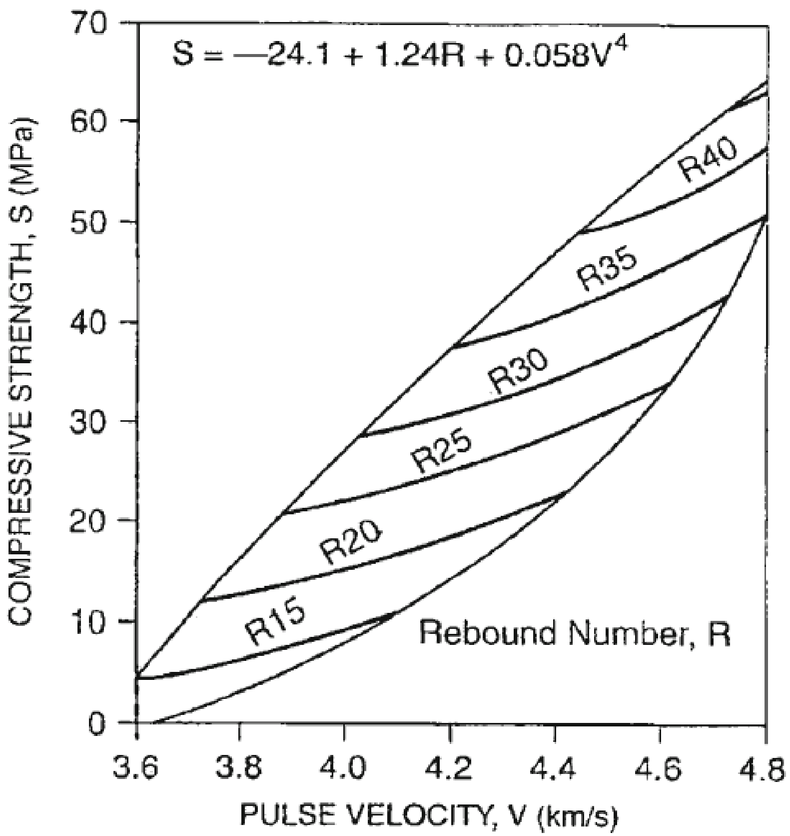
• Type [B]: comparison of results to improve the interpretation of results).

• Type [C]: use of a "quick" technique to have a first rough mapping, followed by a second "slow" technique in the areas selected in the first step.

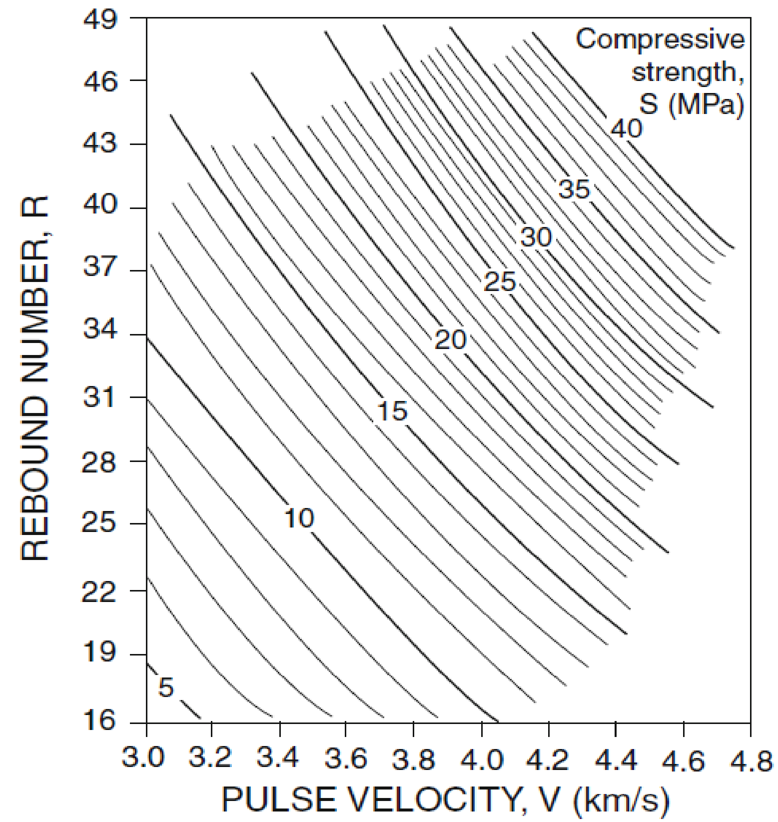
Non-Destructive Evaluation of strength properties

- **Combination of UPV and rebound hammer measurements**

$$f_c = f\,(UPV,R) = a\ UPV^b R^c$$

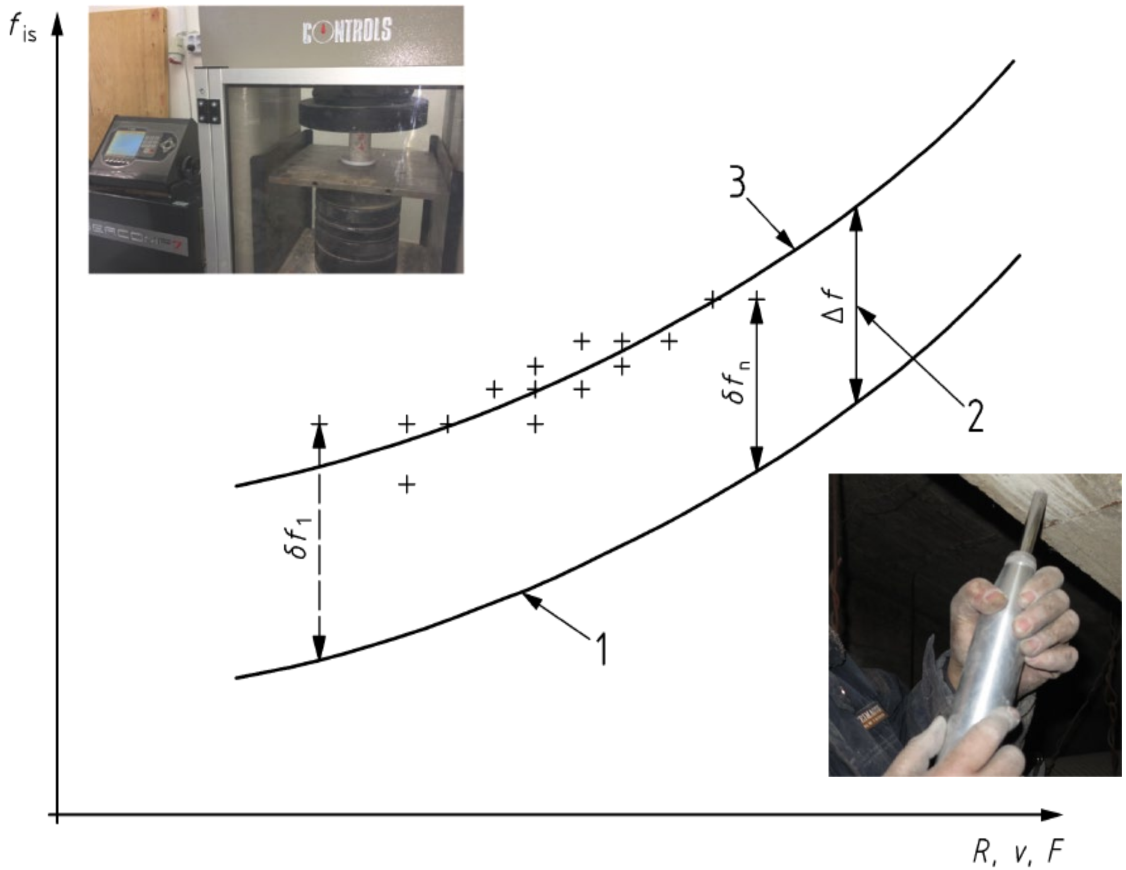


[Australian method IAEA, 2002]



[RILEM Committee TC 43]

Principle for improving the relationship between in-situ compressive strength and indirect test data



$$\delta f = f_{is} - f_{R,\,v}$$

$$\Delta f = \delta f_{m(n)} - k_1 \times s$$

Number of paired test results n	Coefficient k_1
9	1,67
10	1,62
11	1,58
12	1,55
13	1,52
14	1,50
≥15	1,48

1 Basic curve
$\delta f_{1\ldots n}$ Difference between the individual core strength and the strength value according to the basic relationship
2 Δf Shift of the basic curve
3 Relationship between the indirect test method and in-situ compressive strength for the Specific concrete under investigation

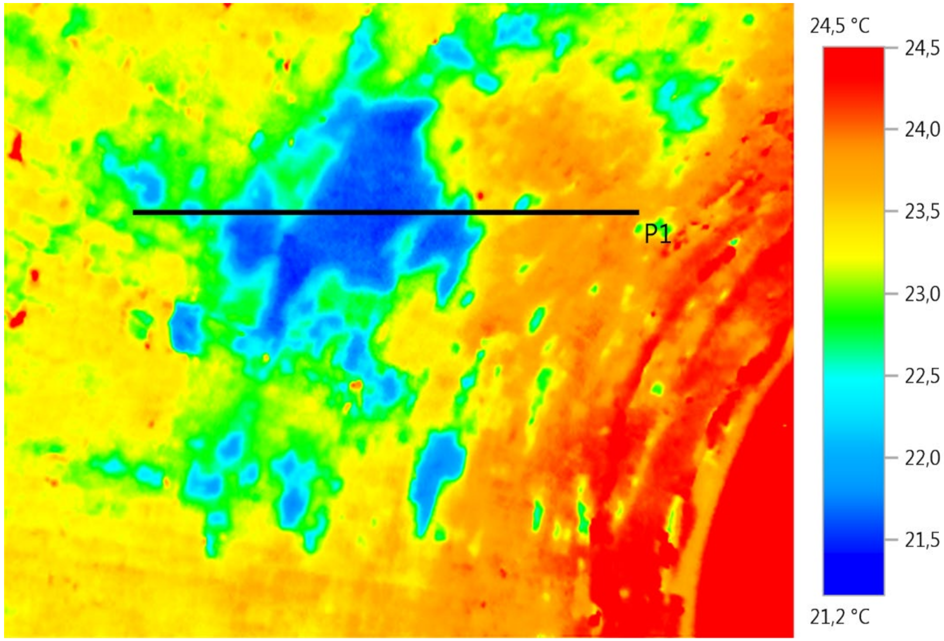
EN 13791

Water content (or moisture content) assessment

- **High value of water content can be the sign of poor quality concrete, and moisture content enables damage mechanisms**

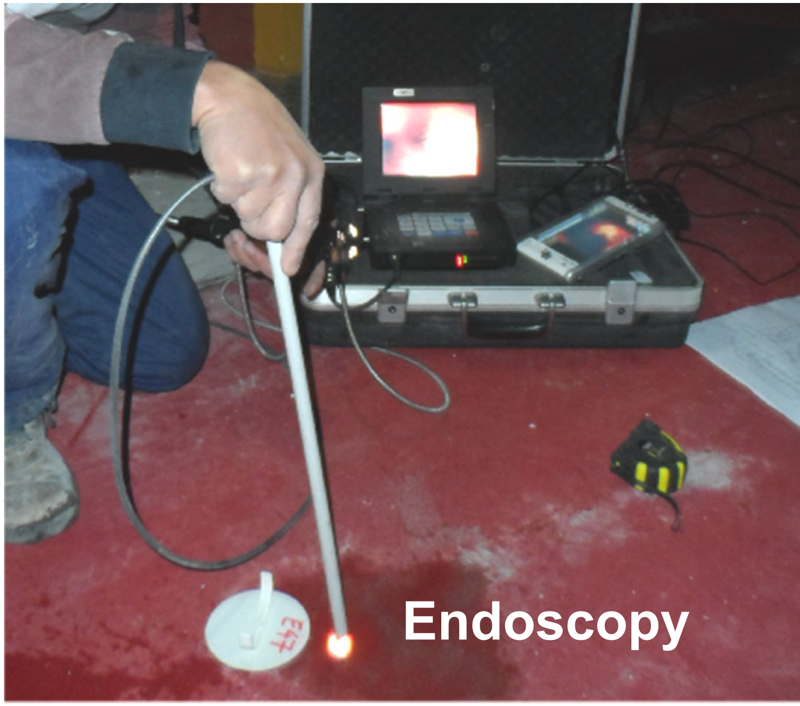
Many NDT methods are sensitive to mechanical parameters (e.g. Young's modulus) and to moisture content. Due this double dependency it is difficult determine the cause for the measured variations in the NDT parameter.

Electrical resistivity

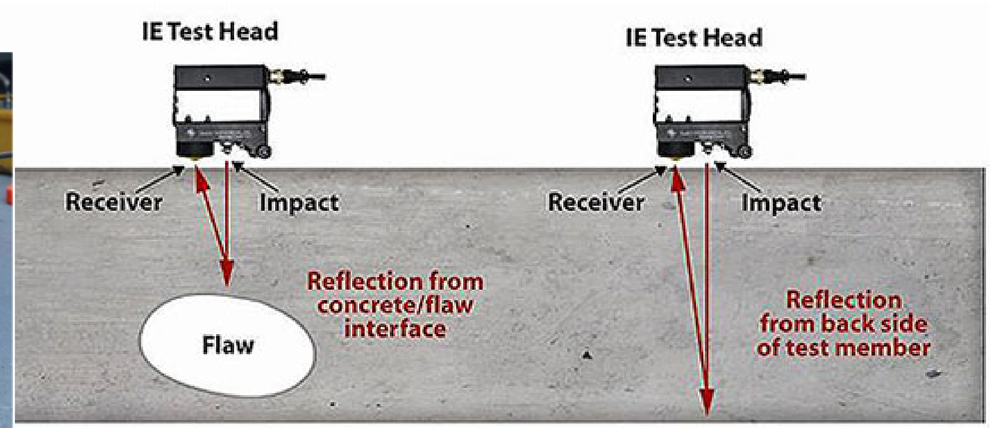


Infrared themography

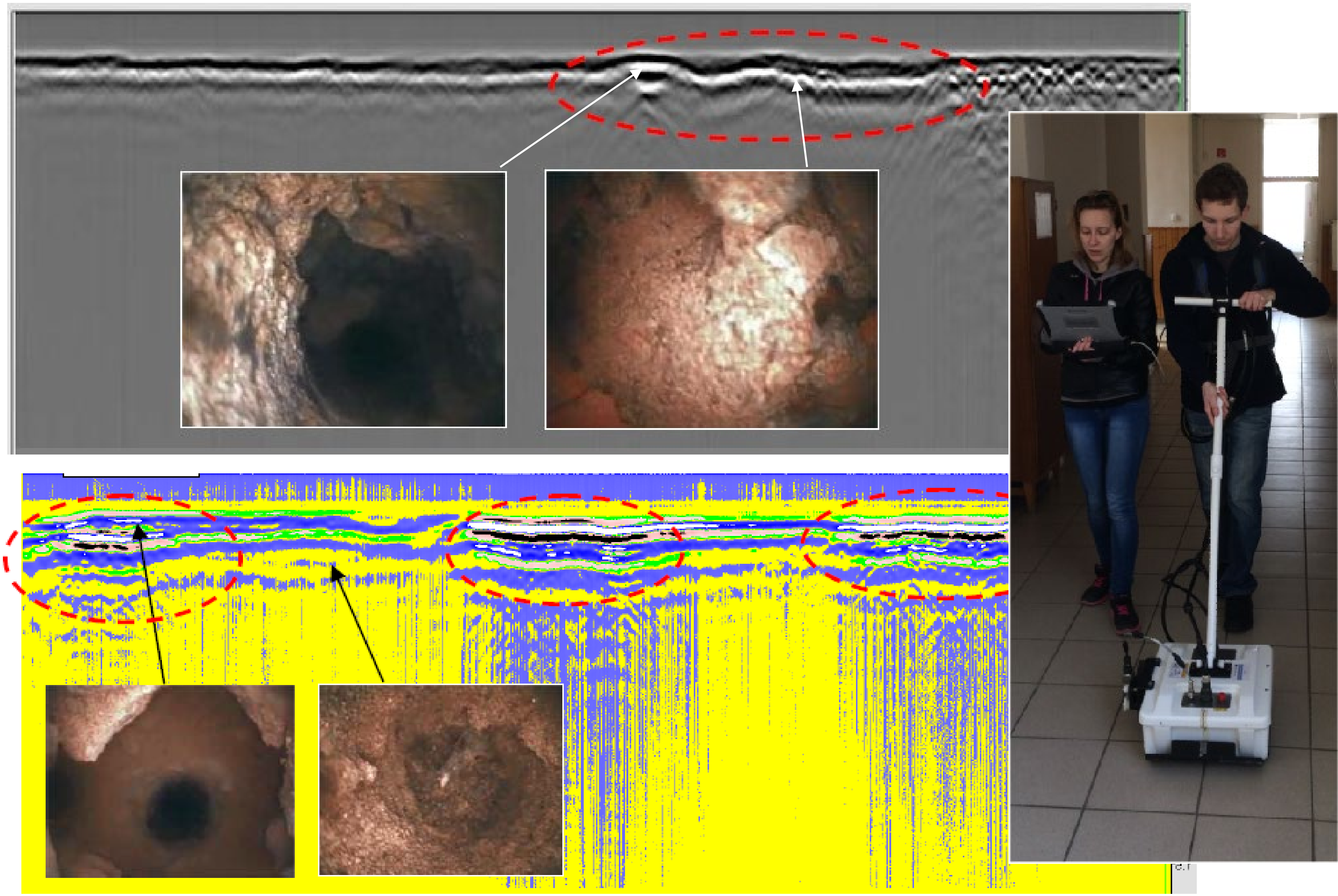
Measuring geometrical parameters, detecting defects



Impact Echo



Combination of georadar and endoscopy tests on concrete slab



Conclusions

- The optimum target reliability level for existing structures can be different from values defined for newly built stuctures

- Assessment of existing concrete structures is a cyclic process in which the preliminary assessment is often supplemented by subsequent detailed investigations and assessment.

- A well chosen combination of test methods can contribute to improved assessment of concrete structures.

DIAGNOSTICS OF STRUCTURES

LECTURE 05

Diagnostics of concrete industrial object
(case study)

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DIAGNOSTICS AND ASSESSMENT OF INDUSTRIAL FIRE-WATER RESERVOIR

Structural defects

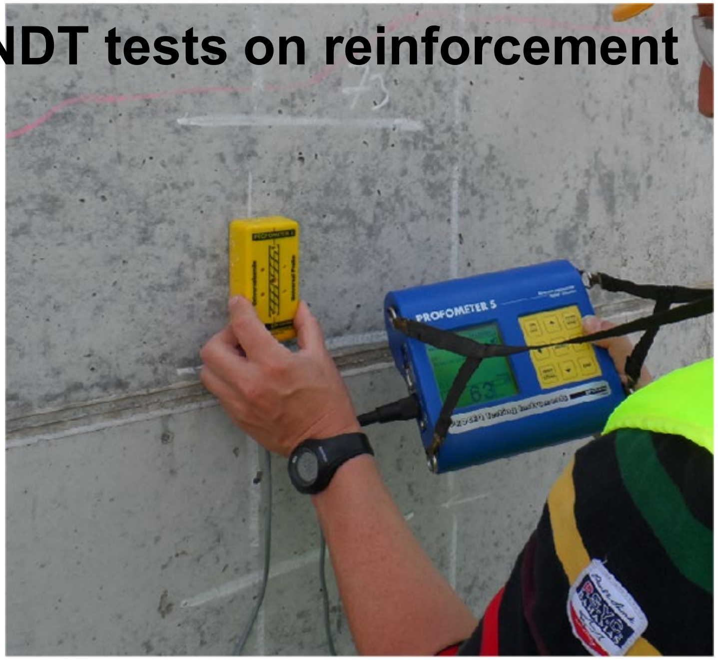

0,6
0,4
0,2

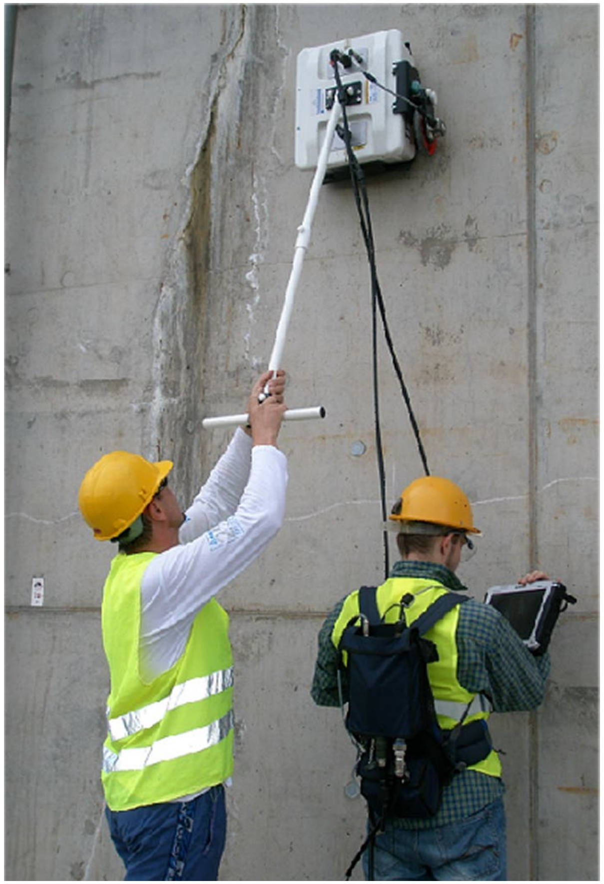
NDT tests on concrete

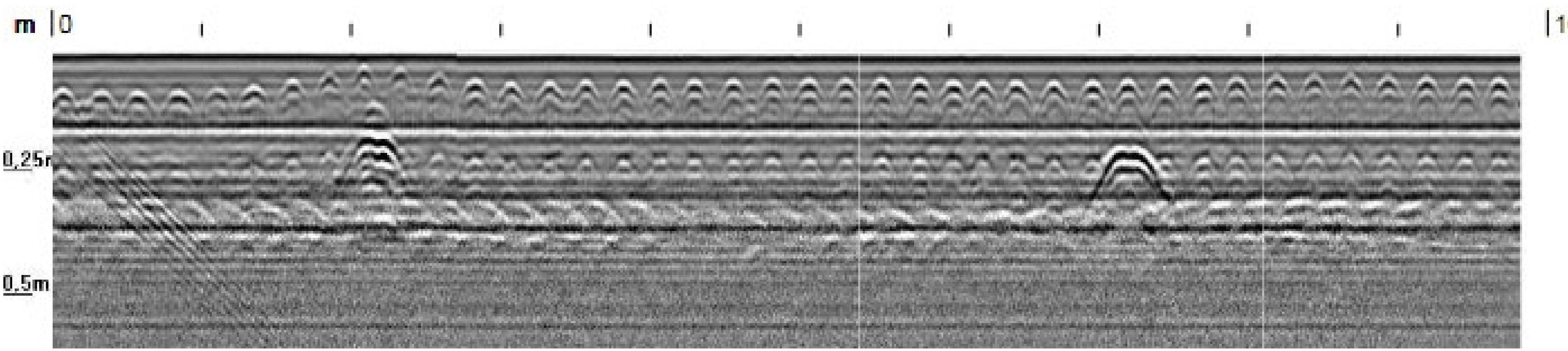
Destructive tests on concrete




NDT tests on reinforcement

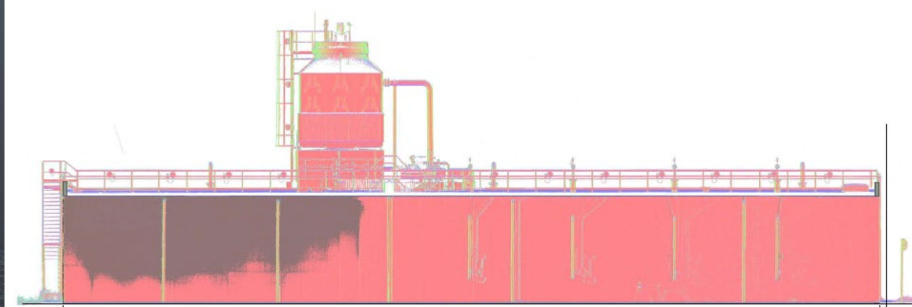


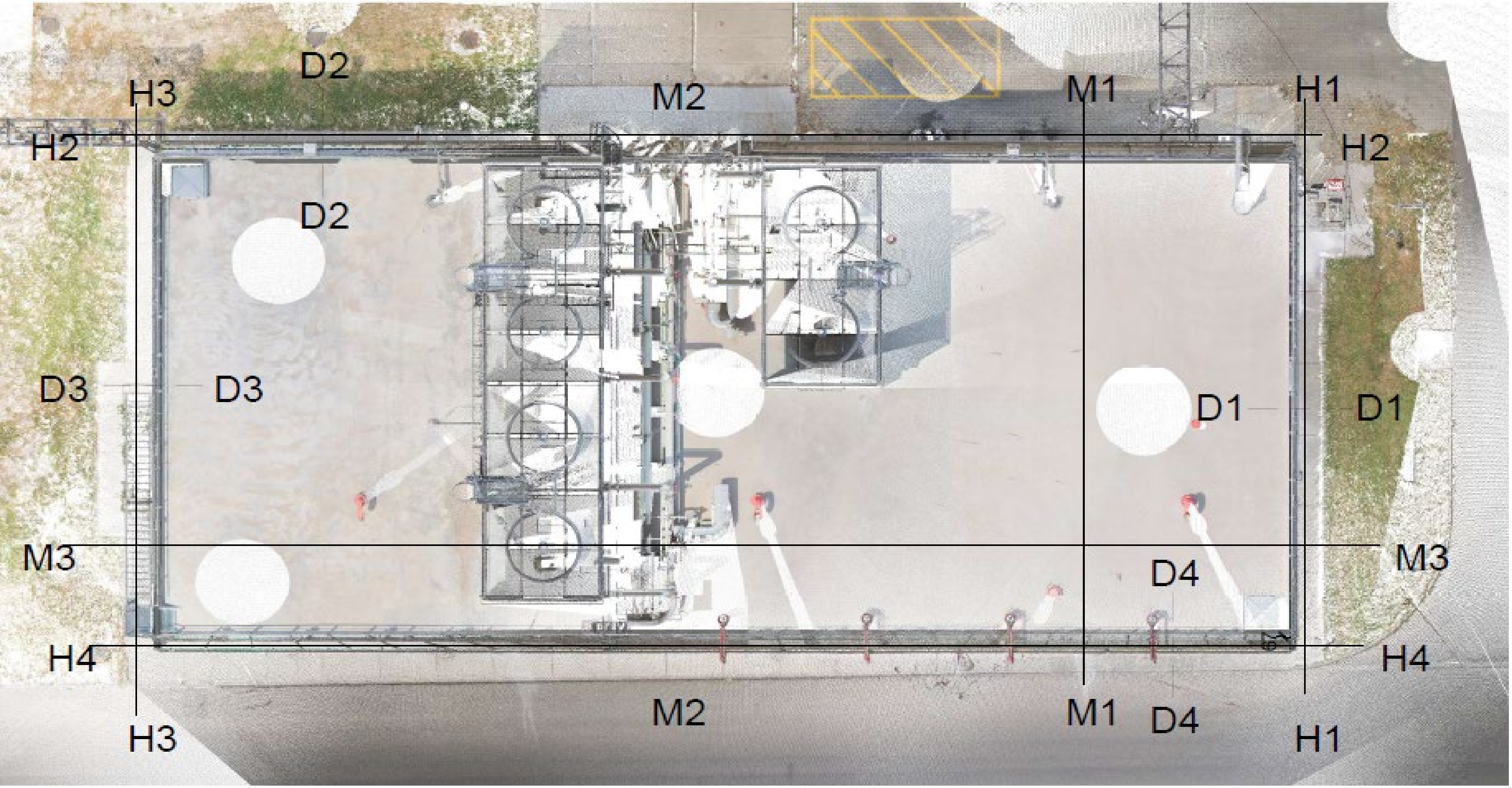


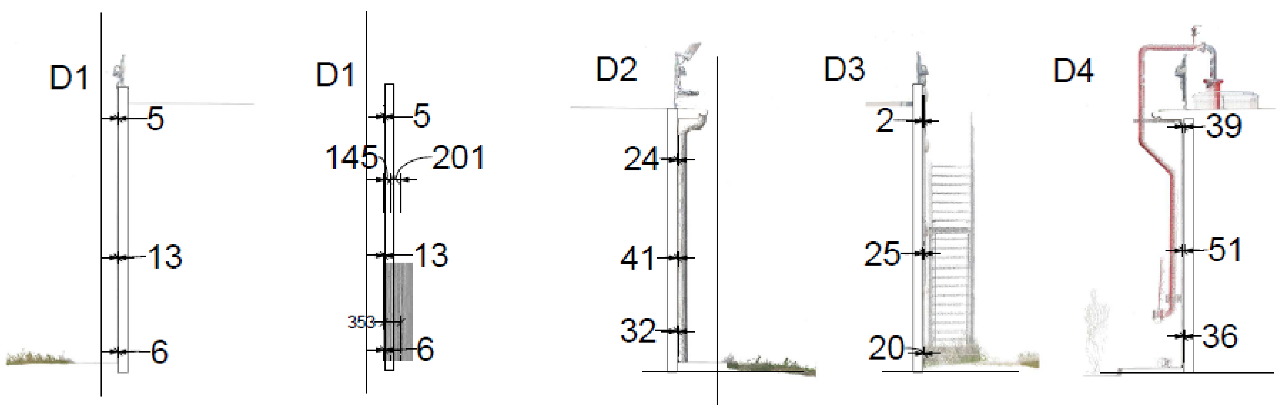


m
0
10
0,25m
0,5m

3D laser scanning

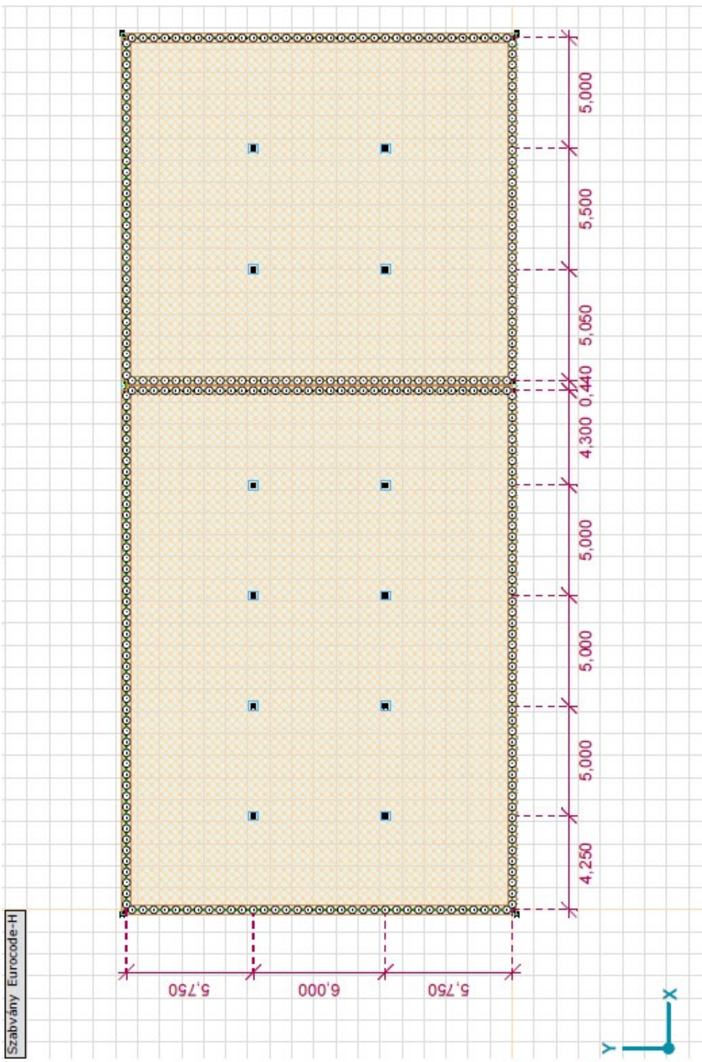


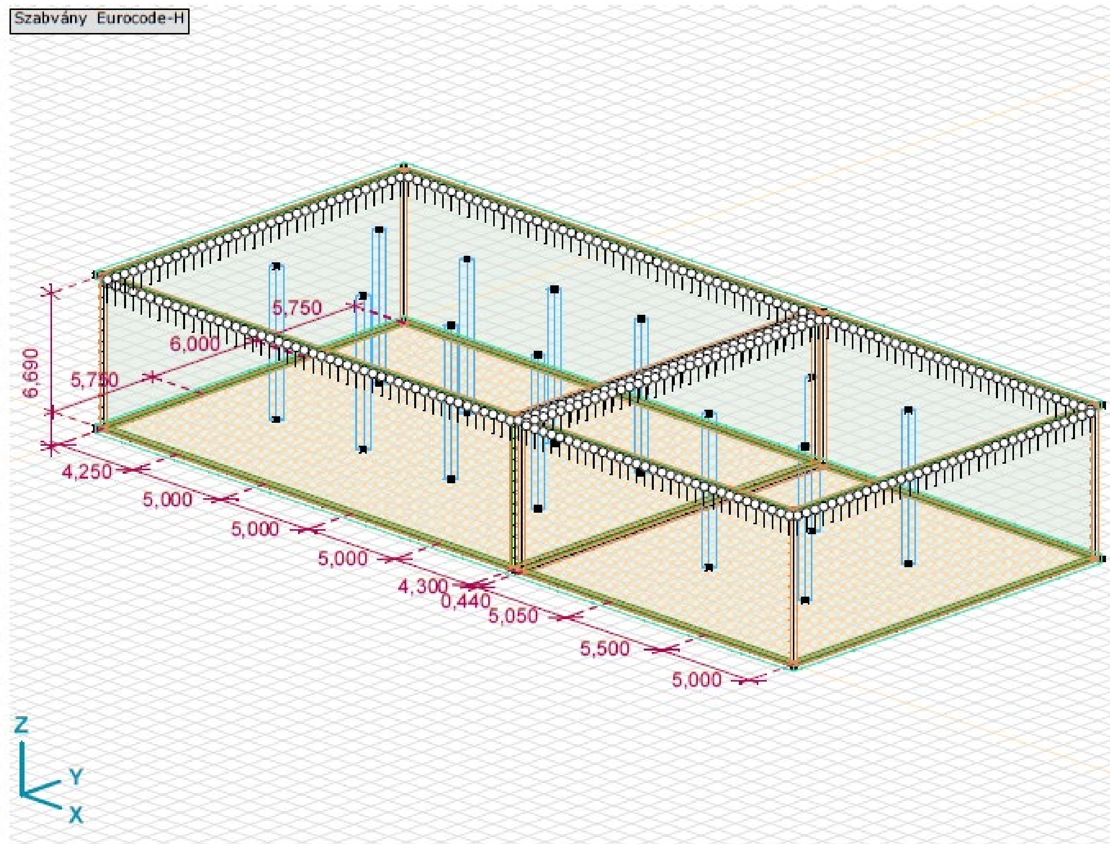




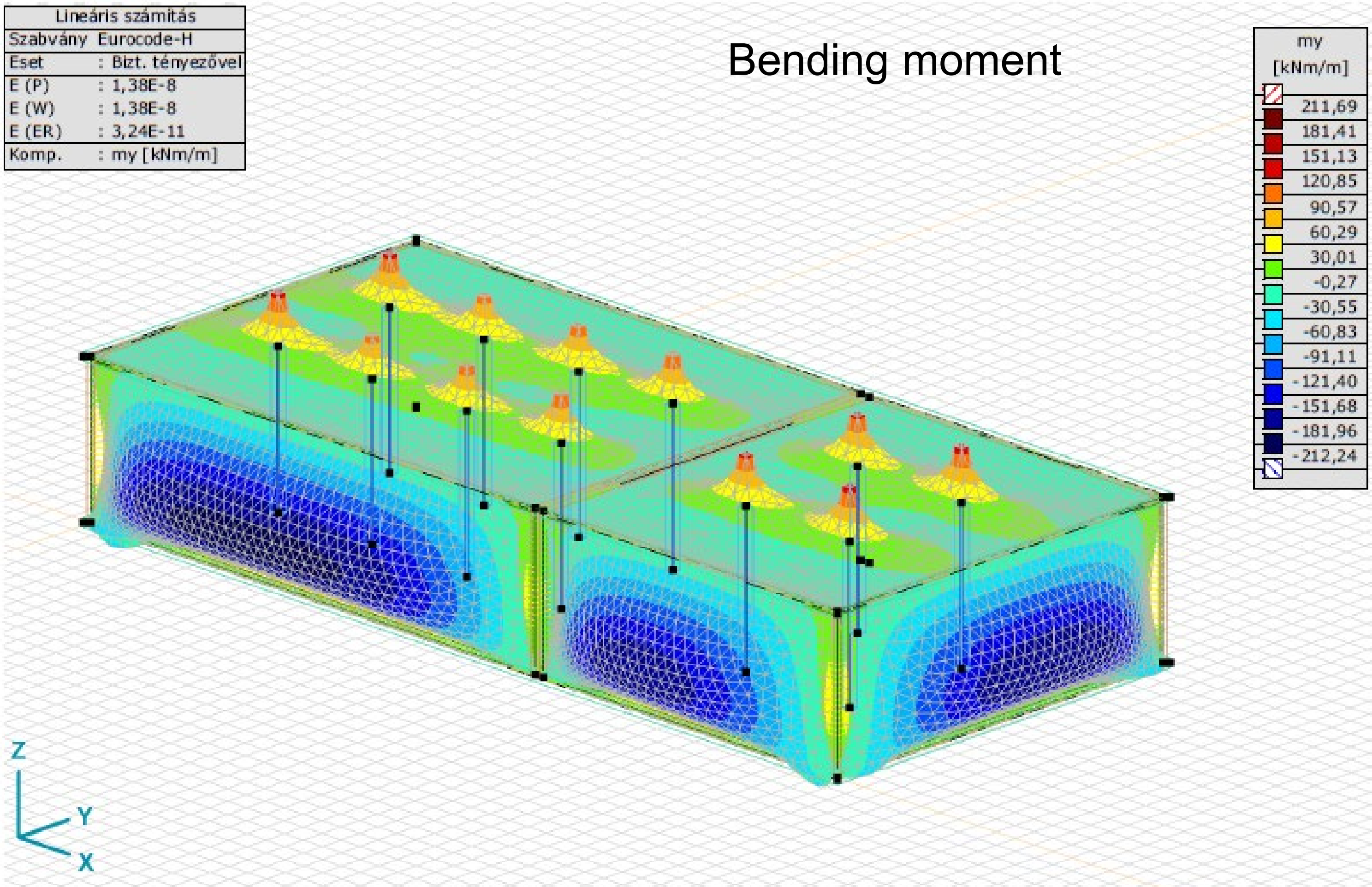
Differences from ideal (planned) contours

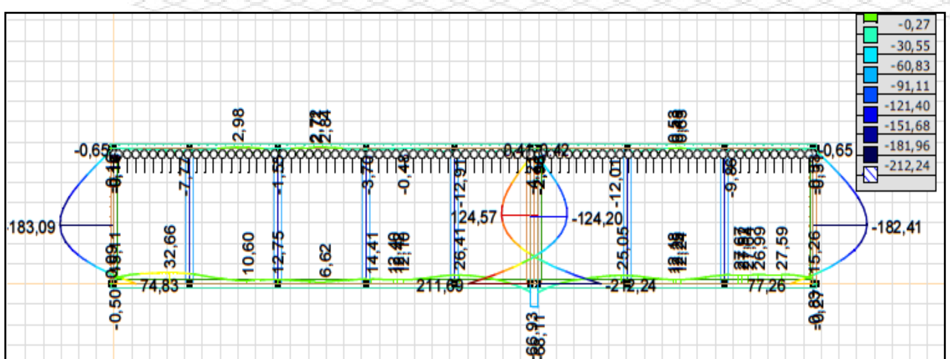
Structural analysis

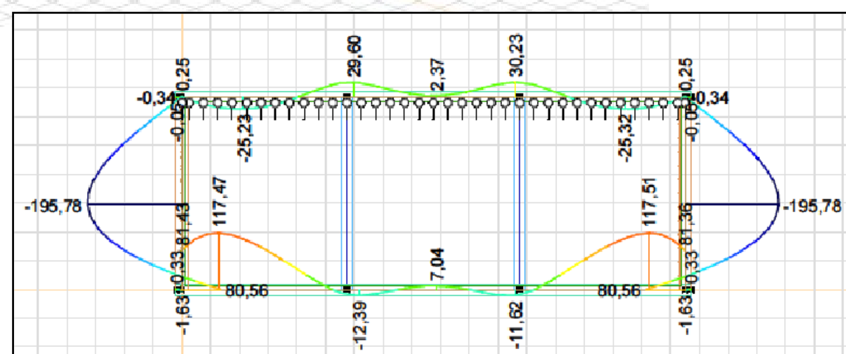




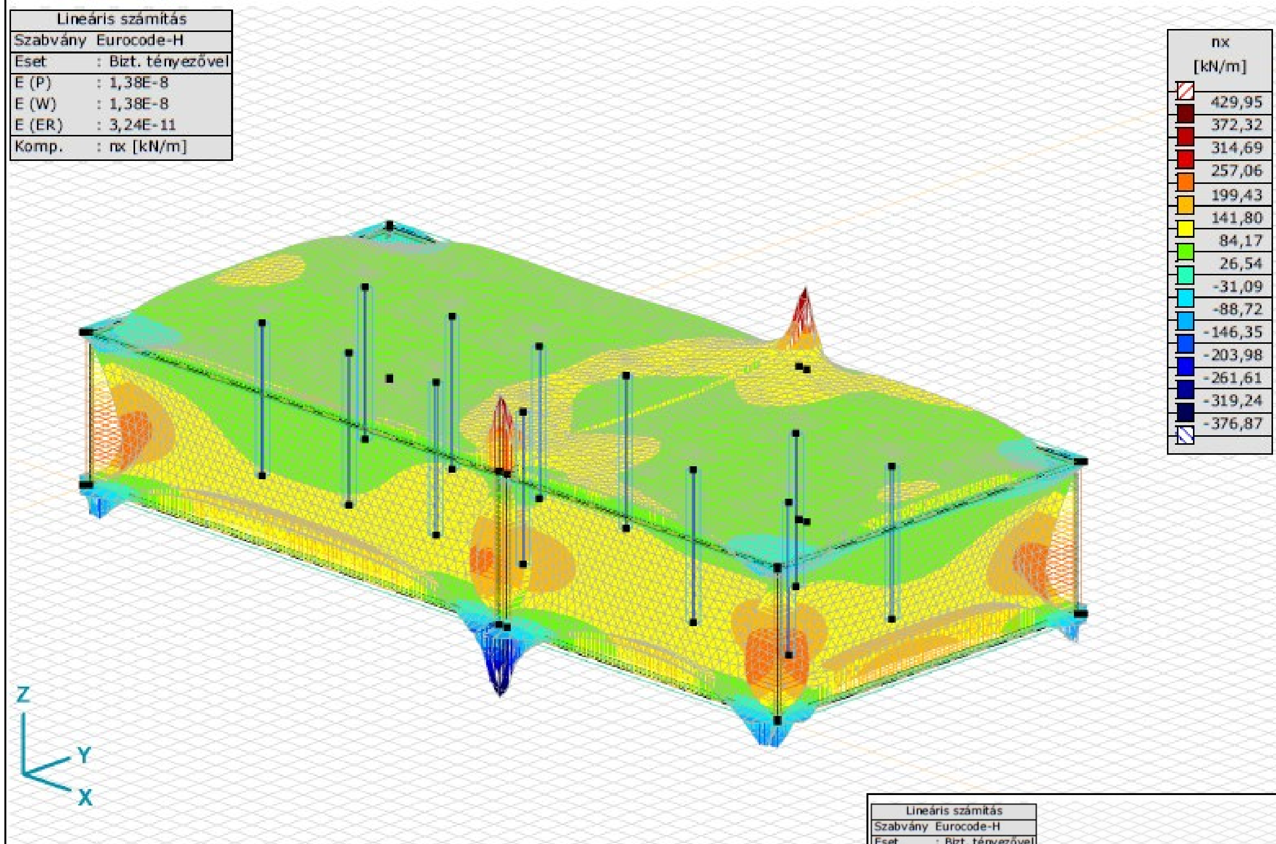
Bending moment

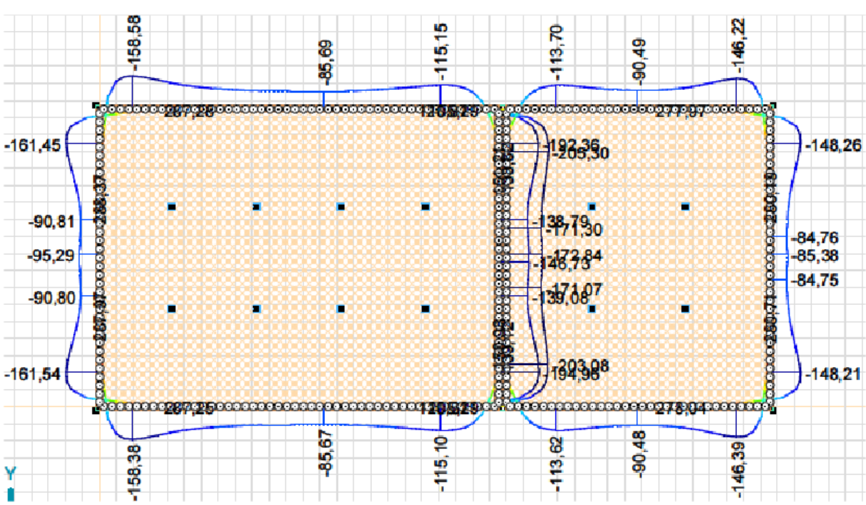


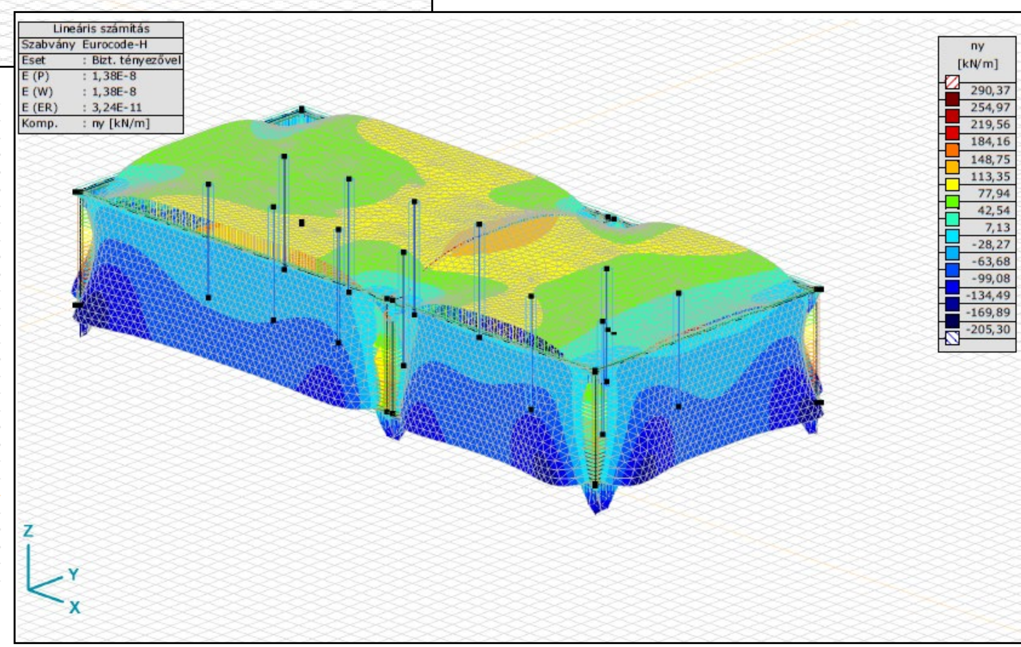




Normal force







DIAGNOSTICS OF STRUCTURES

LECTURE 06

Diagnostics and assessment of railway culvert for rehabilitation
(case study)

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The assessment procedure

Visual inspection (damage map)

Calculation needed?

no

Evaluation by damage map

Supplemetary survey

Non-destructive tests

yes

Approximate methods

(existing design data, geometrical measurements visual inspection)

fails.

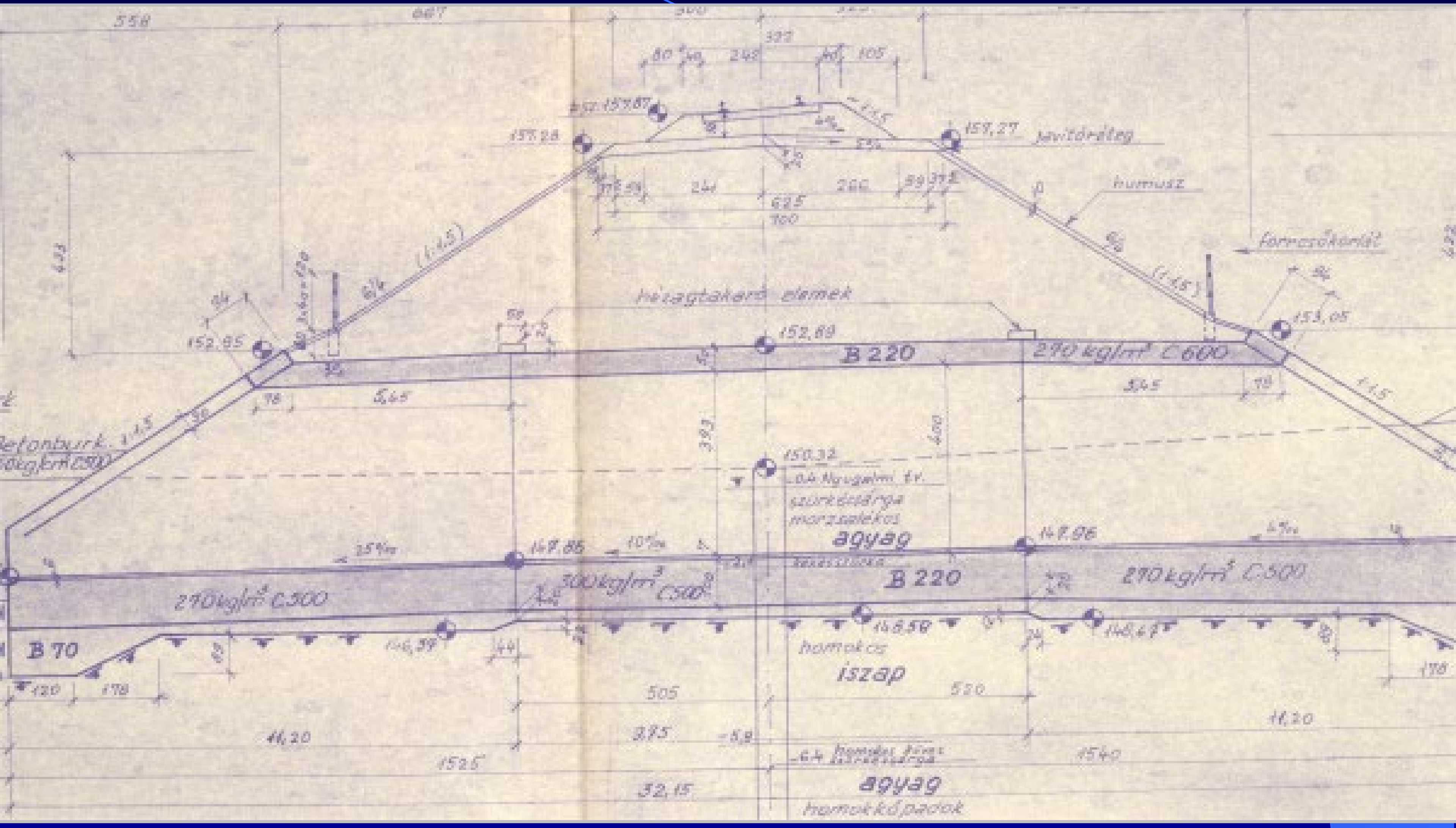
Detailed calculation

(based on destructive and NDT test results)

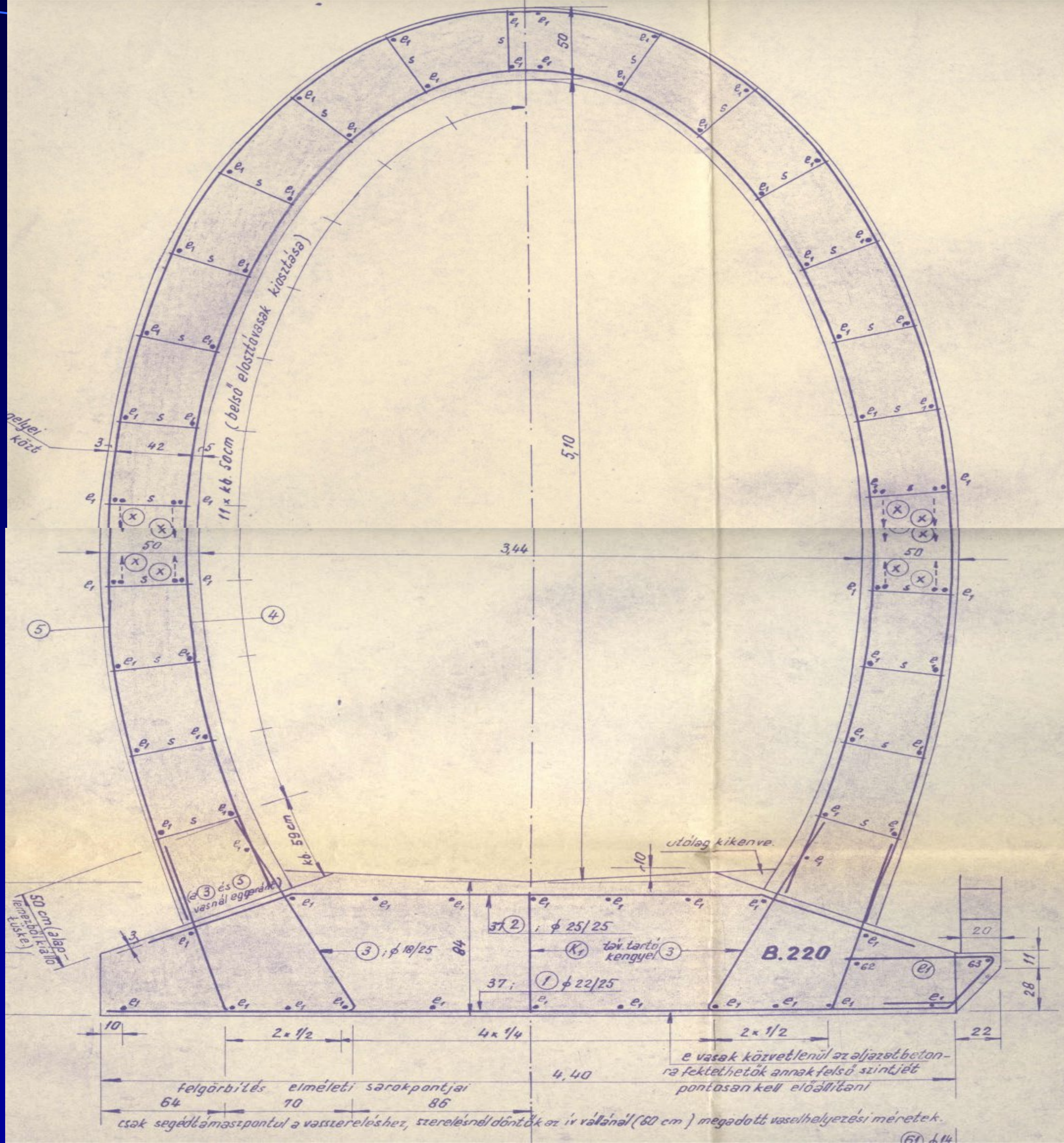
Sufficient (passes)

Assessment

The original structure



javítóréteg
humusz
forrasókorlát
hézagtakaró elemek
B 220
270 kg/m³ C600
Betonburk. 1:1,5
agyag
300 kg/m³ C500
B 220
270 kg/m³ C500
270 kg/m³ C500
B 70
homokos
iszap
agyag
homokkőpadok

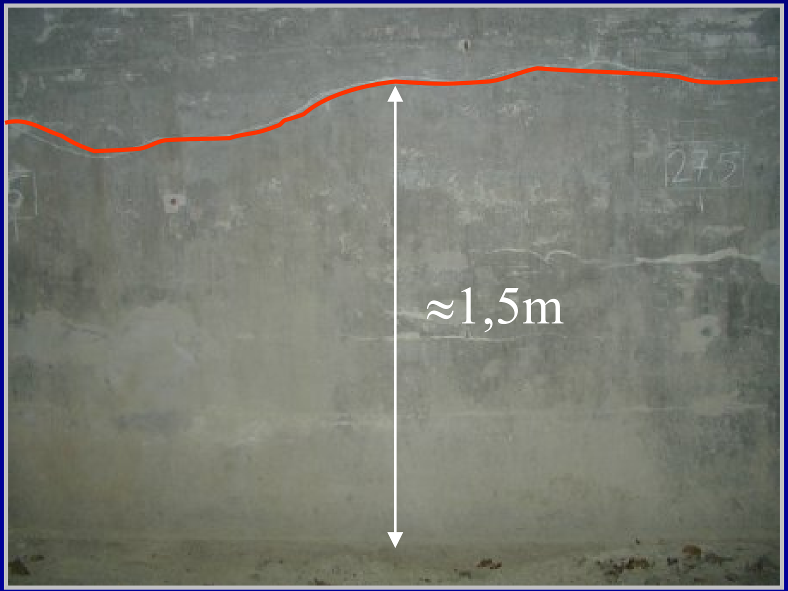

11 × kb. 50cm (belső elosztóvasak kiosztása)
510
50
42
3,44
kb. 59cm
utólag kikenve.
-10
37 ② ; ϕ 25/25
táv. tartó kengyel ③
B.220
③ ; ϕ 18/25
84
37 ; ① ϕ 22/25
50 cm (alaplemezből kiálló tüske)
10
2 × 1/2
4 × 1/4
2 × 1/2
22
20
11
28
4,40
e vasak közvetlenül az aljazatbetonra fektethetők annak felső szintjét pontosan kell előállítani
felgörbítés elméleti sarokpontjai
64
70
86
csak segédtámasztpontul a vasszereléshez, szerelésnél döntők az ív vállánál (60 cm) megadott vaselhelyezési méretek.

Typical damage (by visual survey)








275
≈1,5m

Diagnostical survey (instrumented)

Examination with rebar locator

Purpose:

- Determination of the location of rebars
- Measuring concrete cover
- Estimate rebar diameter


PROFOMETER 5
Bewehrungssucher
Rebar Locator
proceq

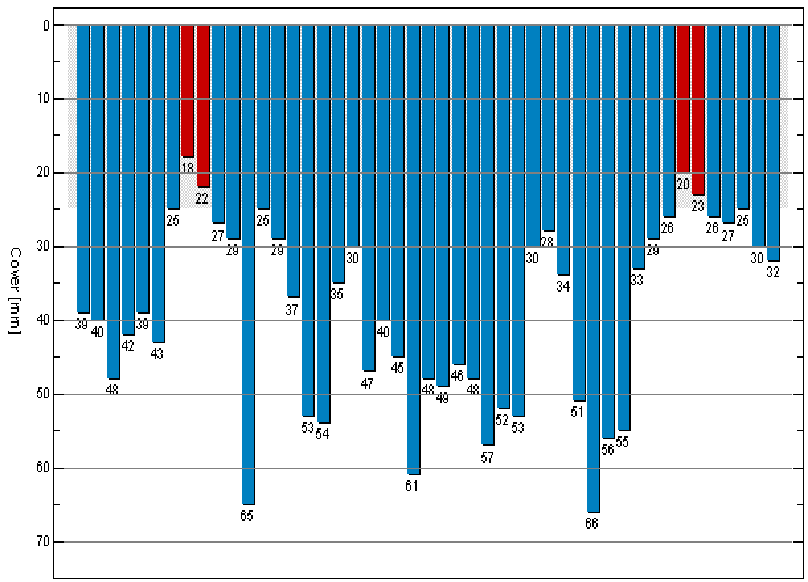

PROFOMETER 5
Universalsonde
Universal Probe
proceq

Statistical analysis of concrete cover

Upper region

PROCEQ - PROFOMETER 5 (V2.2.2, 51.2470) **Rebar Locator**

Title:	2.sz. híd - alsó	**Date:**	08-Nov-2003	**Name:**	PTE
Remarks:	Betonfedés értékek				



Set parameters

Bar diameter	D =	18	mm
Limit value of covers	s(Min) =	25	mm

Statistics

Number of measured bars	N =	47	
Average measured cover	m =	39.1	mm
Standard deviation	sa =	12.8	mm
Maximum of measured covers	Max =	66	mm
Minimum of measured covers	Min =	18	mm
Span	R =	48	mm
Cover values below limit	<s(Min) =	8.5	%

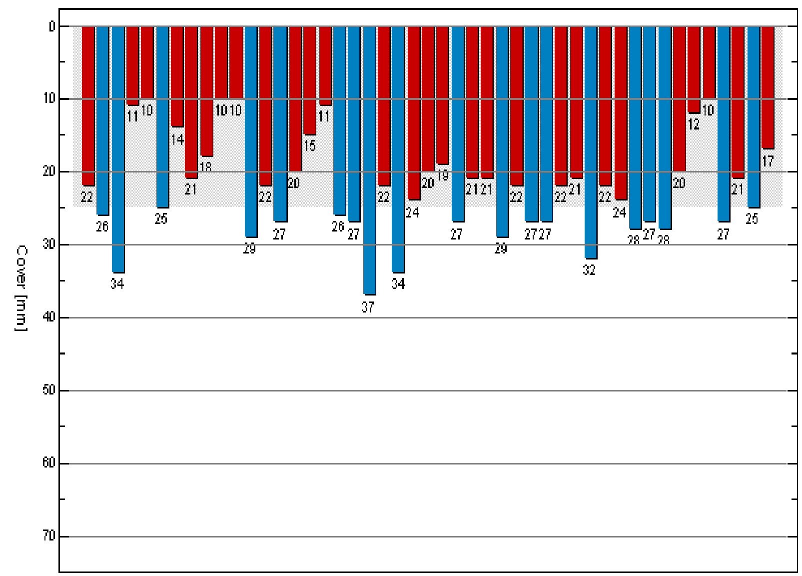
Measured covers [mm]

39	40	48	42	39	43	25	18	22	27	29	65	25	29	37	53	54	35	30	47	40	45	61	48
49	46	48	57	52	53	30	28	34	51	66	56	55	33	29	26	20	23	26	27	25	30	32	

Lower region

PROCEQ - PROFOMETER 5 (V2.2.2, 51.2470) **Rebar Locator**

Title:	2.sz. híd - felső	**Date:**	08-Nov-2003	**Name:**	PTE
Remarks:	Betonfedés értékek				



Set parameters

Bar diameter	D =	18	mm
Limit value of covers	s(Min) =	25	mm

Statistics

Number of measured bars	N =	47	
Average measured cover	m =	22.2	mm
Standard deviation	sa =	6.8	mm
Maximum of measured covers	Max =	37	mm
Minimum of measured covers	Min =	10	mm
Span	R =	27	mm
Cover values below limit	<s(Min) =	59.6	%

Measured covers [mm]

22	26	34	11	10	25	14	21	18	10	10	29	22	27	20	15	11	26	27	37	22	34	24	20
19	27	21	21	29	22	27	27	22	21	32	22	24	28	27	28	20	12	10	27	21	25	17	

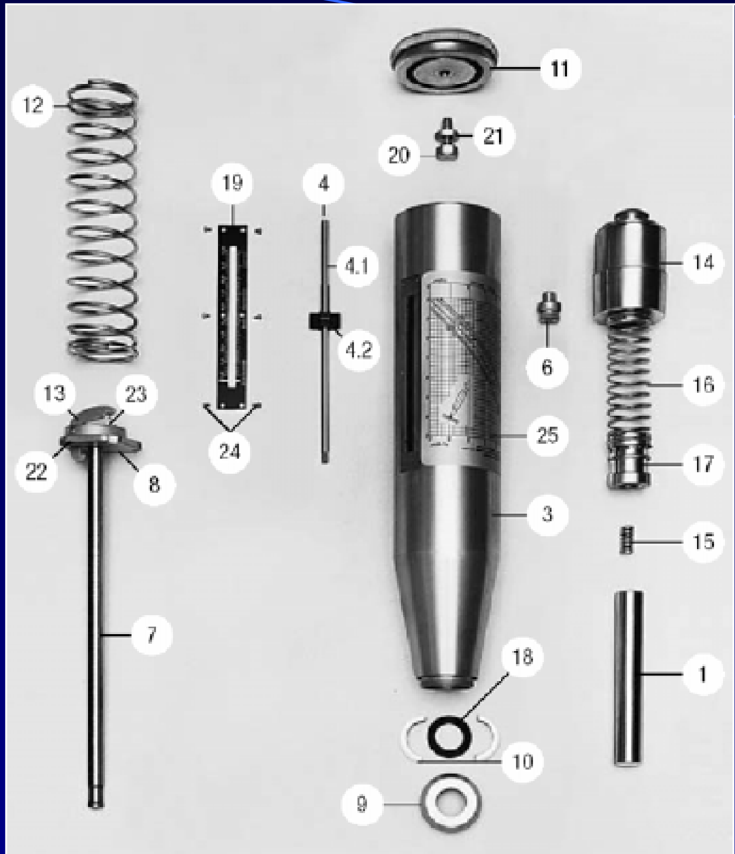
Examination with Schmidt hammer

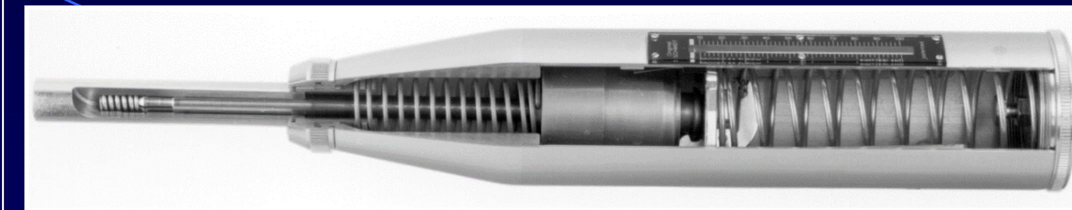
		Dátum/idő:	2003	11	4	11	1	
6.	Jobb alsó	Konverzió:	7	1	1	28	0,81	0,7
			22					
			19					
			19					
			18					
			21					
			20					
			24					
			22					
		Statisztika:	20,6	18	24	2,00	11,8 N/mm2	
		Dátum/idő:	2003	11	4	11	2	
7.	Jobb alsó	Konverzió:	8	1	1	28	0,81	0,7
			23					
			34					
			31					
			24					
			27					
			32					
			27					
			25					
		Statisztika:	27,9	23	34	4,02	14,6 N/mm2	
		Dátum/idő:	2003	11	4	11	2	
8.	Jobb alsó	Konverzió:	9	1	1	28	0,81	0,7
			22					
			24					
			25					
			20					
			22					
			28					
			24					
			30					
		Statisztika:	24,4	20	30	3,29	13,0 N/mm2	
		Dátum/idő:	2003	11	4	11	3	
9.	Jobb alsó	Konverzió:	10	1	1	28	0,81	0,7
			31					
			24					
			24					
			21					
			19					
			25					
			23					
			22					
		Statisztika:	23,6	19	31	3,54	12,2 N/mm2	
		Dátum/idő:	2003	11	4	11	4	
10.	Jobb alsó	Konverzió:	11	1	1	28	0,81	0,7
			26					
			23					
			21					
			19					
			23					
			19					
			25					
			26					
		Statisztika:	22,8	19	26	2,87	12,3 N/mm2	

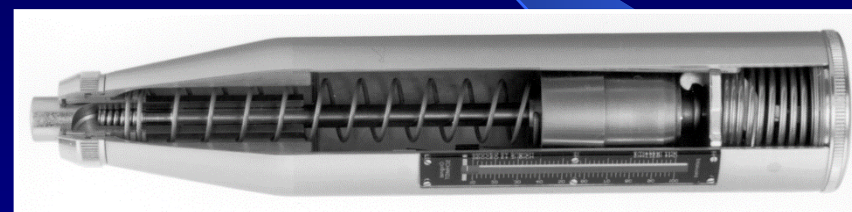
σ átlag	szórás
13,50	1,22

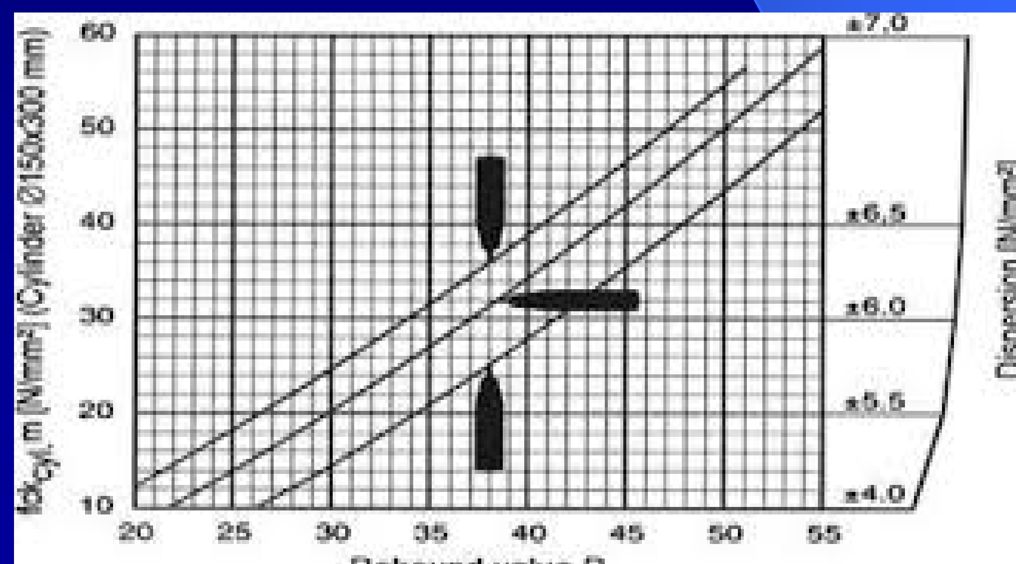
<u>Purpose:</u>

- Estimation of concrete strength
- Variation of concrete strength
- Pointing at anomalies

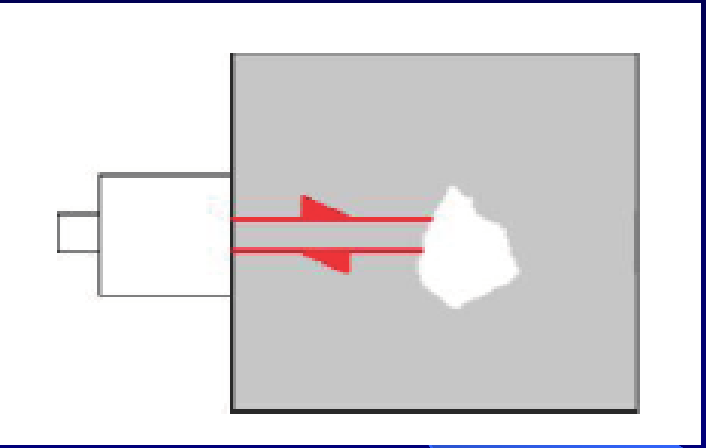

12
19
4
4.1
4.2
13
23
22
8
24
7
11
20
21
25
3
6
14
16
17
15
18
10
9
1

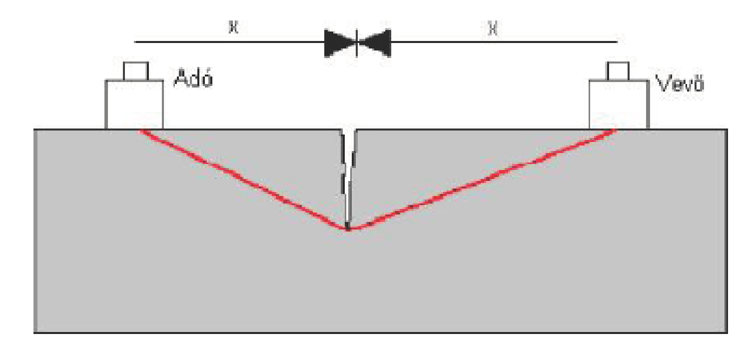





fck,cyl,m [N/mm²] (Cylinder Ø150x300 mm)
60
50
40
30
20
10
20
25
30
35
40
45
50
55
Rebound value R
±7.0
±6.5
±6.0
±5.5
±4.0
Dispersion [N/mm²]

Ultrasonic measurement with betonoscope





Purpose:

- Measuring concrete strength (indirect)

- Pointing at anomalies (cavities)

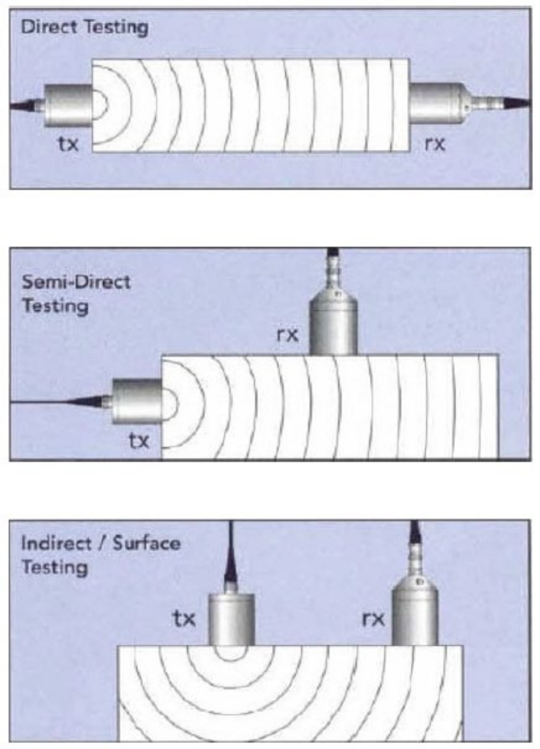
- Measuring crack depth

To estimate the material properties, the relationships between elastic constants and the velocity of respectively ultrasonic pressure wave (VL) and shear wave (VT) are derived from equations in an isotropic elastic medium of infinite dimensions:

$$V_L = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad V_T = \sqrt{\frac{E_d}{2\rho(1+\nu)}}$$

E_d = the dynamic elastic modulus (MPa)
ν = the dynamic Poisson's ratio.
ρ = the density (kg/m^3).
V_L = the pressure (longitudinal) wave velocity (km/s).
V_T = the shear wave (transversal) velocity (km/s).

Concrete condition	P-wave velocity (100 kHz)
Damaged	velocity < 3000 m/s
Sound	velocity > 4500 m/s



Examination with boroscopy, endoscopy

Purpose:

- Determination internal condition
- Cracks, cavities, layers
- Structural dimensions

A small camera is inserted into boreholes drilled in the structure allowing a detailed study of its surface

Tests on cored samples

Purpose:

- Determination of concrete strength
- Classification of concrete
- Confirm success of intervention

Results:

Lower region:

f_{cm}=11,7 N/mm^2

s $\approx$ 6 N/mm^2

f_{ck} $\approx$ 2,5 N/mm^2 $\approx$ C2

Upper region:

f_{ck} $\approx$ 16,5 N/mm^2 $\approx$ C16/20




Repair solution

Concept

- Thin shotcrete layer with addition of fibres and mesh reinforcement

  $\Rightarrow$ stabilization of concrete surface

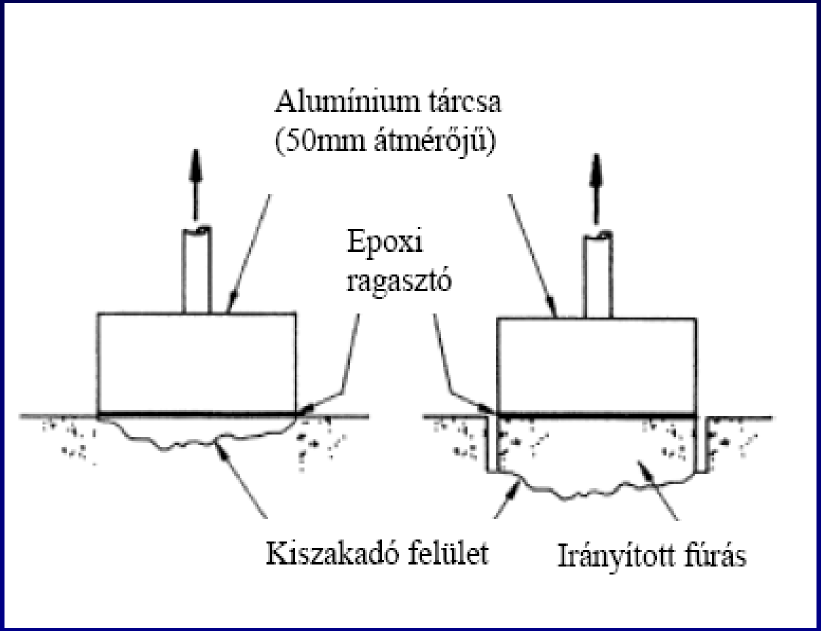
- Injection (micro-cement, other cement-based materials)

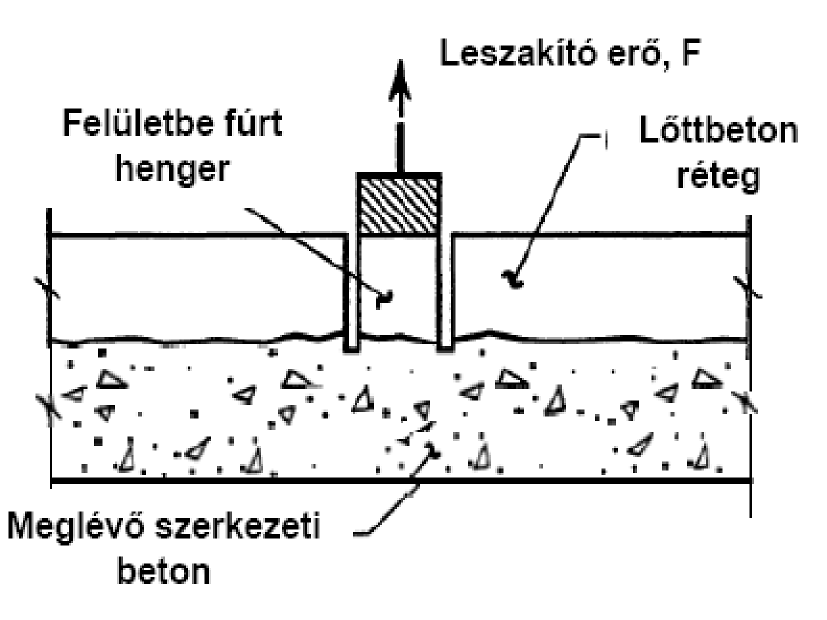
  $\Rightarrow$ strength enhancement, water resistivity enhancement

- Injection of fill

  $\Rightarrow$ water resistivity enhancement

Measuring bond strength (Pull-off test)



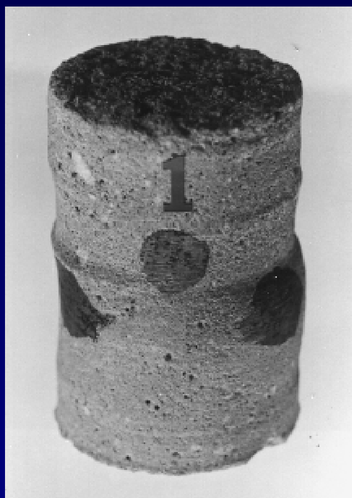


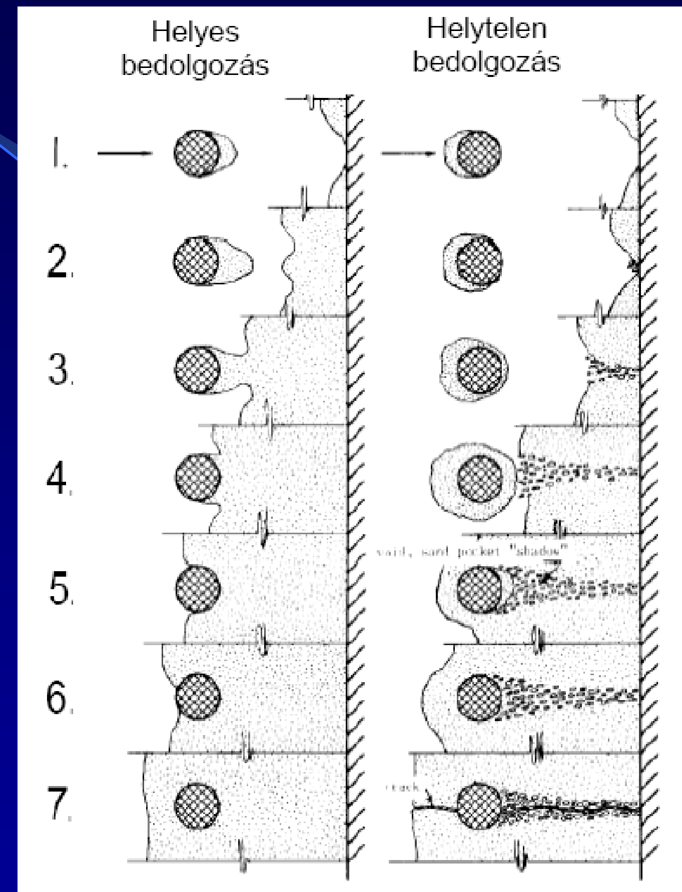
Purpose:

- Before intervention:
  $\Rightarrow$ testing surface bond to prepare substrate
- After intervention:
  $\Rightarrow$ testing surface bond for quality control


CE
PICCOLO
SN 9524

Visual assessment of cored samples



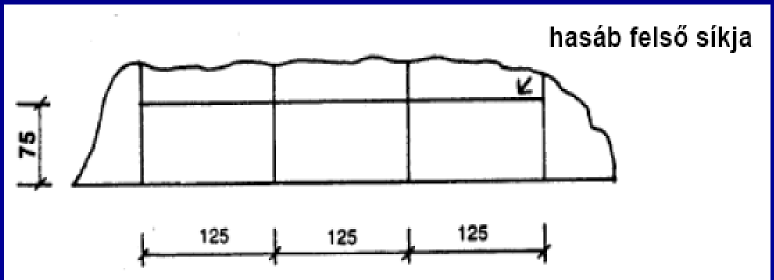


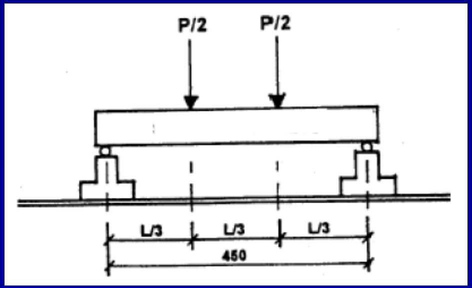
Classification of shotcrete samples
ACI ⇒ 5 categories

Testing efficiency of injection on cored samples

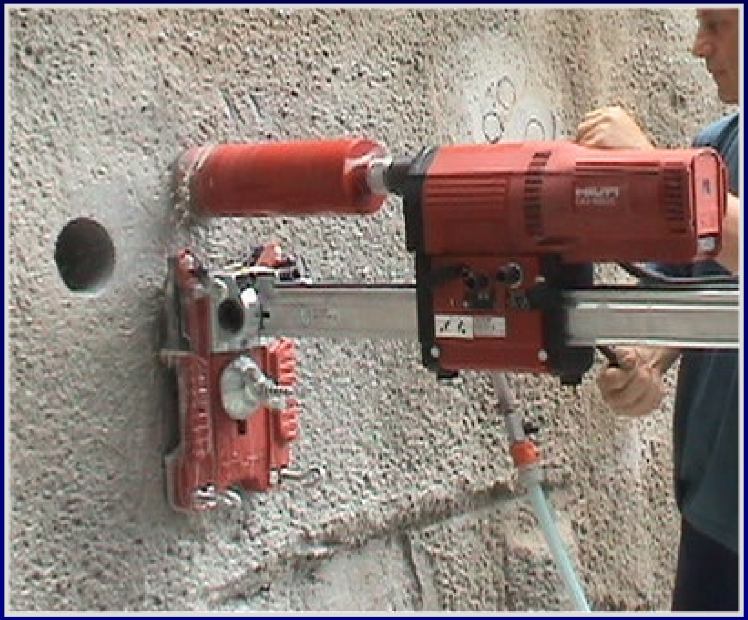
Destructive tests

Tests on shotcrete panels





Tests on shotcrete cored samples



d = 100mm
l/d= 1,0-2-0

d = 50mm
l/d= 1,0-2-0

N≥15

$$f_{ck,is} = f_{m(n),is} - k_2 \cdot s \quad \text{or} \quad f_{ck,is} = f_{is,lowest} + 4$$

where

$f_{ck,is}$ = Characteristic compressive strength of the concrete.
$f_{m(n),is}$ = Arithmetic mean of n test results of the compressive strength of the concrete.
$f_{is,lowest}$ = Lowest test result of the compressive strength of the concrete.
k_2 = Defined in national standards. If they don't exist, k_2 = 1.48 is assumed.
s = The standard deviation of the test results or 2 N/mm². The greatest value is to be used.

N is between 3 and 14

$$f_{ck,is} = f_{m(n),is} - k \quad \text{or} \quad f_{ck,is} = f_{is,lowest} + 4$$

The range of k for a small number n of test results is defined as follows:

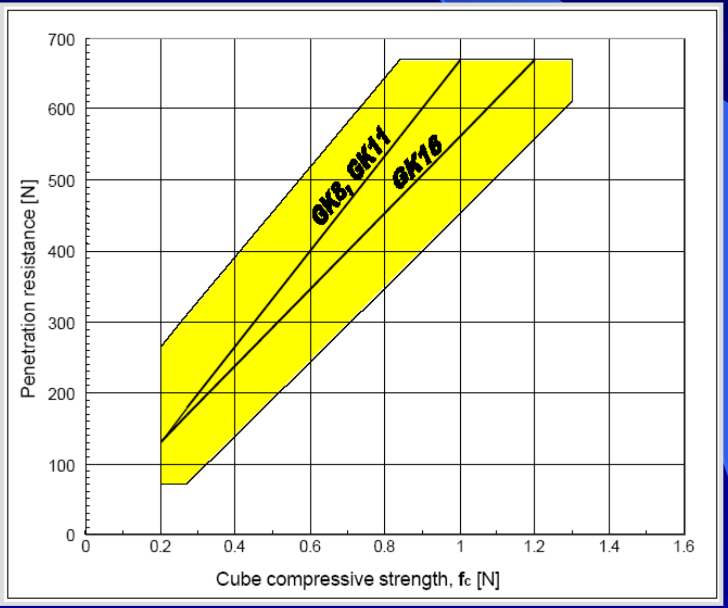
n	k
10–14	5
7–9	6
3–6	7

EN 13791:2008

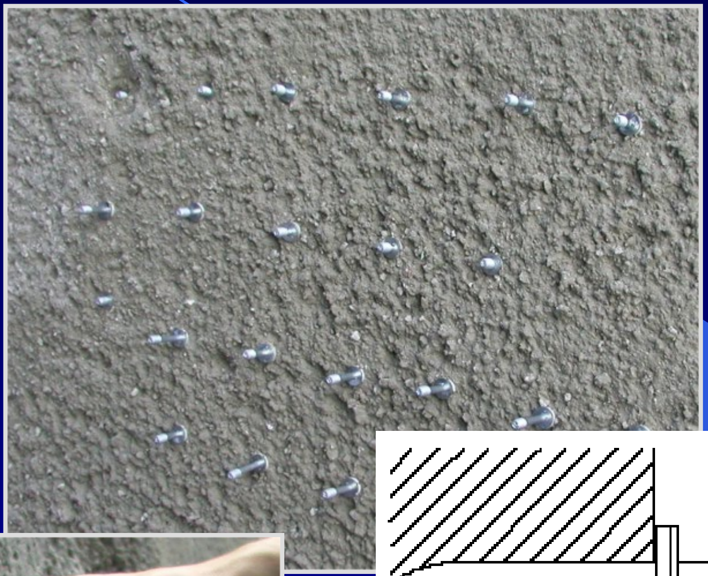
Non-destructive Tests

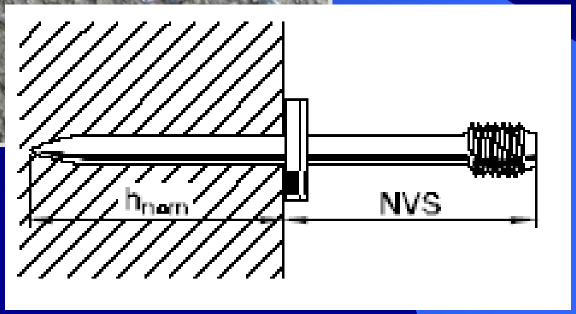
- Schmidt hammer test is not appropriate

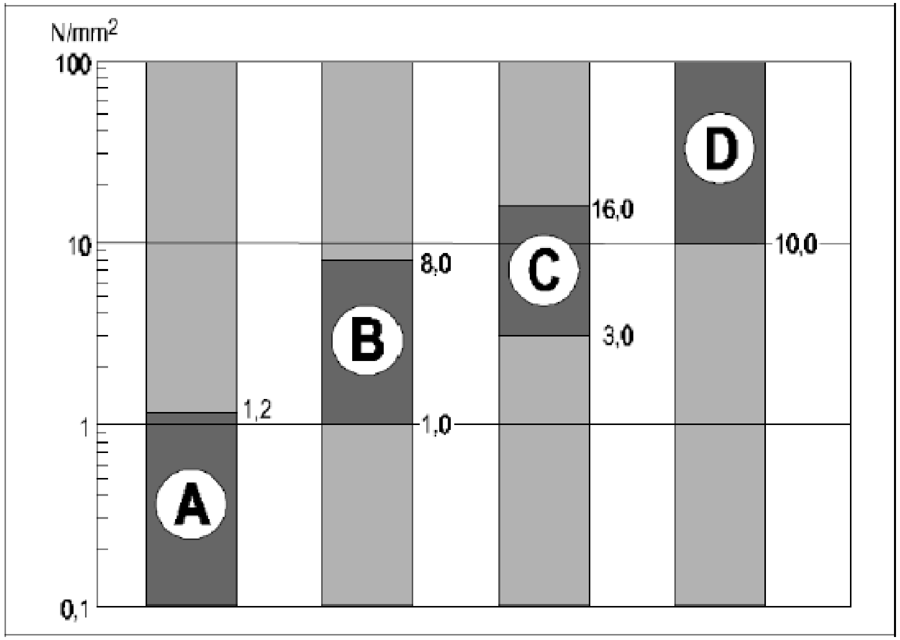
- Testing early strength with penetration needle



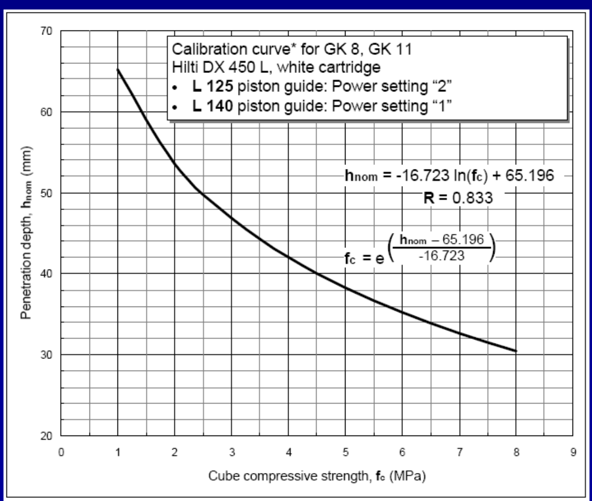
- Testing early strength with HILTI stud driving method

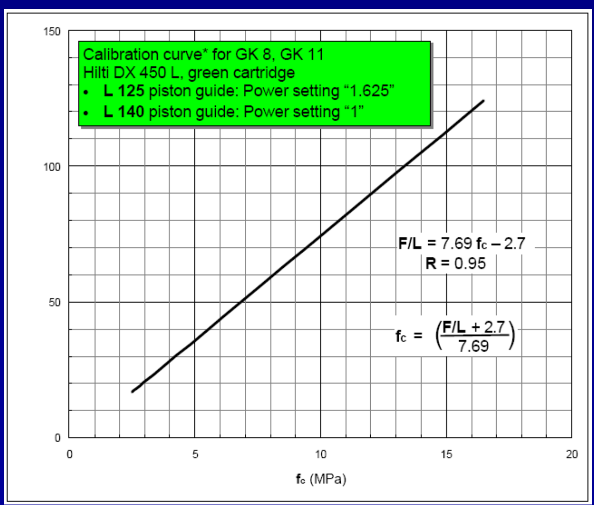


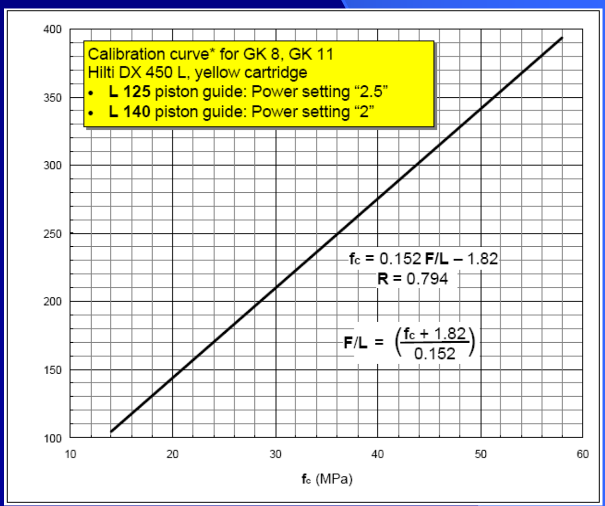




A - Vizsgálat Penetrációs tű módszerrel
B – Vizsgálat csapszeg belövéses módszerrel (pl. HILTI DX 450, fehér patron)
C – Vizsgálat csapszeg belövéses módszerrel (pl. HILTI DX 450, zöld patron)
D – Vizsgálat csapszeg belövéssel és kihúzó vizsgálattal (pl. HILTI DX 450, sárga patron)







DIAGNOSTICS OF STRUCTURES

LECTURE 07

Assessment and rehabilitation of heritage structures help de by combined non-destructive tests – Part1

Zoltán Orbán

University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

A Multidisciplinary Approach

HISTORICAL SURVEY

ARCHITECTURAL ANALYSIS

STRUCTURAL ASSESSMENT

DESIGN FOR REHABILITATION

Diagnosis
- Geometry
- Material properties
- Structural properties
- Defects

Static analysis
- Numerical analysis
- Deterioration modelling
- Safety assessment

Rehabilitation & Preservation
- Maintenance
- Repair
- Strengthening

COMPATIBILITY

SUSTAINABILITY

Preservation of Heritage Structures is a key to Sustainable Development

• **Construction industry is one of the biggest users of energy**

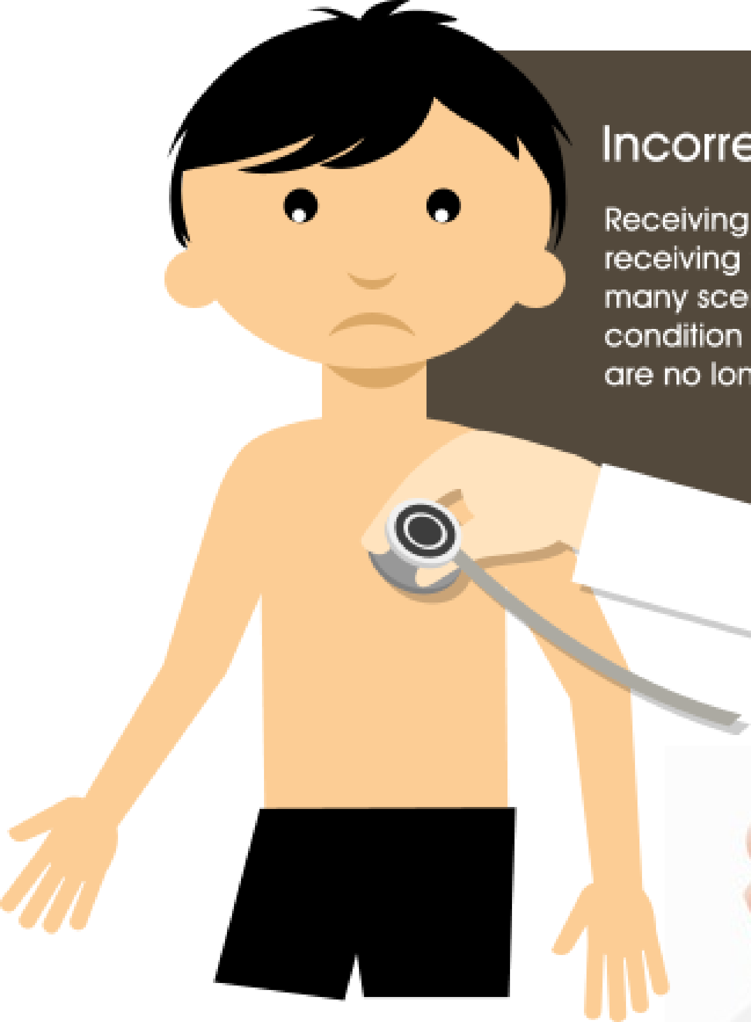
⇨ **Prolongation of the service life of existing structures**

⇨ **Do as little as possible and only what is necessary**

• **Interventions should be done in a manner that harmonizes with the existing structure (compatibility)**

The role of Diagnostics

- Survey the causes, type and extent of defects
- Provide input parameters for structural analysis and assessment
- Help prepare intervention
- Quality control of intervention

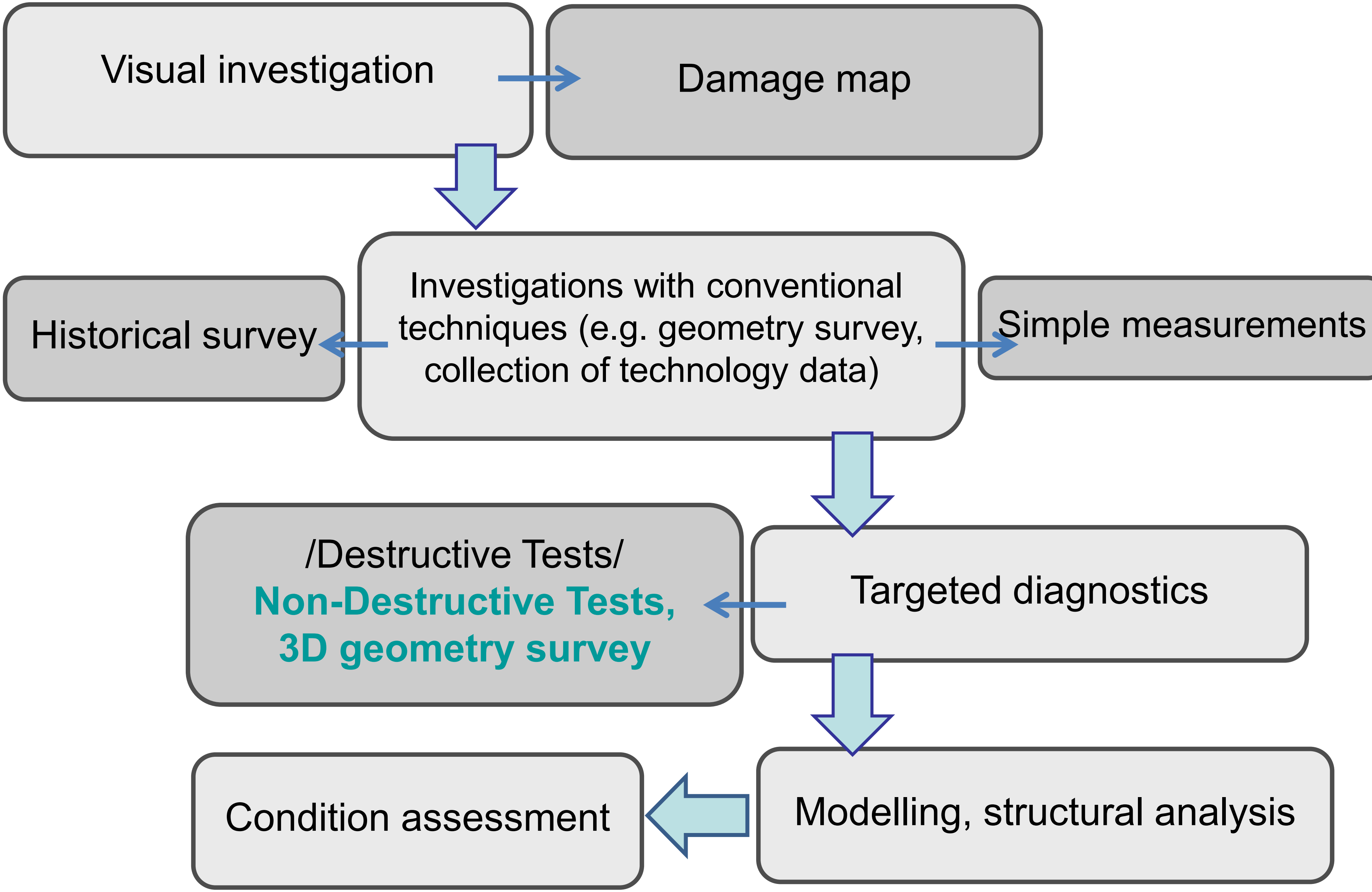


Incorrect or Delayed Diagnosis

Receiving a correct and timely diagnosis is essential to receiving the medical attention a condition requires. In many scenarios, a delayed diagnosis could cause a condition to progress so far that regular treatment options are no longer possible.

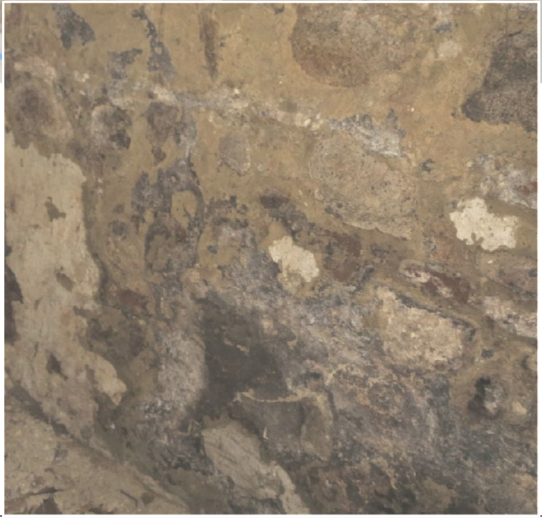
CASE STUDIES

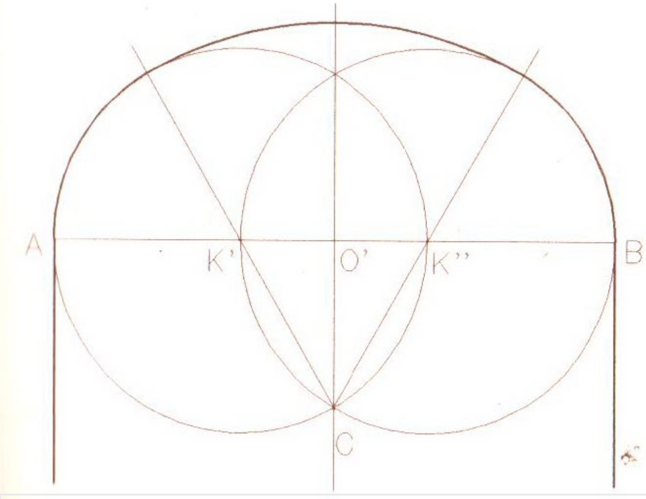
Case Study 1.

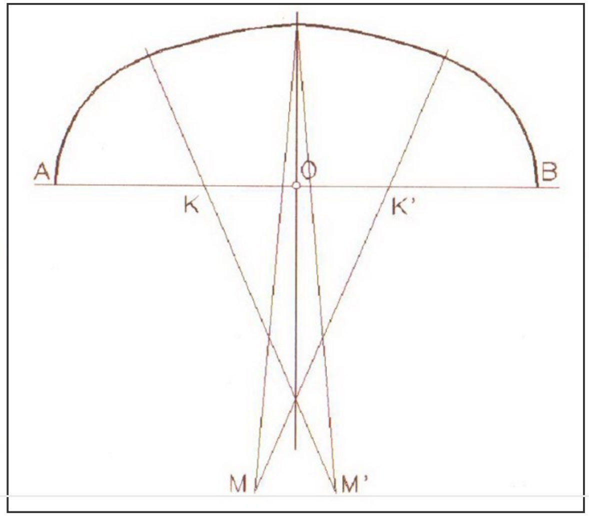

Visual investigation
Damage map
Historical survey
Investigations with conventional techniques (e.g. geometry survey, collection of technology data)
Simple measurements
/Destructive Tests/
Non-Destructive Tests,
3D geometry survey
Targeted diagnostics
Condition assessment
Modelling, structural analysis

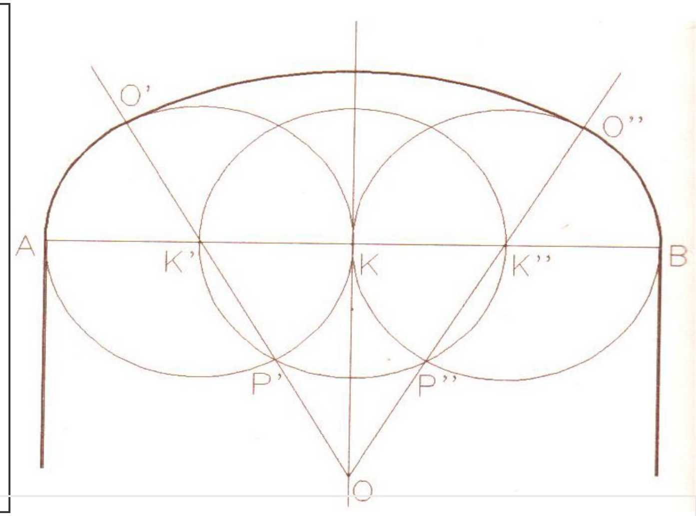
Structural relevance of the history of the building

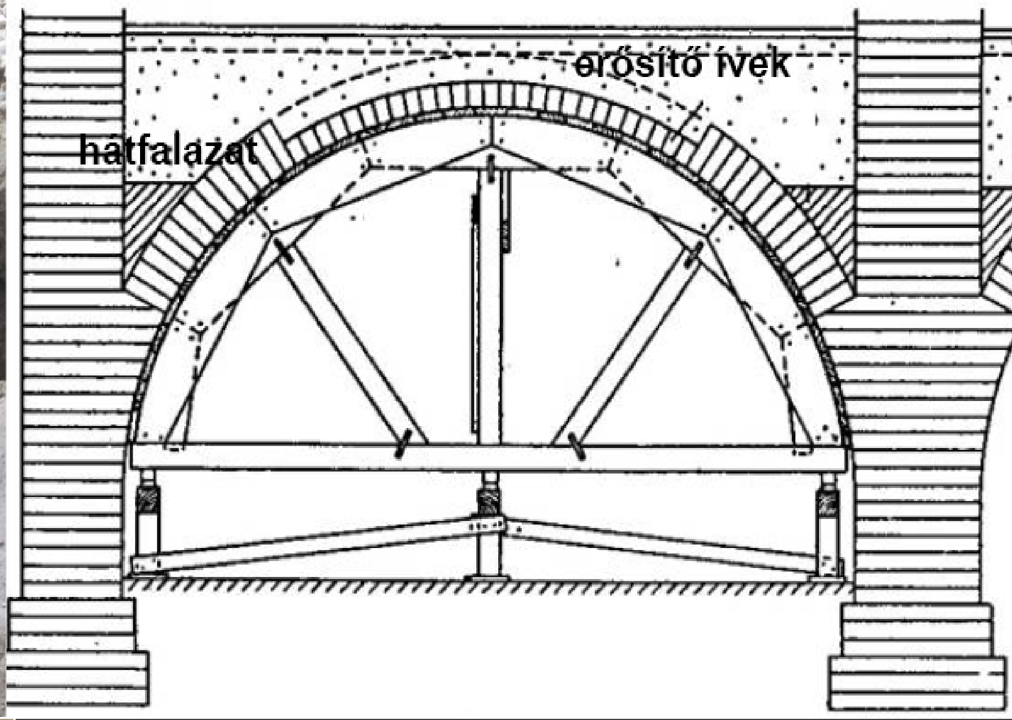
- Inclusions of previous buildings
- Materials and geometry of walls
- Connection of walls
- Construction technique of vaults
- Previous loading conditions and environmental effects

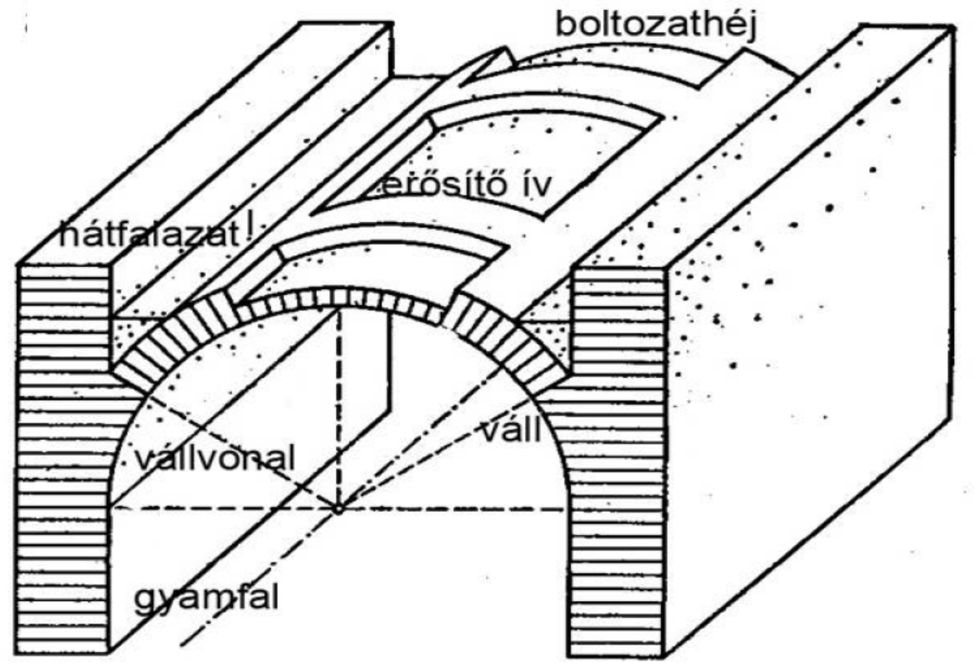



A
K'
O'
K''
B
C


A
O
B
K
K'
M
M'

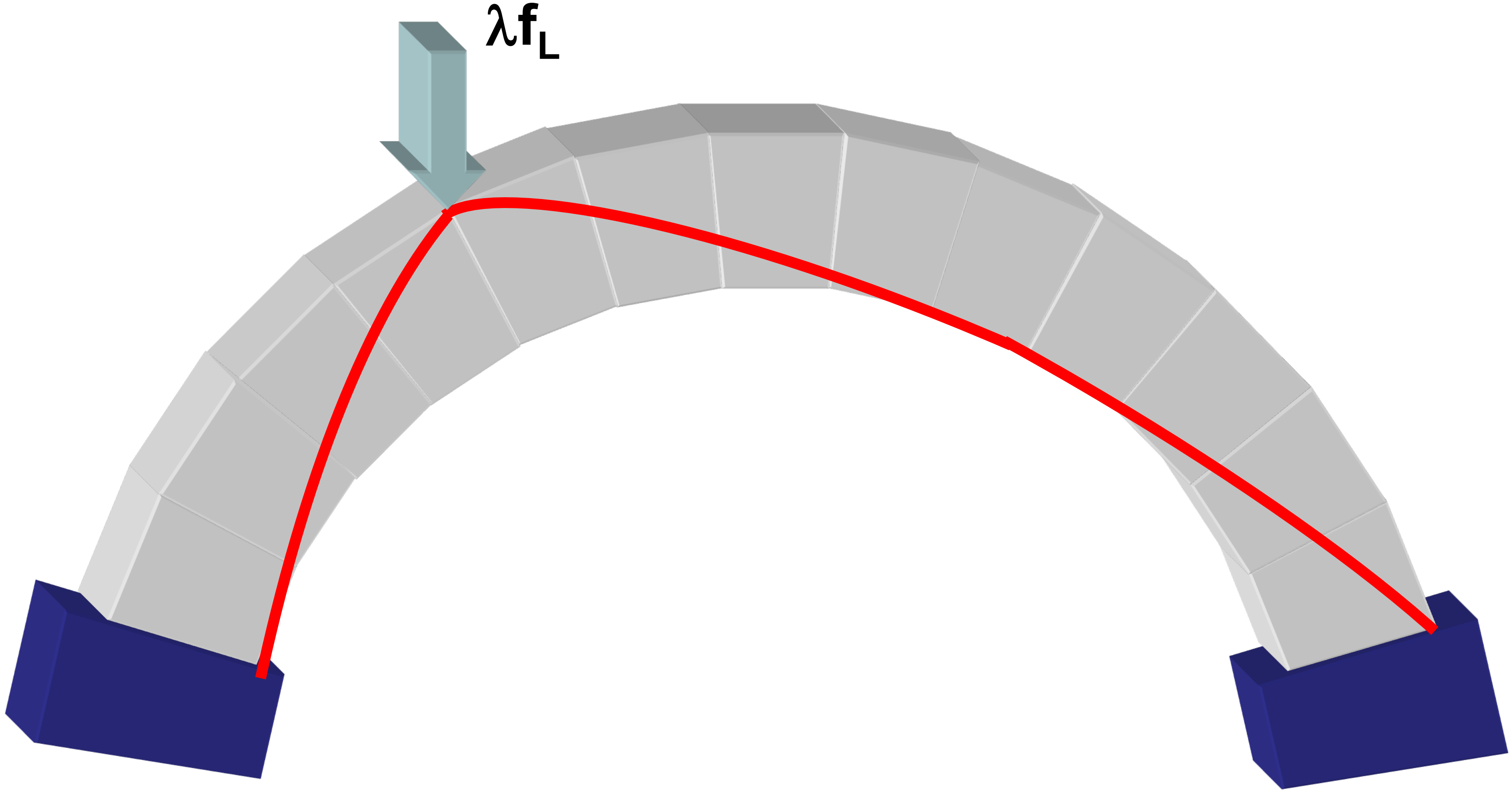

O'
O''
A
K'
K
K''
B
P'
P''
O



erősítő ívek
hátfalazat

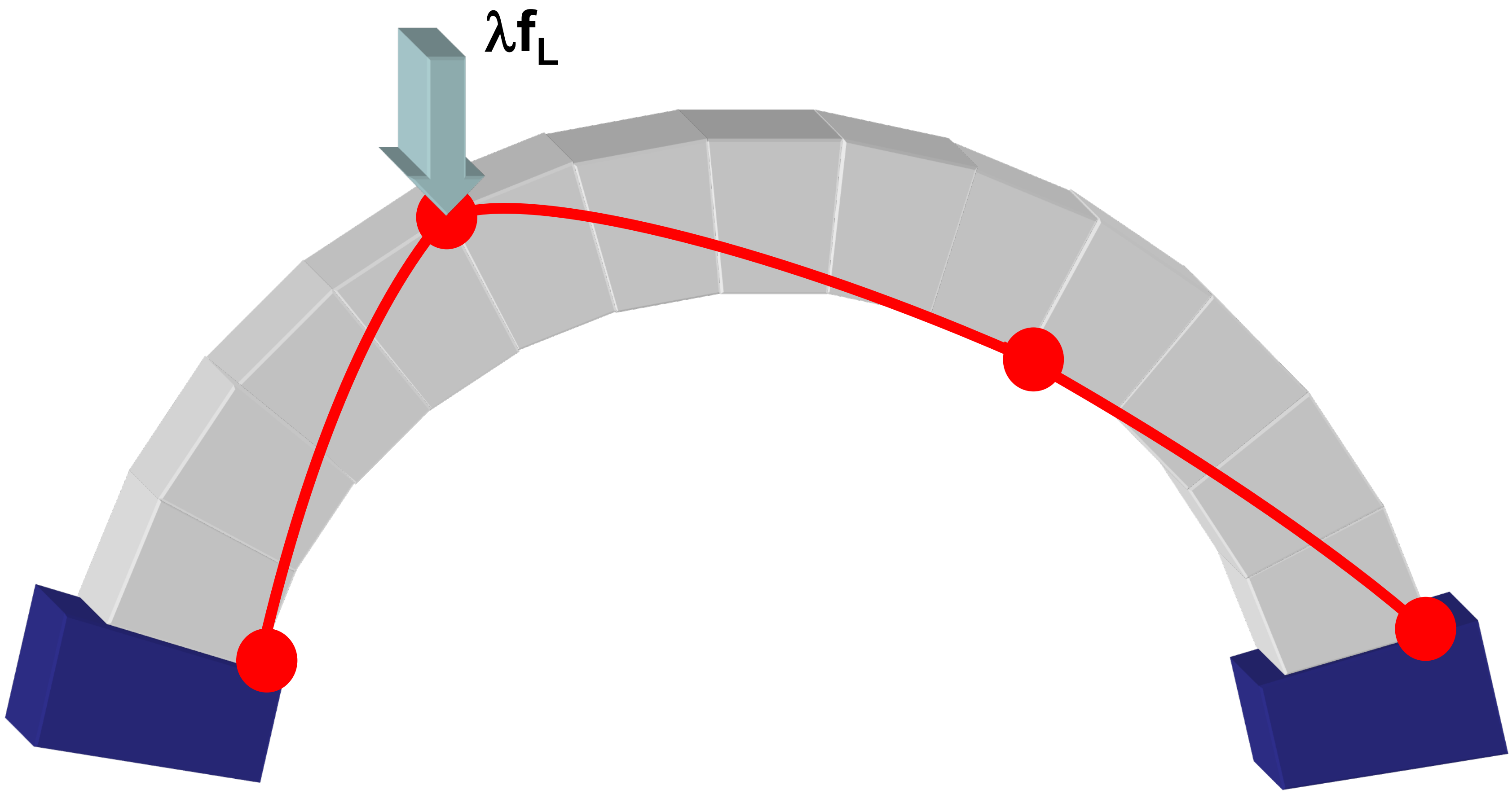

boltozathéj
erősítő ív
hátfalazat
váll
vállvonal
gyamfal

Stiffening of vaults (later excavation)

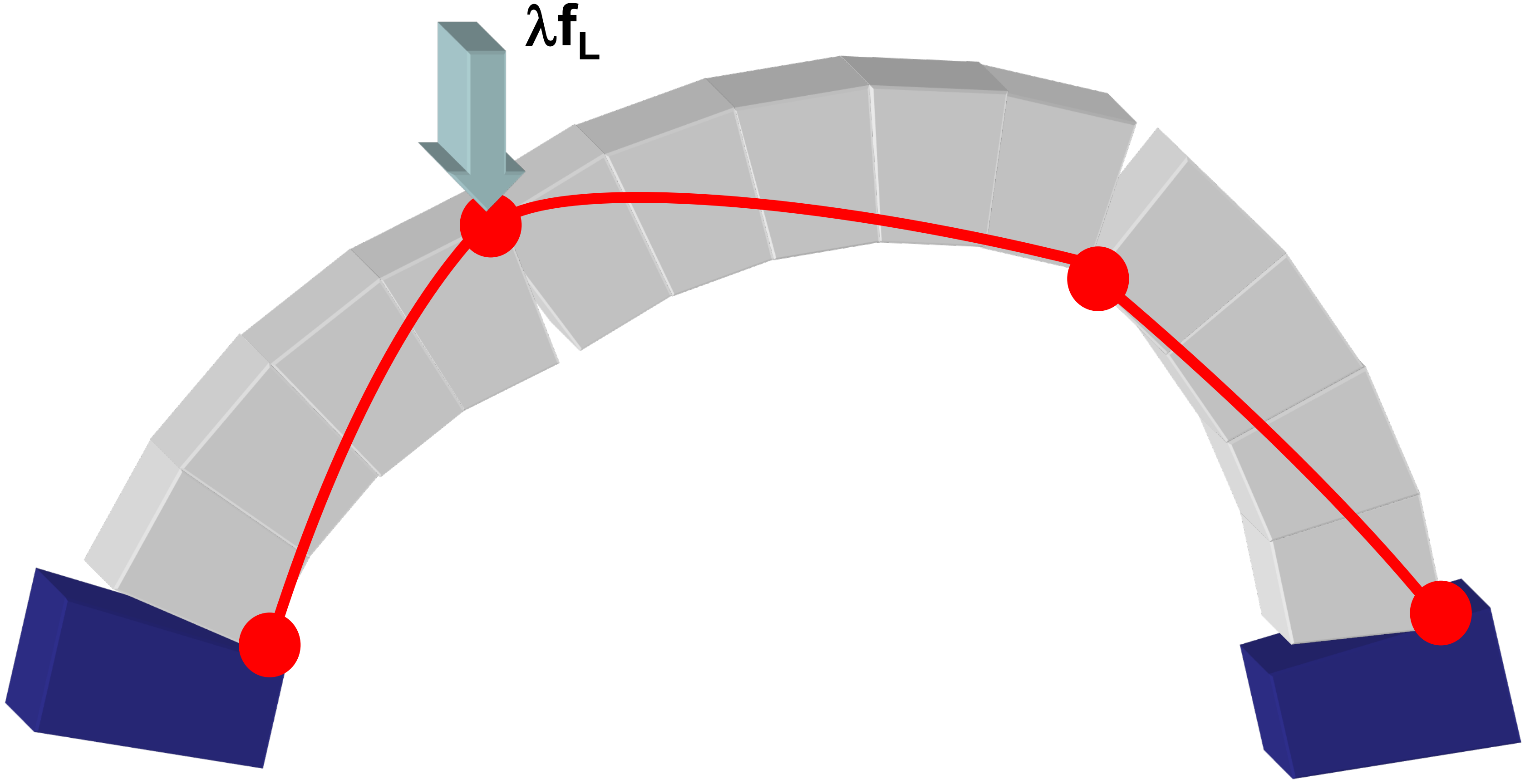
Principle failure mechanism of a masonry vault



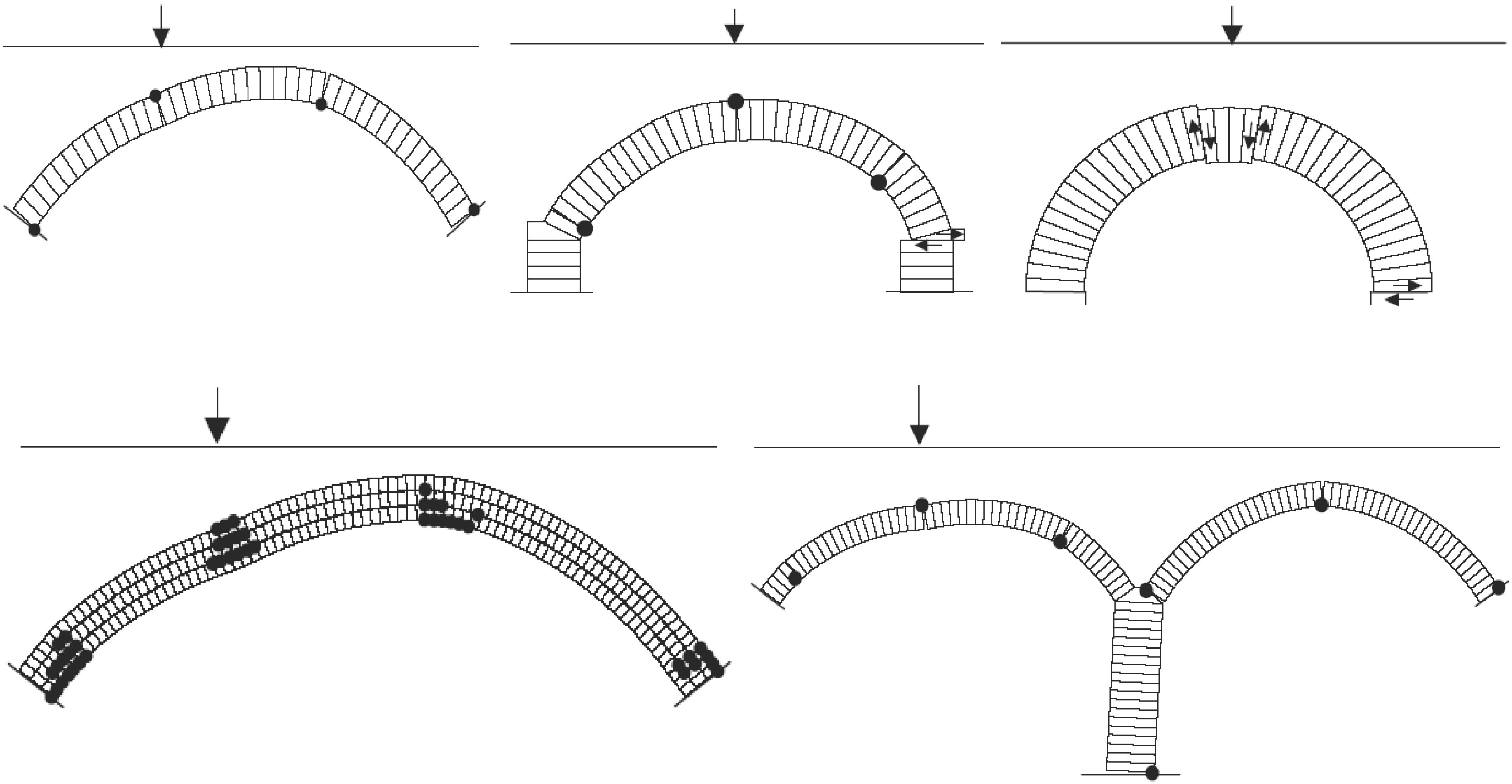
Principle failure mechanism of a masonry vault



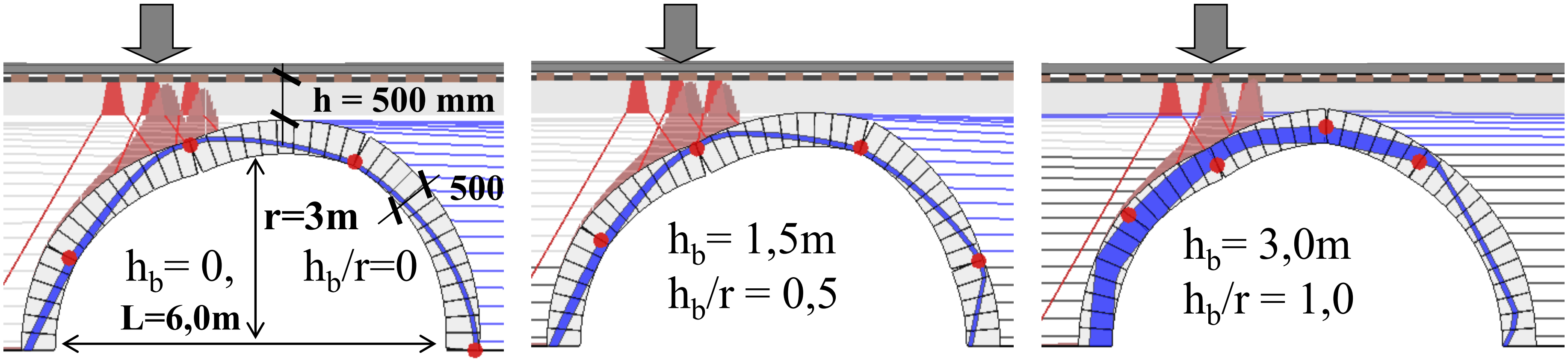
Principle failure mechanism of a masonry vault

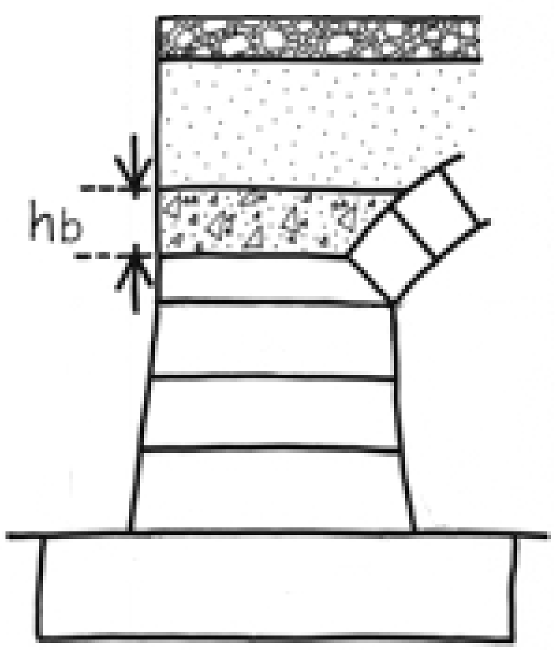


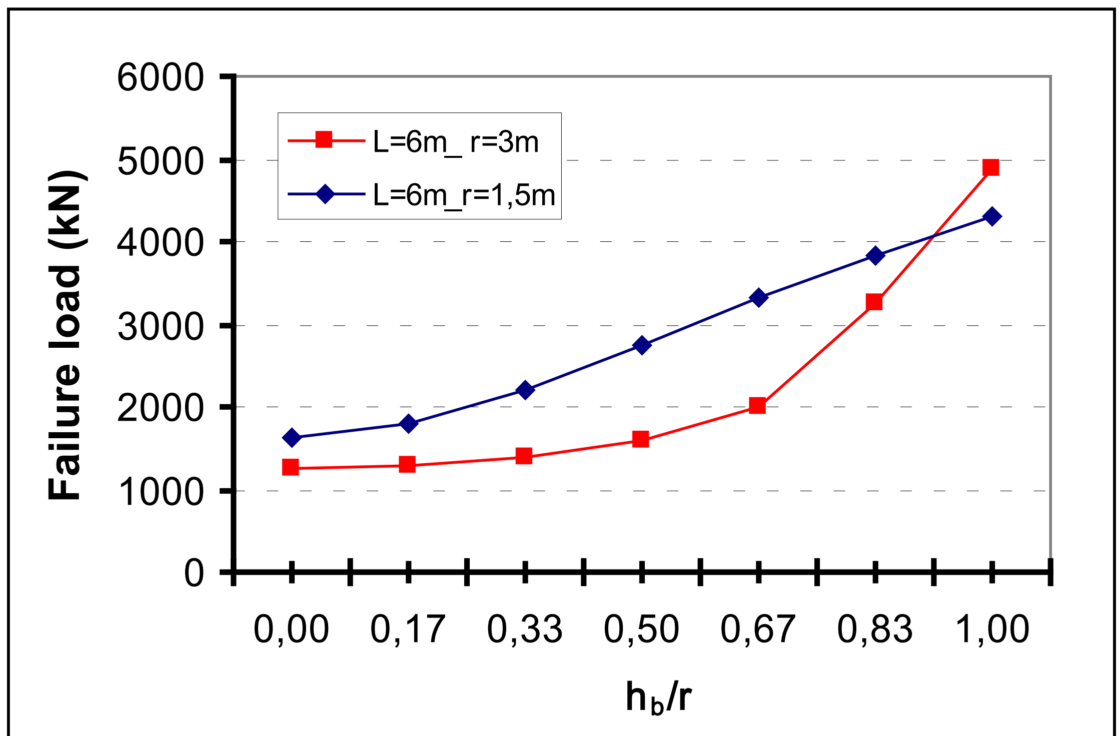
Possible failure mechanisms of a masonry vault

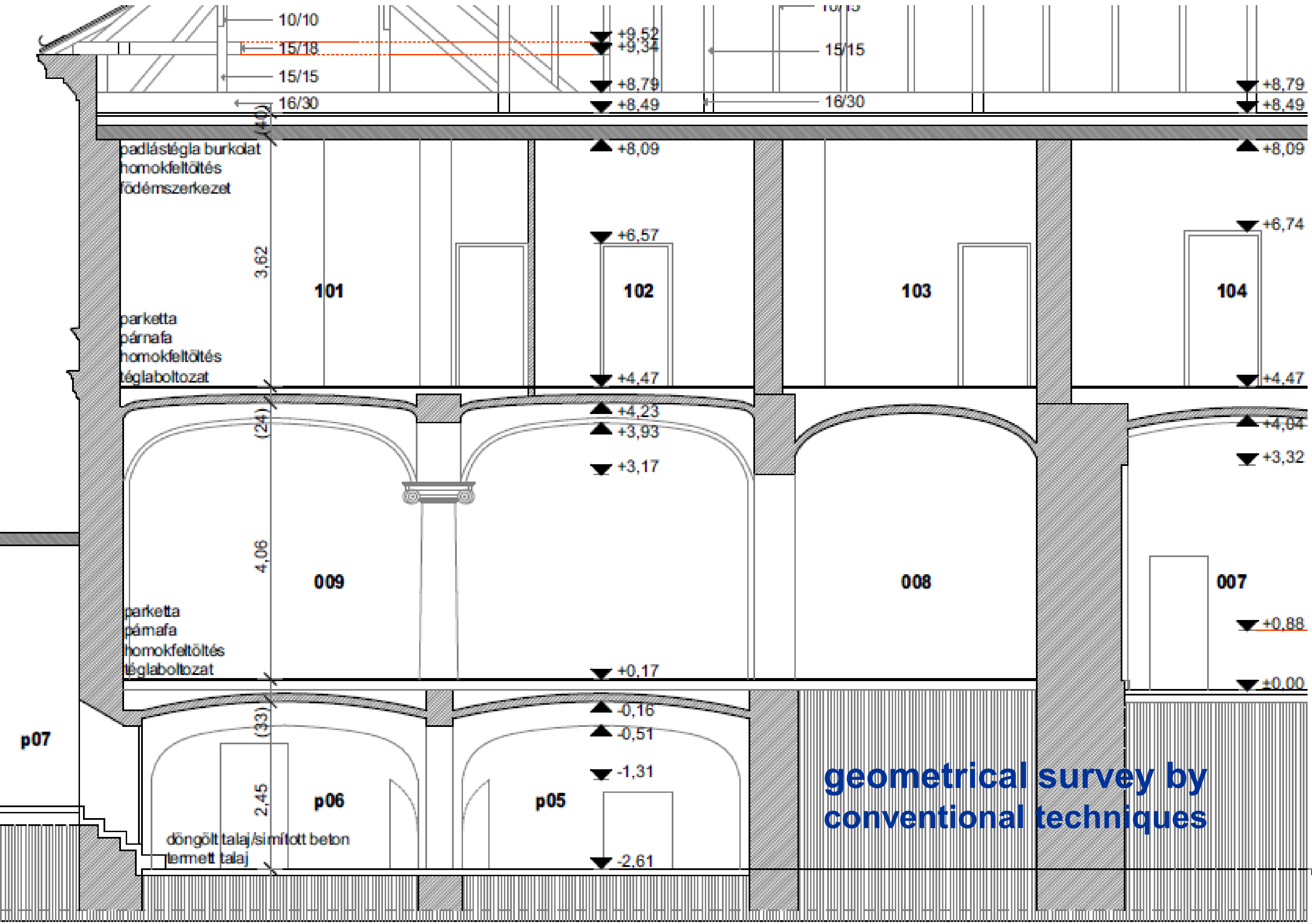


Effect of backing on failure load of vaults





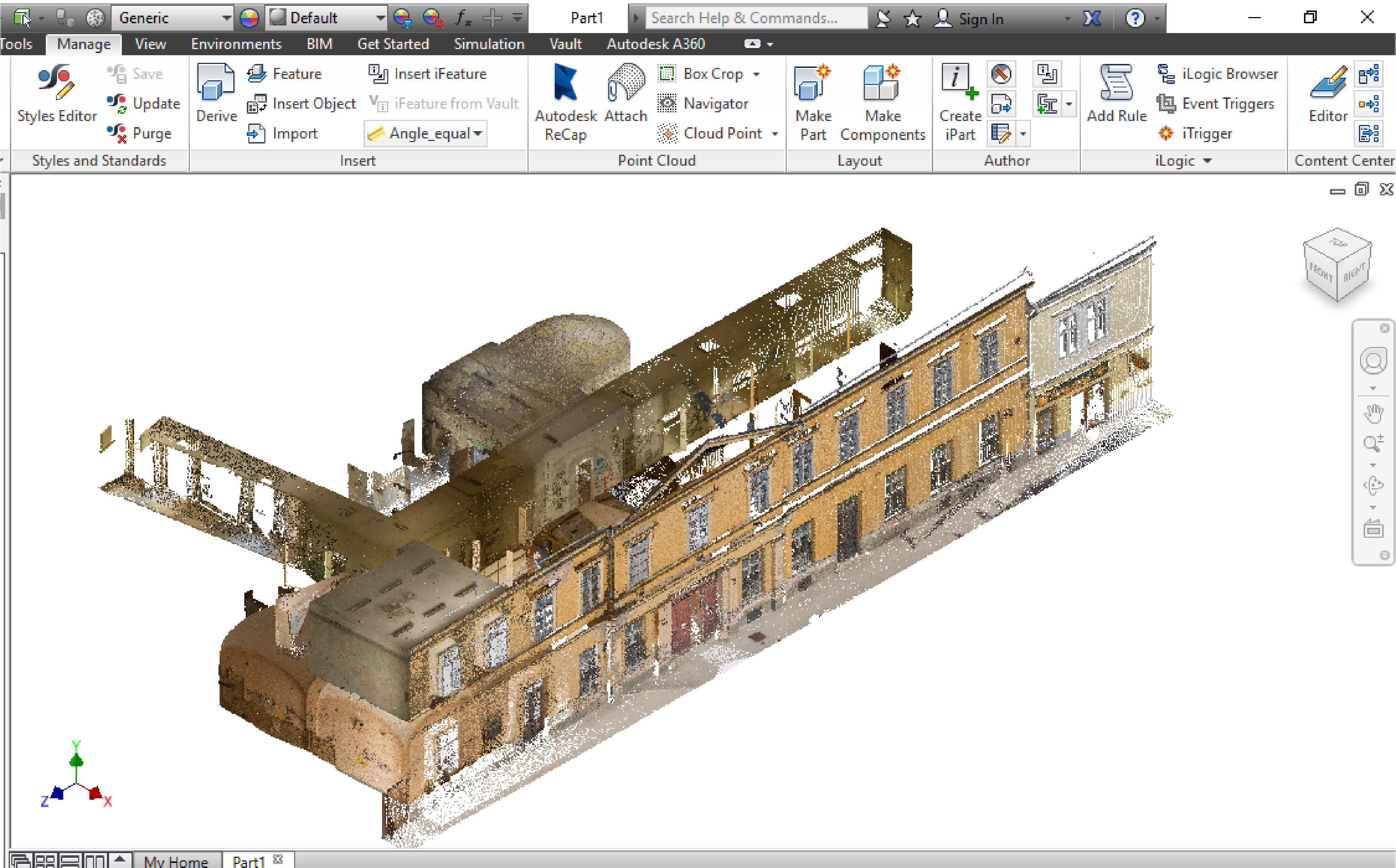


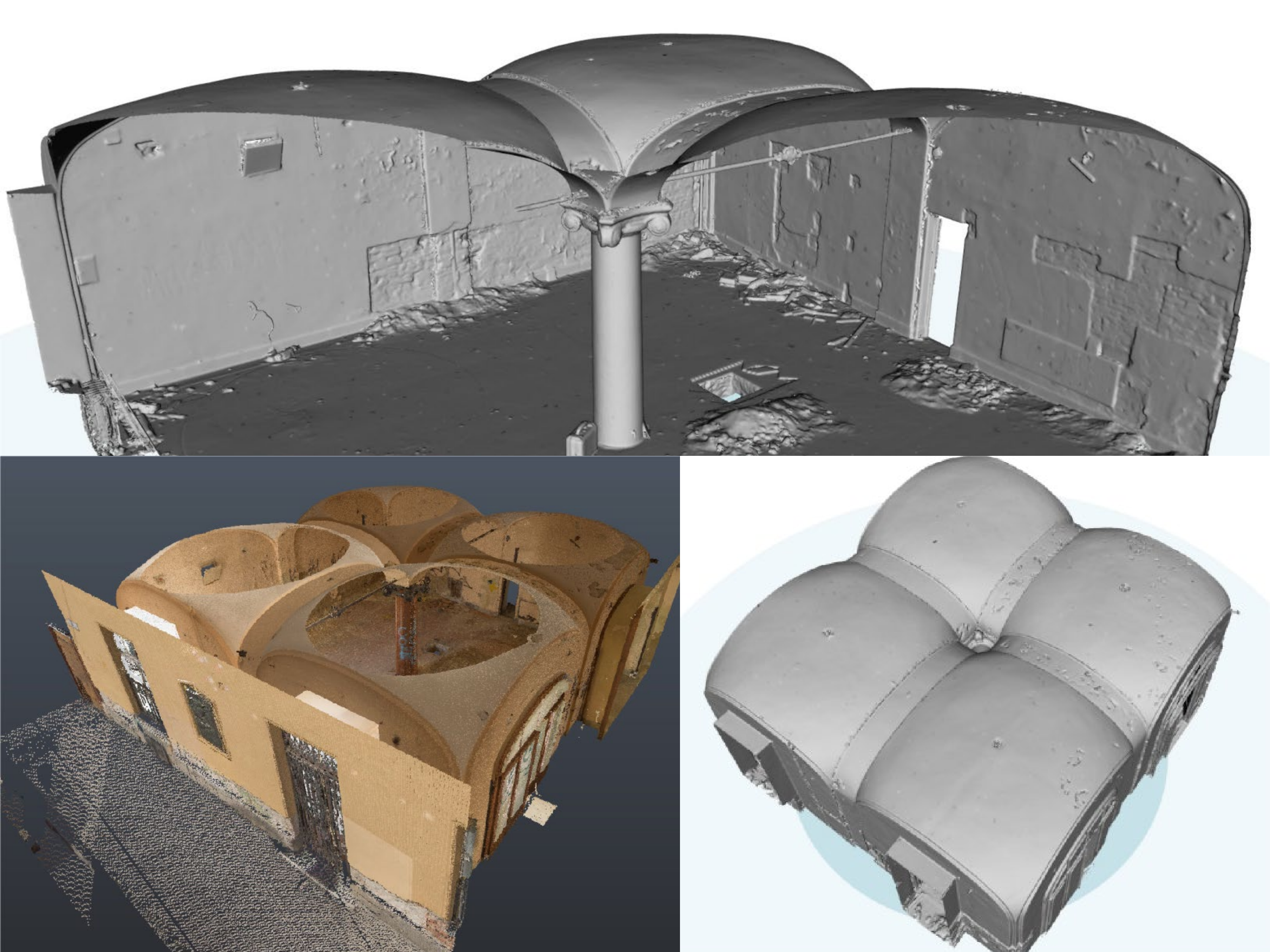


geometrical survey by conventional techniques

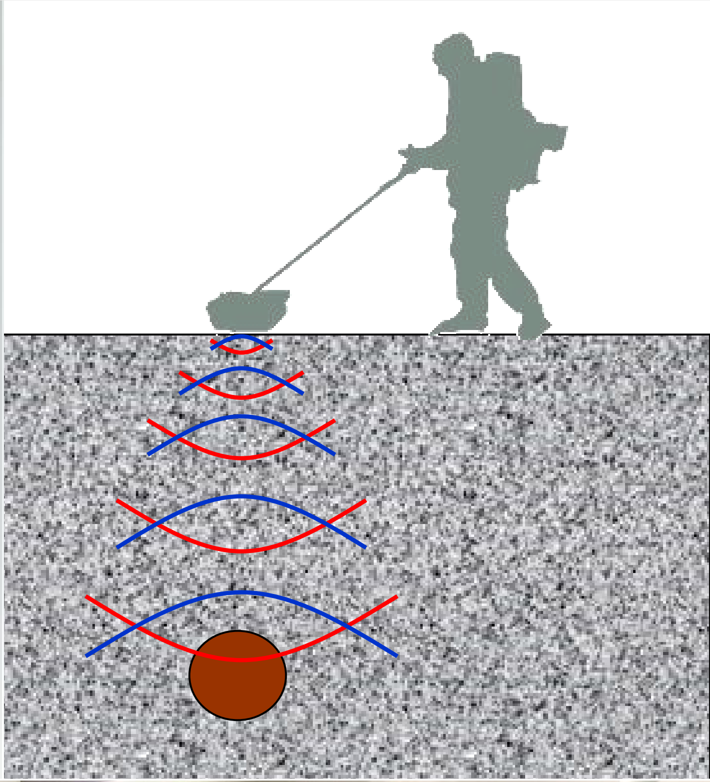
Geometrical survey (external) with 3D laser scanning

Processing of point cloud



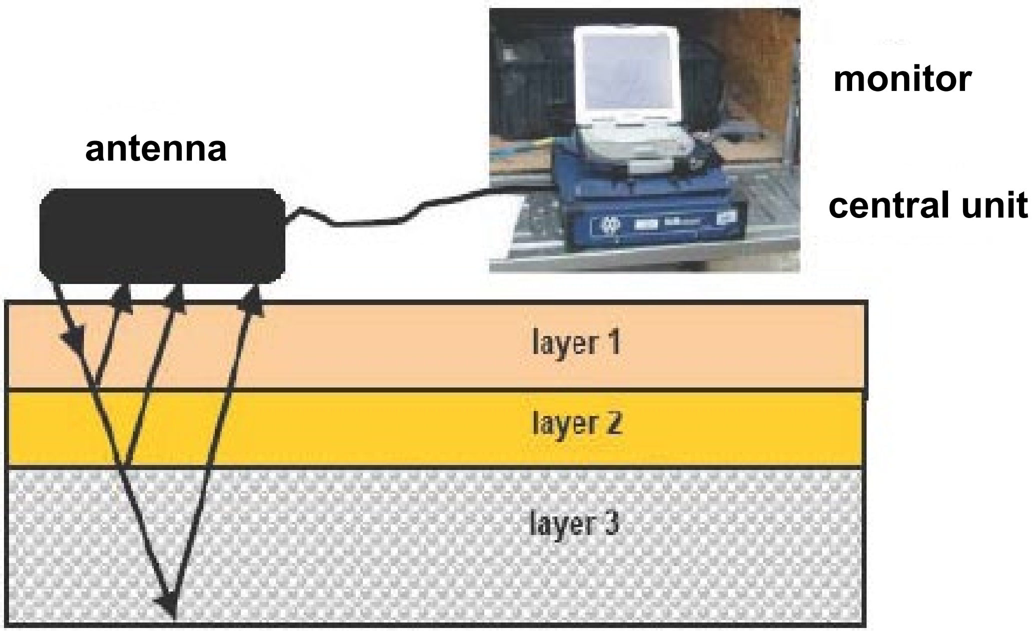


Geometrical survey (internal) by georadar

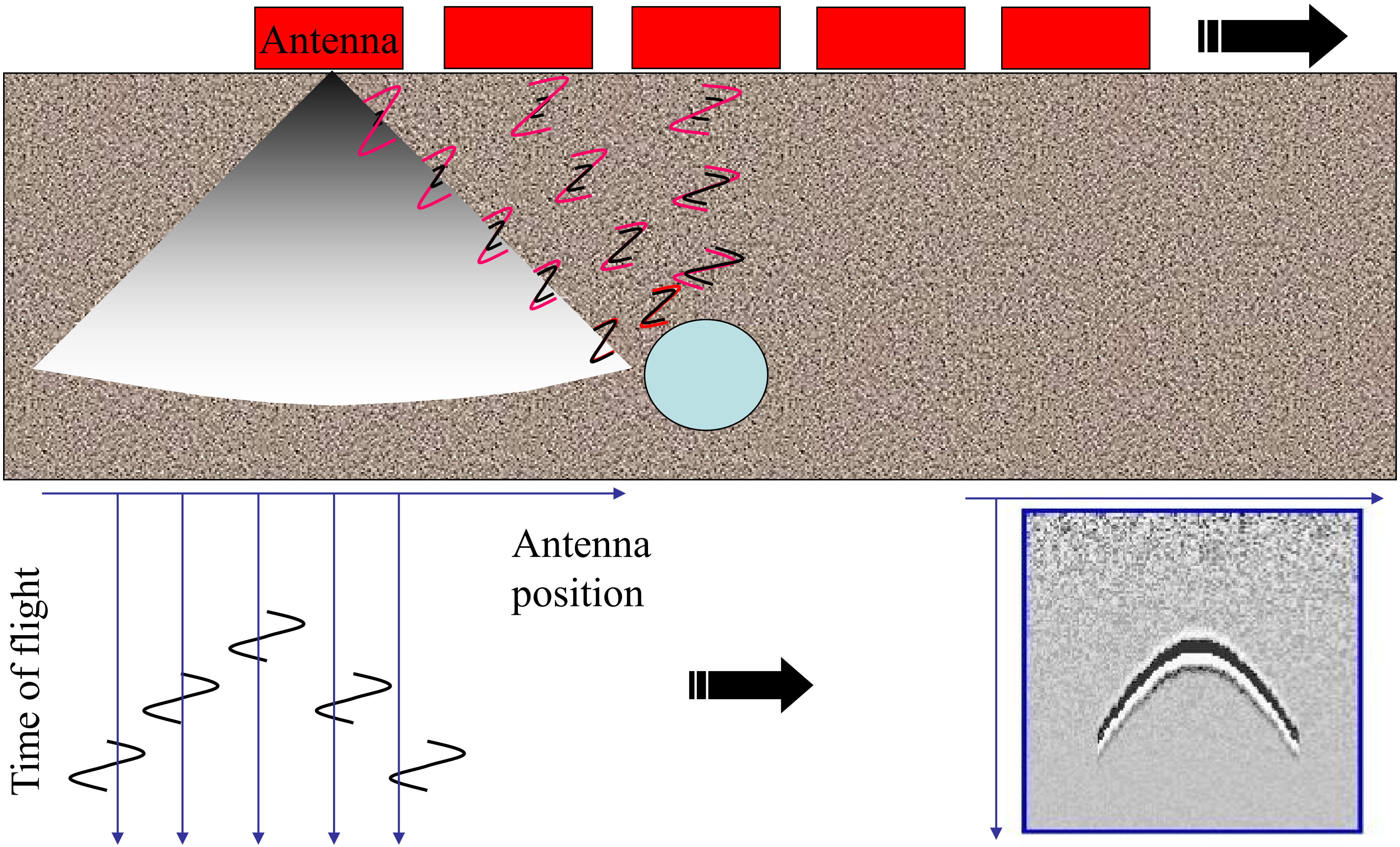


Ground Penetrating Radar (GPR)

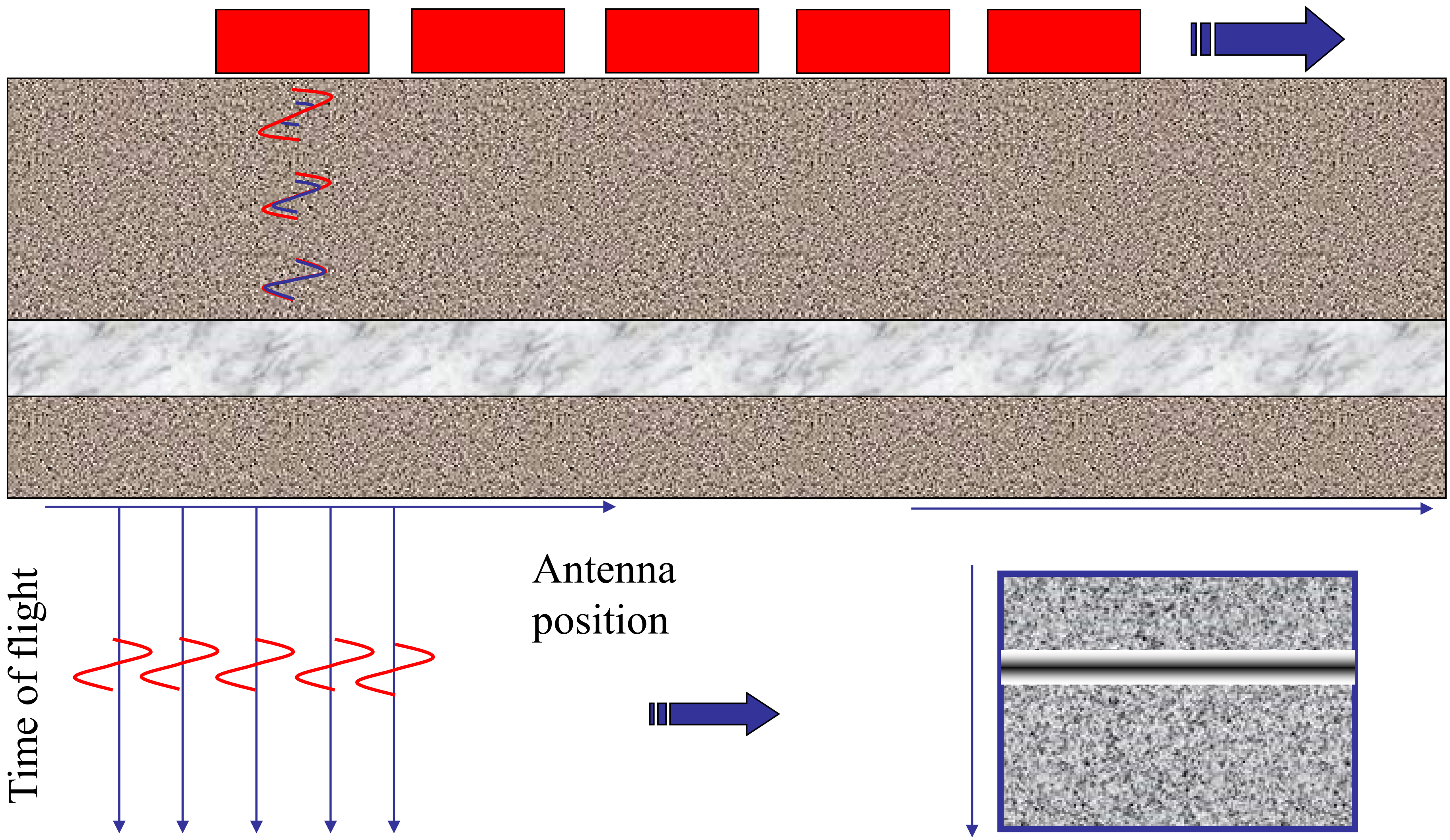
Electromagnetic impulses are transmitted into the material and recorded by a receiver.



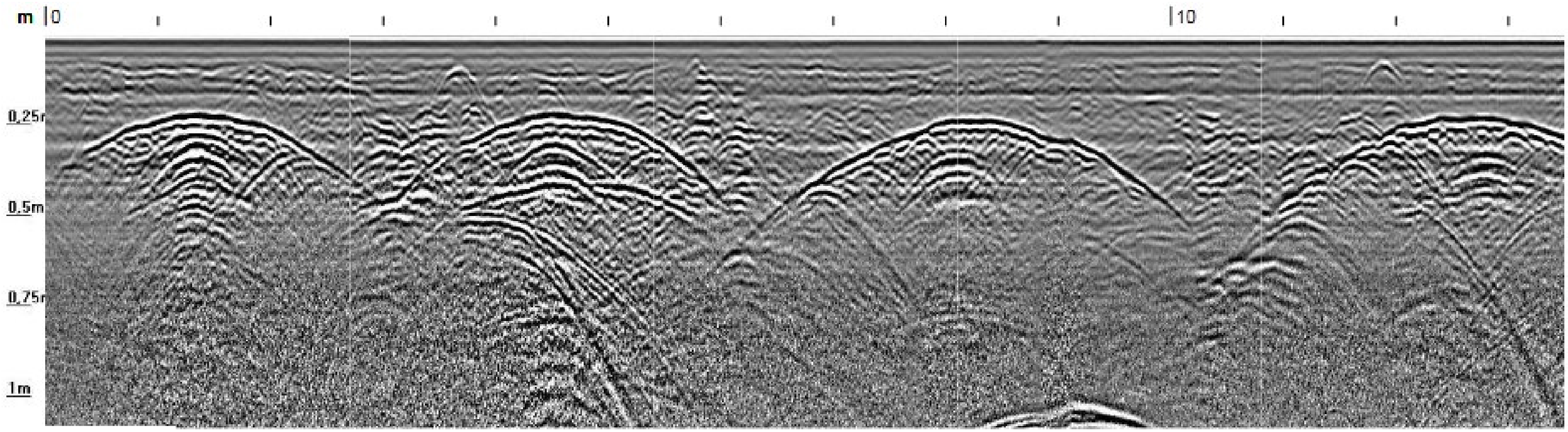
Detecting "point target" with GPR

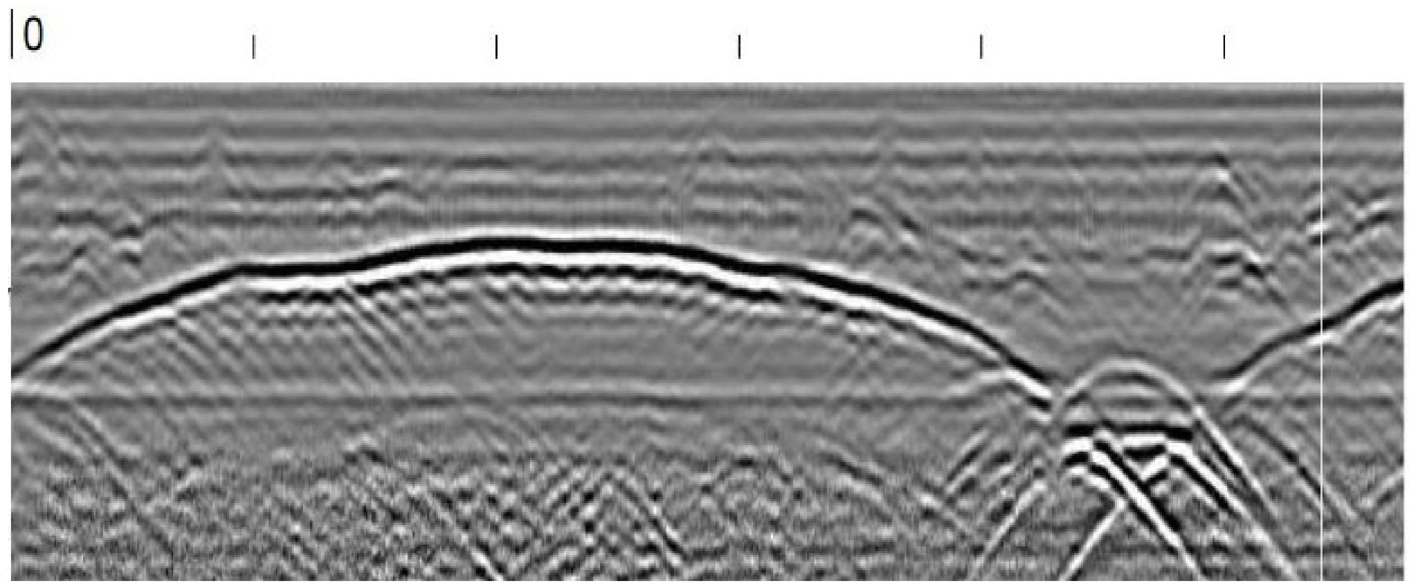


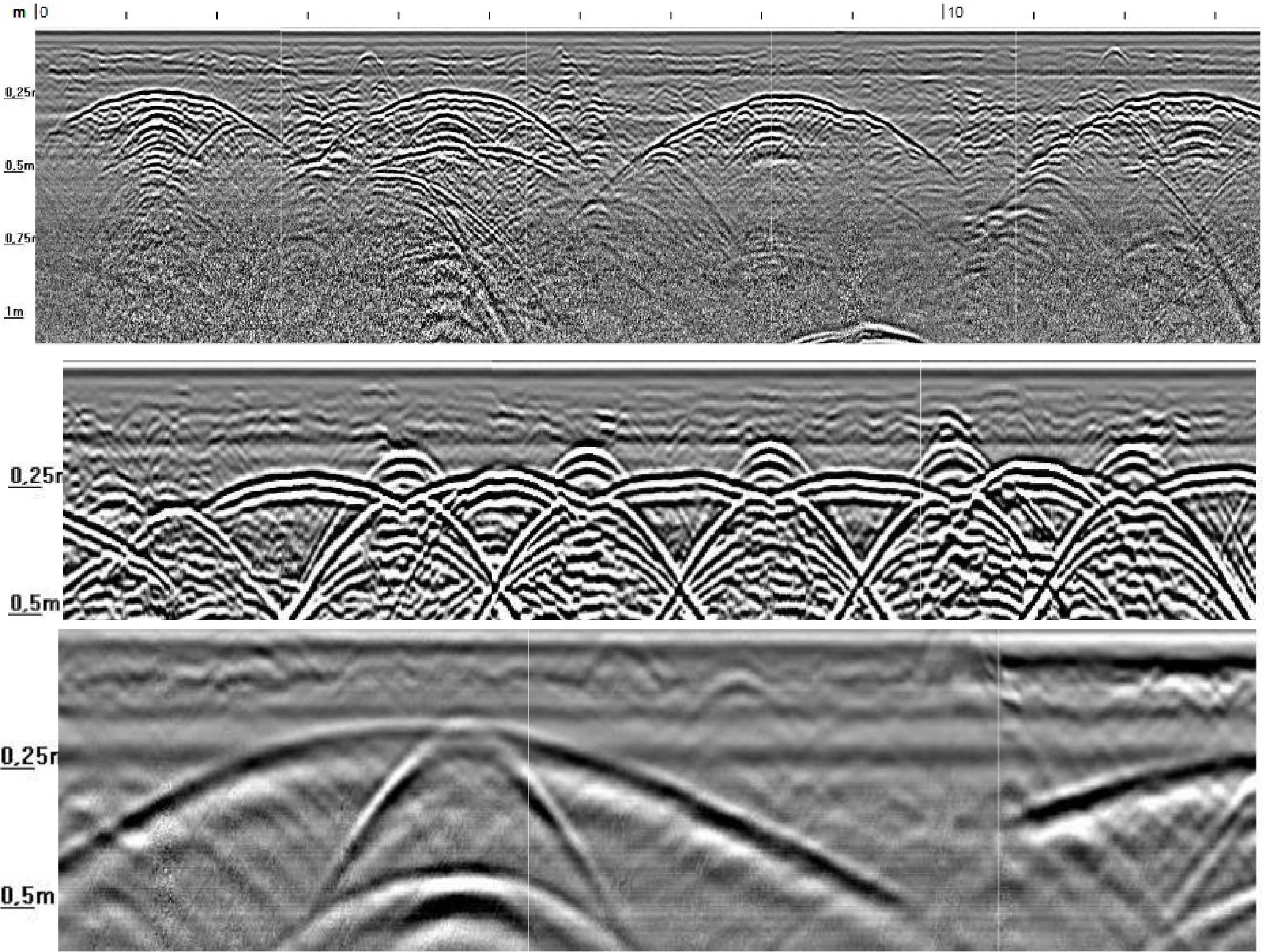
Detecting "linear target" with GPR



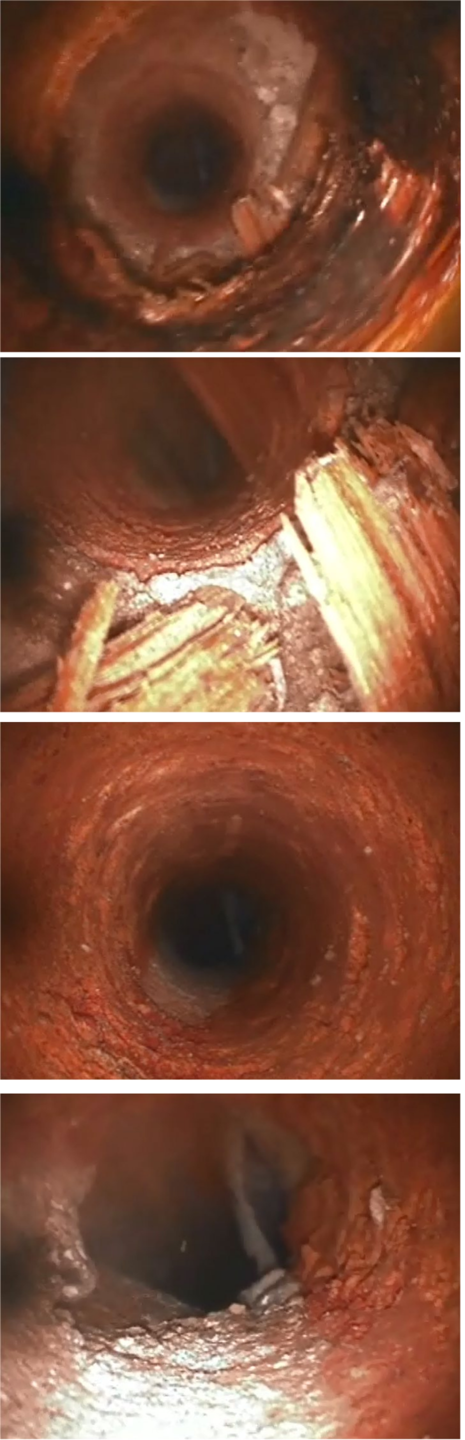
Tests on arches from upper surface

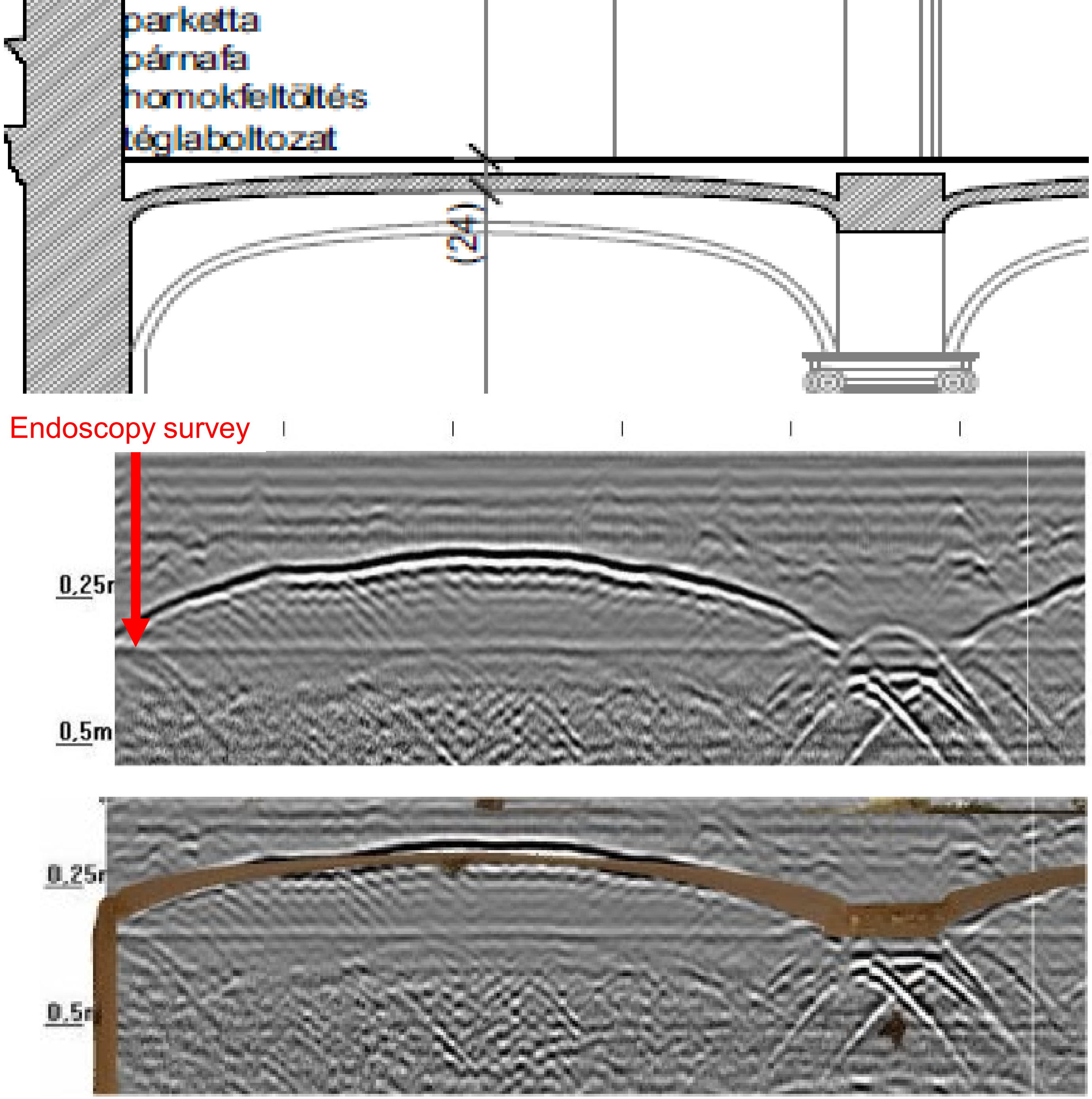




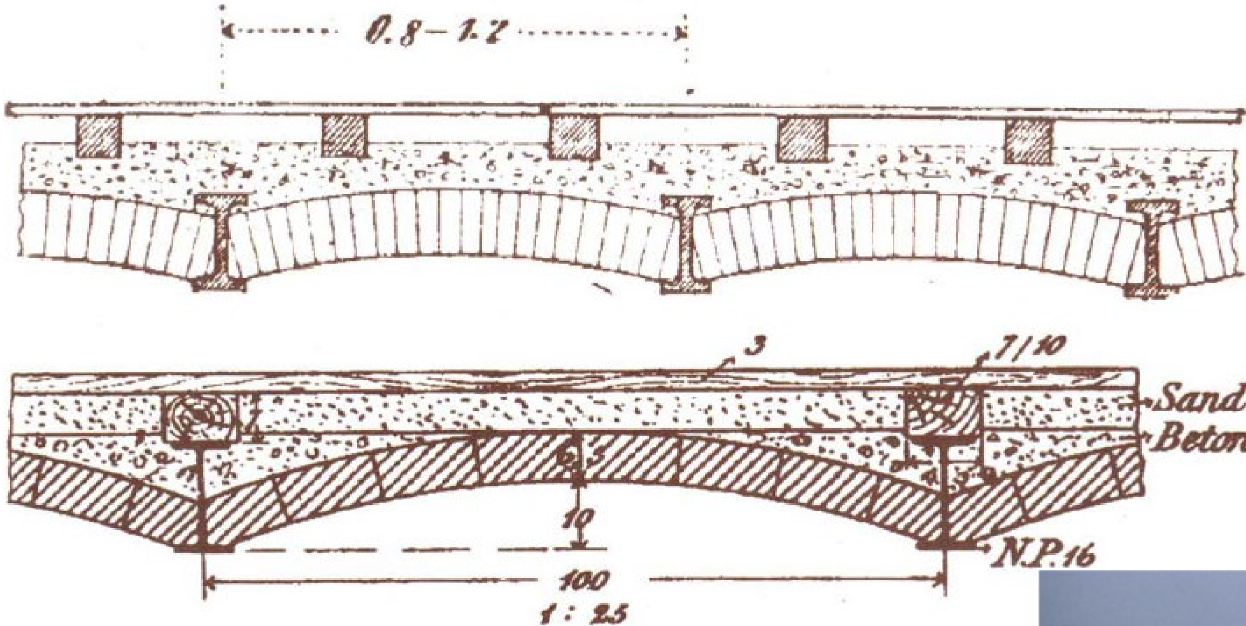

m
0
10
0,25r
0,5m
0,75r
1m
0,25r
0,5m
0,25r
0,5m

Geometrical survey and material tests with endoscopy

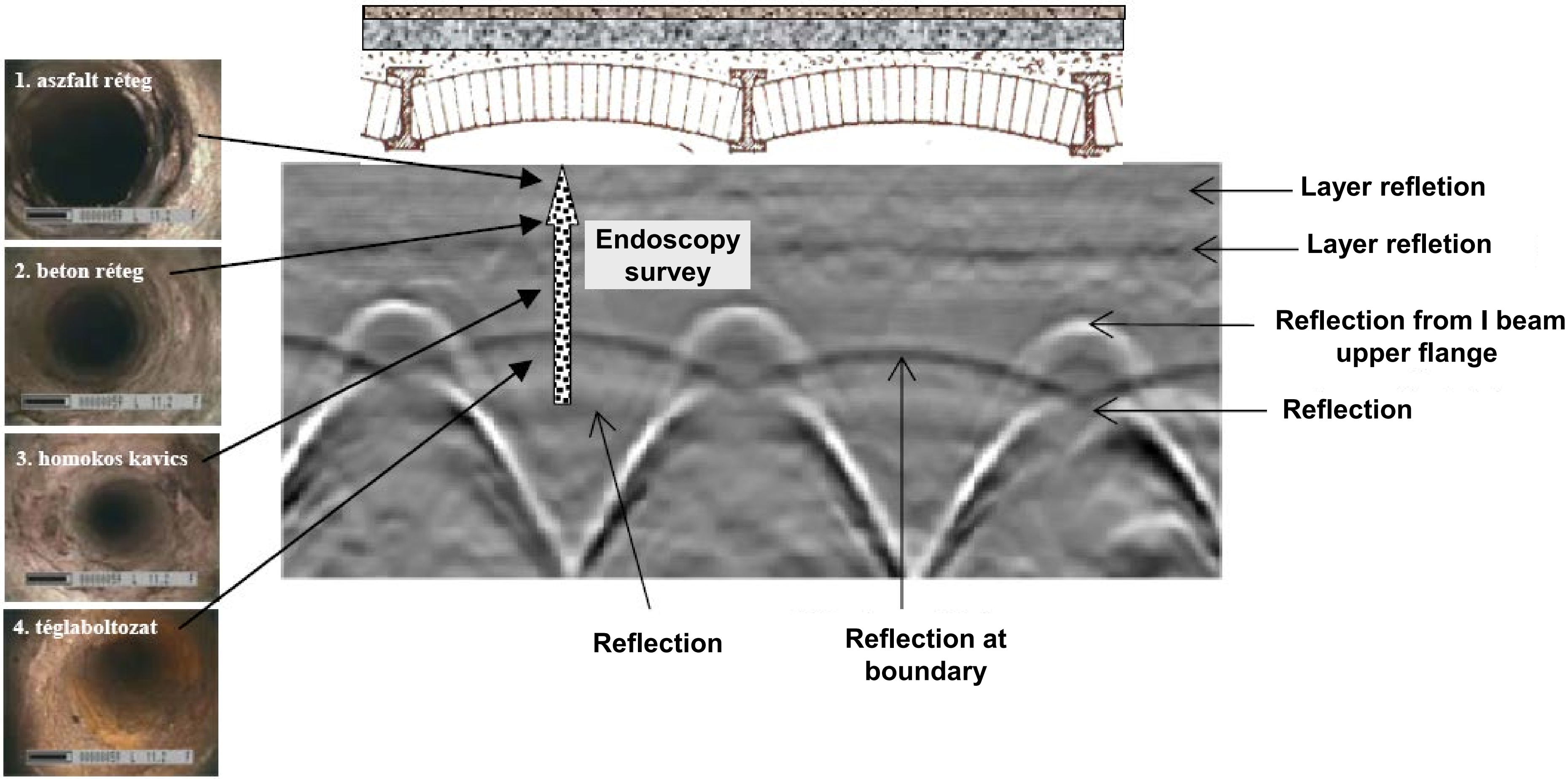



parketta
párnafa
homokfeltöltés
téglaboltozat
(24)
Endoscopy survey
0,25m
0,5m
0,25m
0,5m

Tests on Jack-arch floor structure



Tests on Jack-arch floor structure



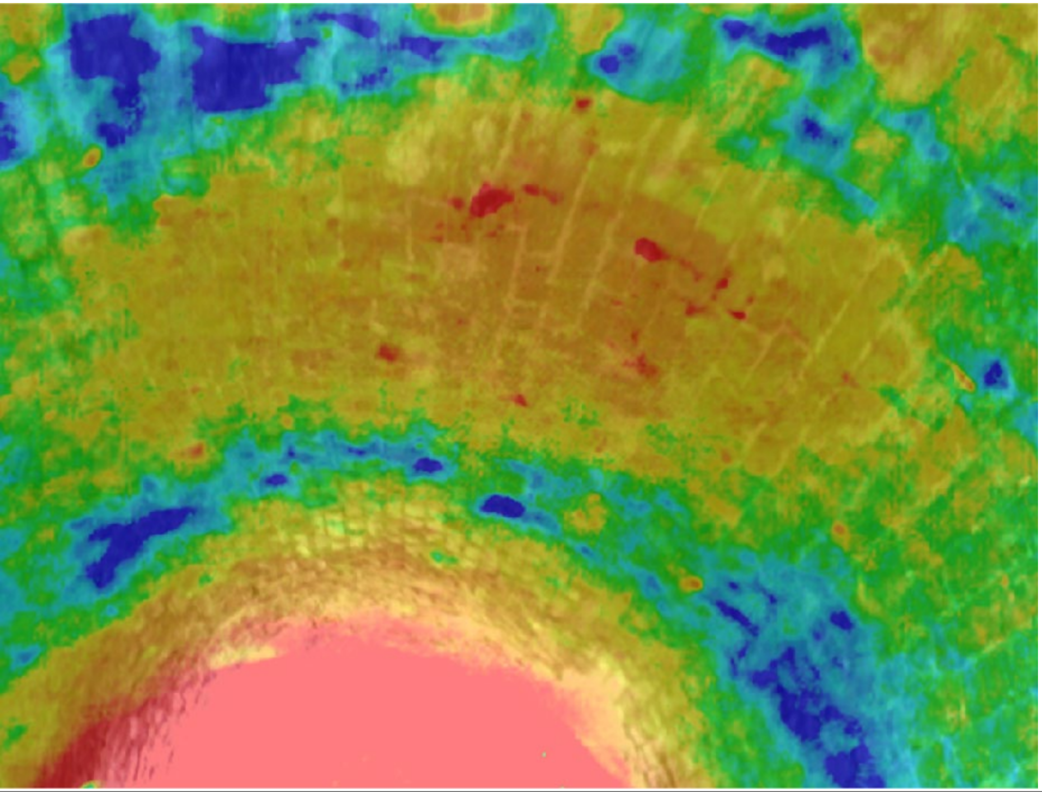
EF/F2 endoszkópos vizsgálat

Combination of GPR with endoscopy

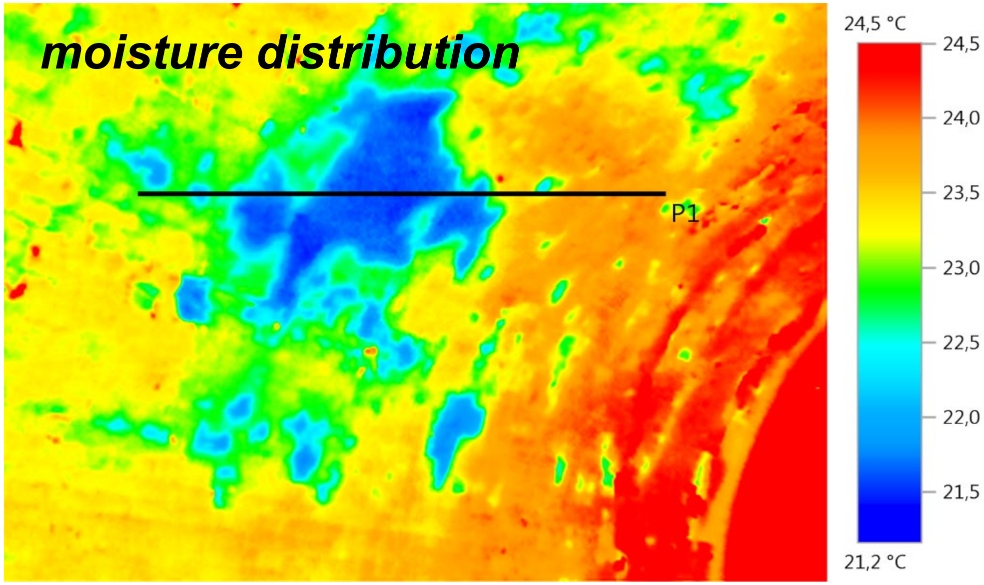
Other Non-Destructive Tests

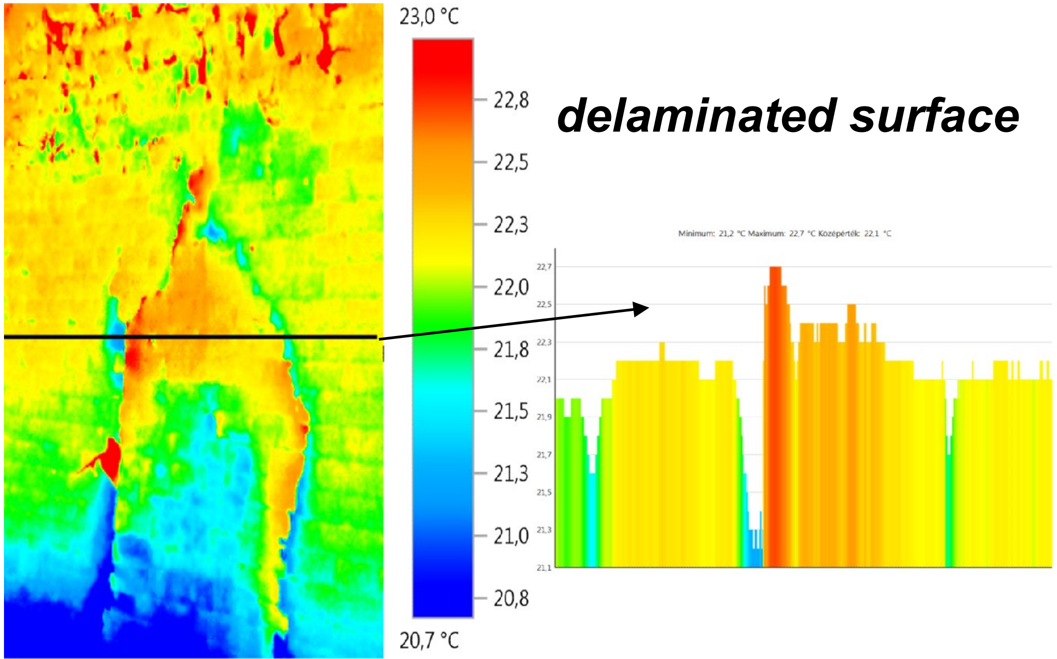
Infrared Thermography (IRT)

The thermal radiation from the surface is collected by an infrared camera.
The thermal radiation pattern is converted into a visual image.
Used to detect subsurface defects, material anomalies, cracks, moisture, etc.



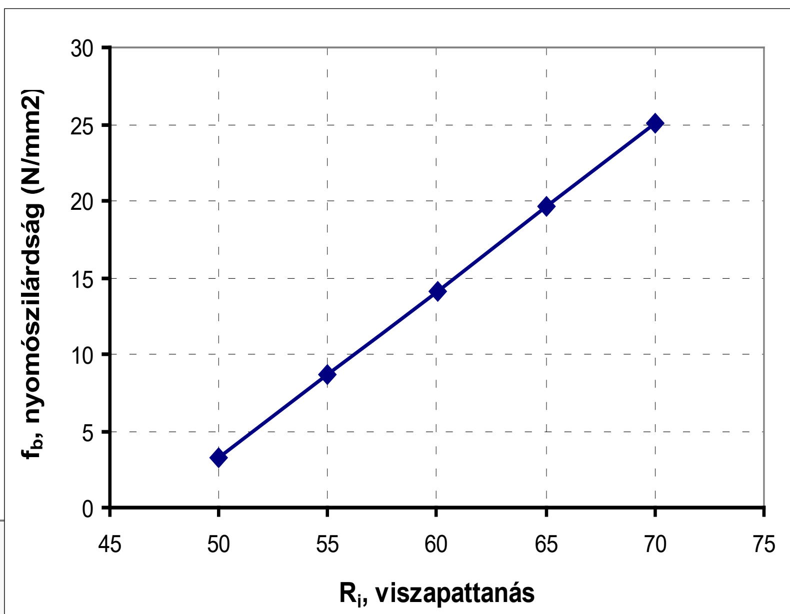
Combination of resistivity measurement and Infrared Thermography



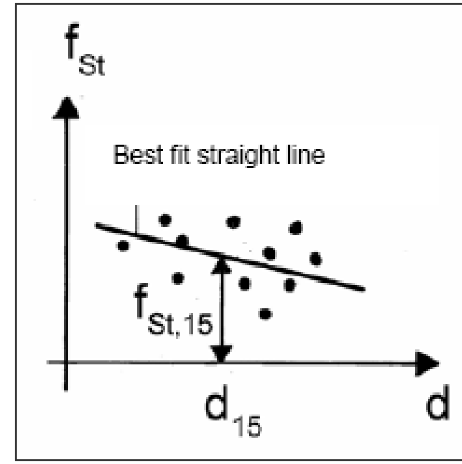


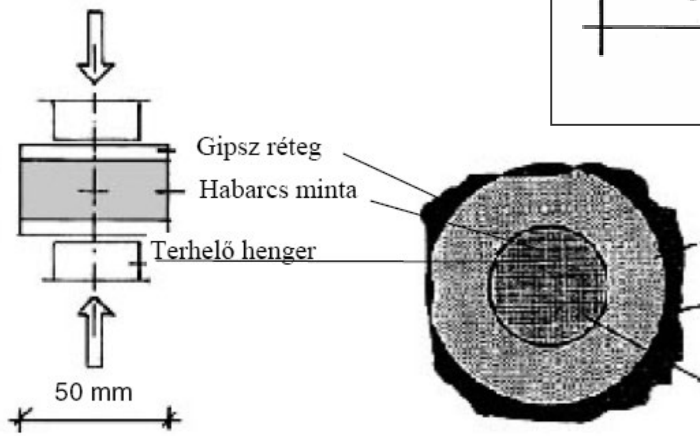
Other NDT tests

Measuring masonry strength with duroscope



Punch test on mortar





1 Housing with handle

2 Reset lever

3 Hammer complete (PM/PT)

4 Trigger button

5 Scale (Rebound value)

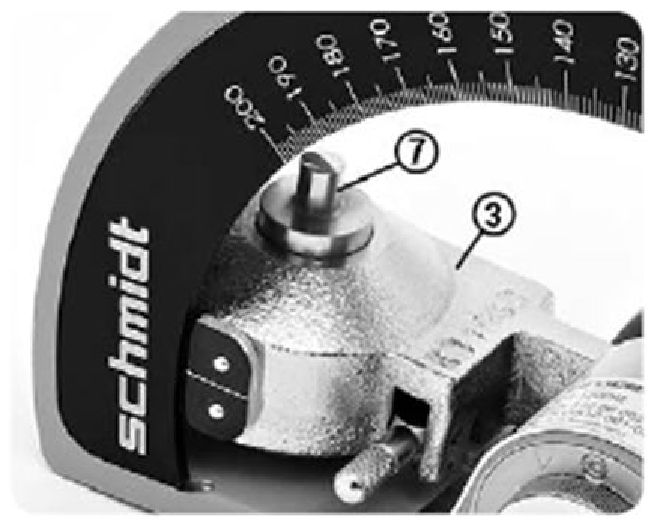
6 Control knob

7 Hammer head (PM/PT)

A Contact surface

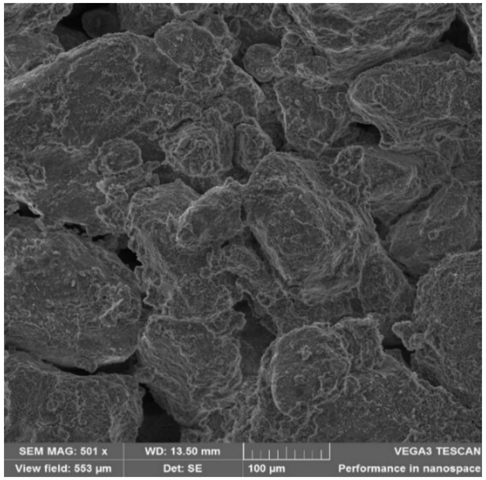
B Loading position

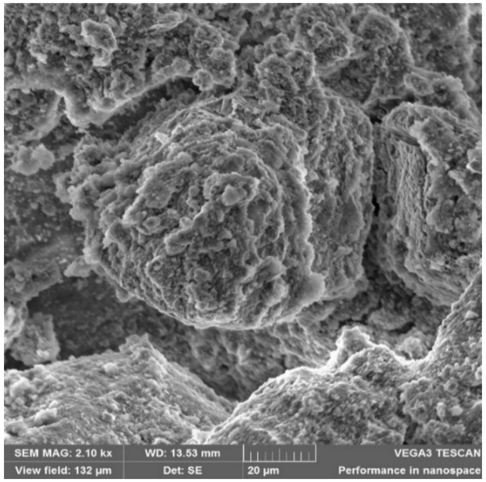
Hammer head Schmidt OS-120PT (7)

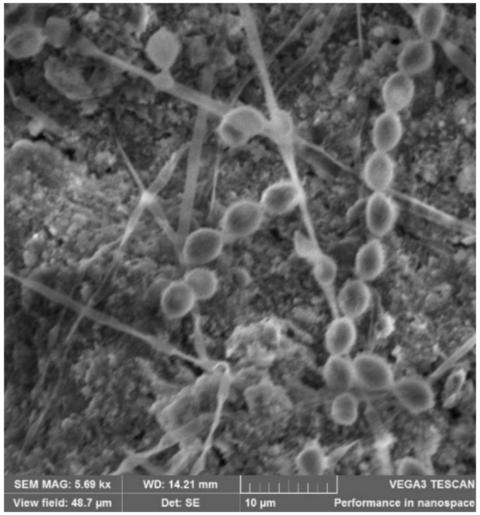


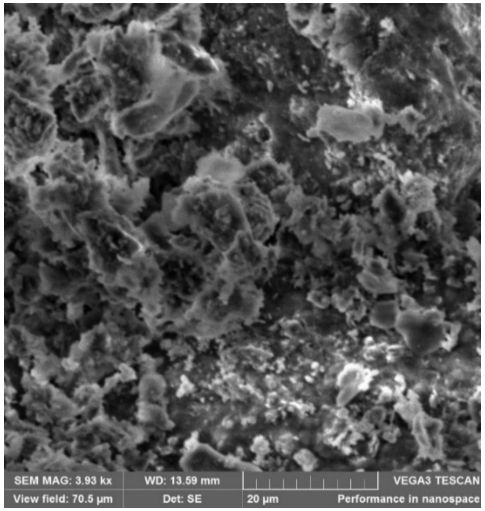
Hammer head Schmidt OS-120PM (7)

Material tests with electron microscope

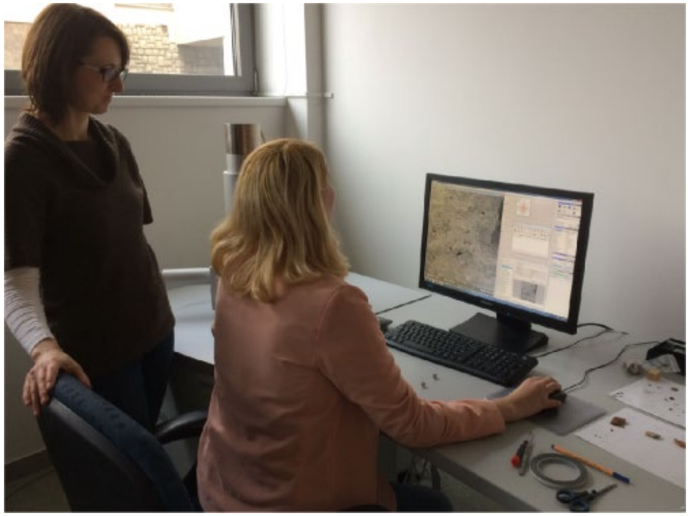






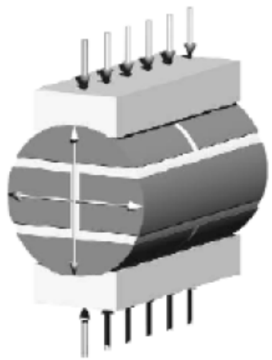


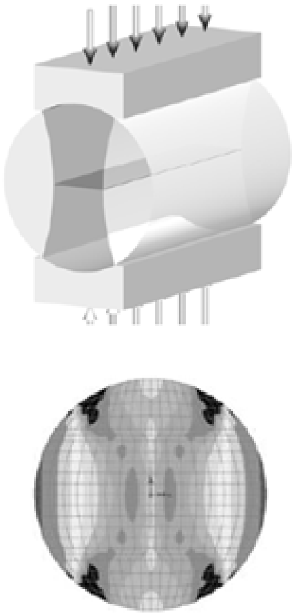
Tests on mortar



Destructive tests

Test on large diameter cored samples





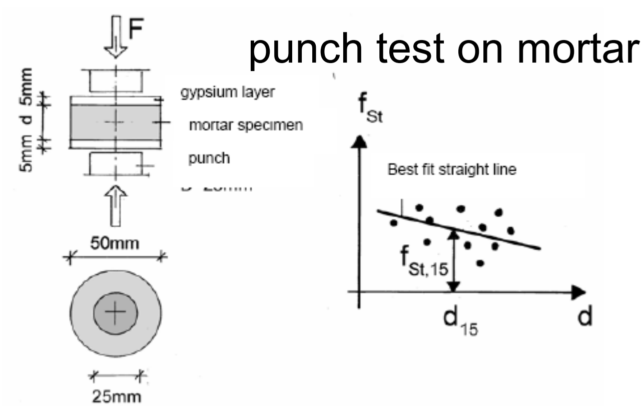
$$f_c^{\,M} = q\frac{F_{ult}}{\phi\, l}$$

where

q = correction factor ∈ (1,8 or 2,2)
ϕ = the cylinder diameter
l = the specimen length (typically 100 - 240 mm)

The strength of masonry

Test on small diameter cored samples



$$f_k = K f_b^{0.7} f_m^{0.3}$$

f_b is the normalized compressive strength of the masonry units in N/mm^2,

f_m is the specified compressive strength of the general purpose mortar in N/mm^2

K constant (K≈0,5)

DIAGNOSTICS OF STRUCTURES

LECTURE 08

Assessment and rehabilitation of heritage structures help de by combined non-destructive tests – Part2

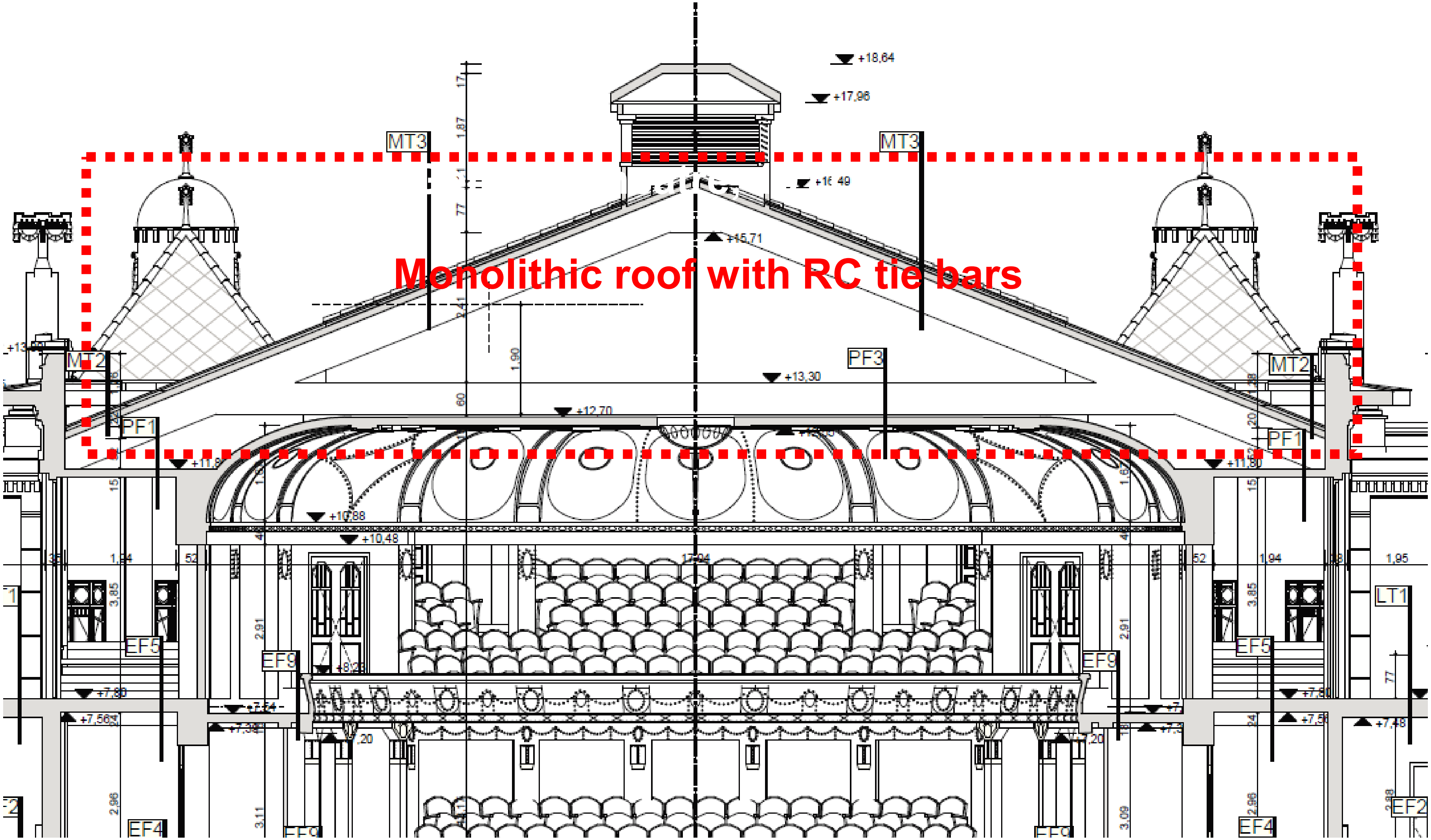
Zoltán Orbán

University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Case Study 2.


Csíky Gergely Theatre in Kaposvár, 1911
CSIKY GERGELY SZINHAZ
SZÍNHÁZ
MŰEMLÉK
ÉPÜLET
ÉPÜLT 1911-BEN
SZECESSZIÓS
STÍLUSBAN



Csiki Gergely Theatre, 1911

ASSESSMENT AND REHABILITATION OF HERITAGE STRUCTURES HELPED BY COMBINED NDT TESTS


Real splay?

Aim of survey

Determination of the load-bearing structural system

Visual inspection of structural damages

Measuring the strength of building materials
(concrete, steel, masonry – with various methods)

Investigation of structural properties
(dimensions, reinforcement, concrete cover, layers)

Investigation of durability properties
(moisture content, carbonation, corrosion)

DESTRUCTIVE

Non-Destructive

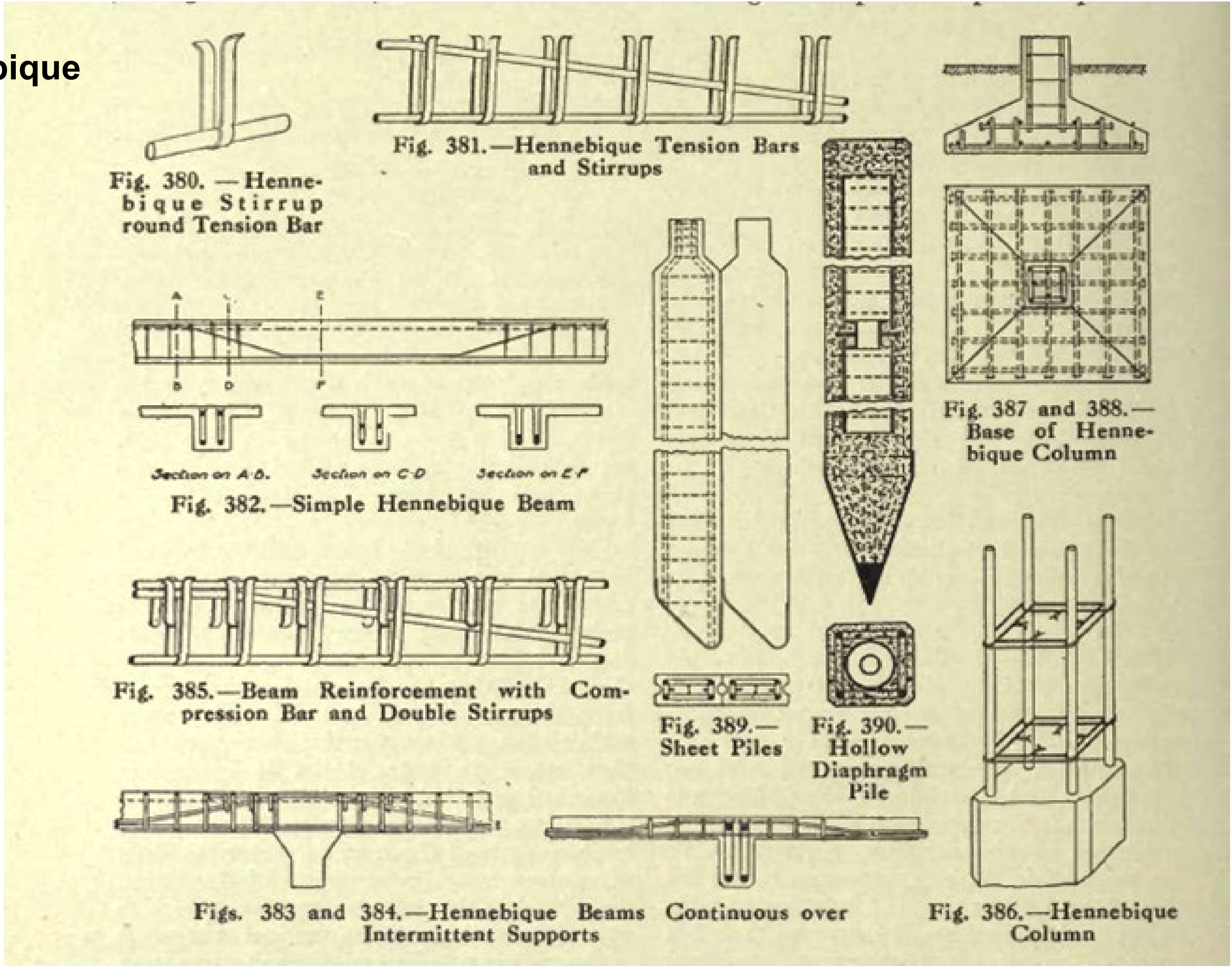
Semi-Destructive

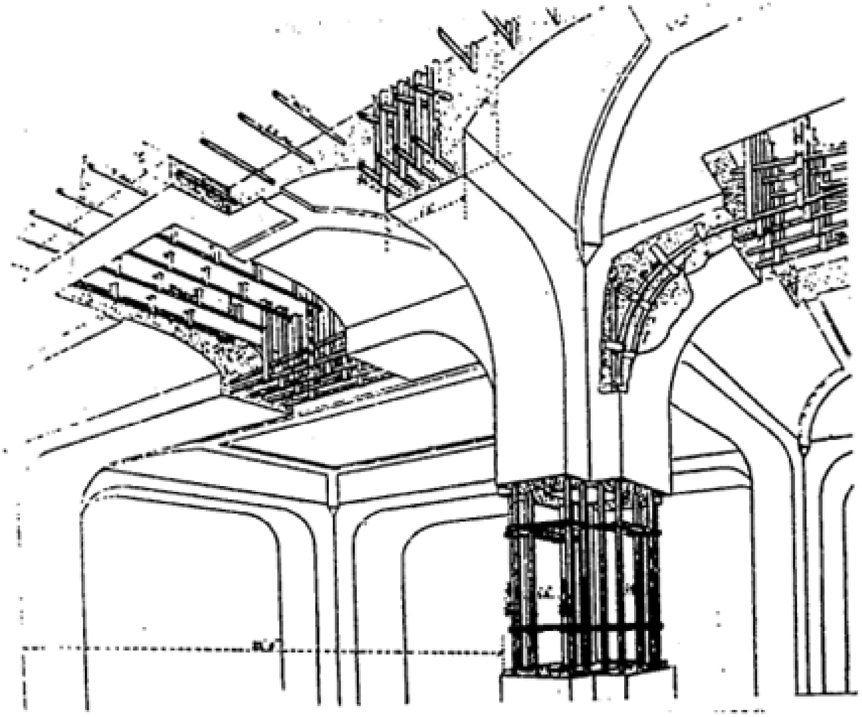
Providing basic parameters for the static analysis, assessment of structural safety and preparation of repair/strengthening measures

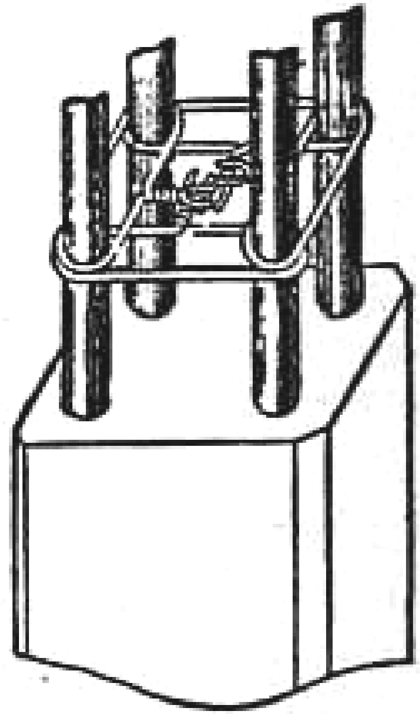
Concrete technology aspects

- No designed grading curve for aggregates
- The rule of water to cement ratio was not known (only after 1918)
- The term fineness modulus was not known yet
- Mixing machines were used
- Manual transportation of mixed concrete
- Compaction of concrete with tampering

Hennebique system







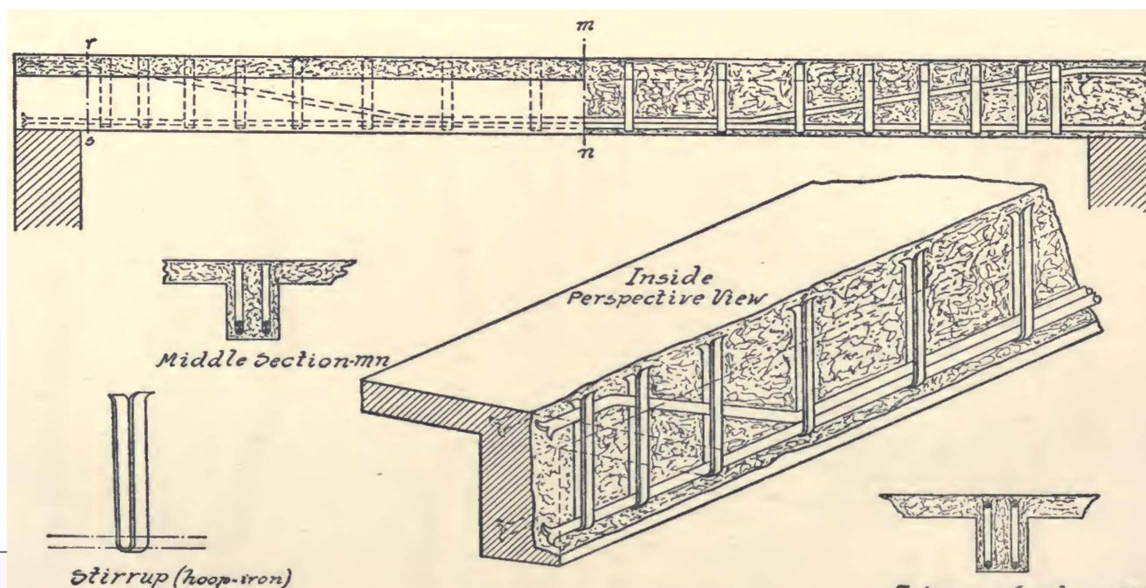


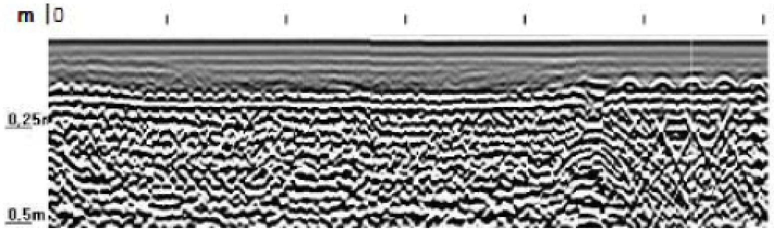
Fig. 99. Typical Hennebique Beam.

The test project

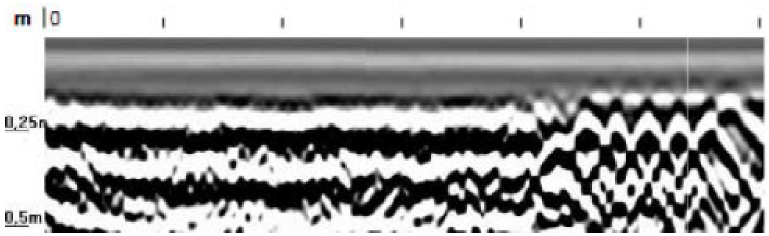
- **Magnetic rebar locator**


● Test with georadar
(with dual frequency antenna)

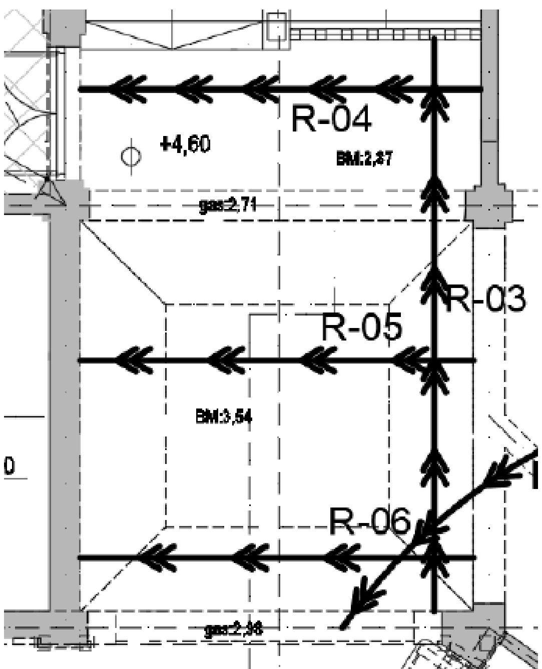
R03. vizsgálati hely – 1. emeleti födémen
A radarszelvény hossza: 6,05 m



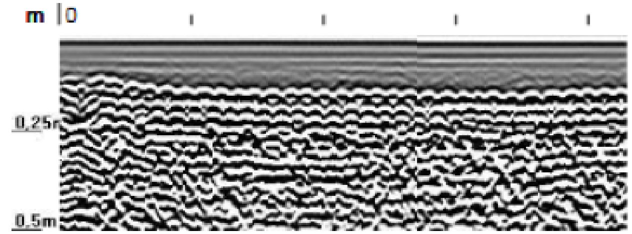
1600 MHz frekvenciás felvétel



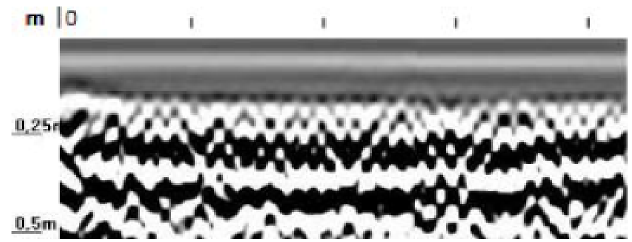
600 MHz frekvenciás felvétel



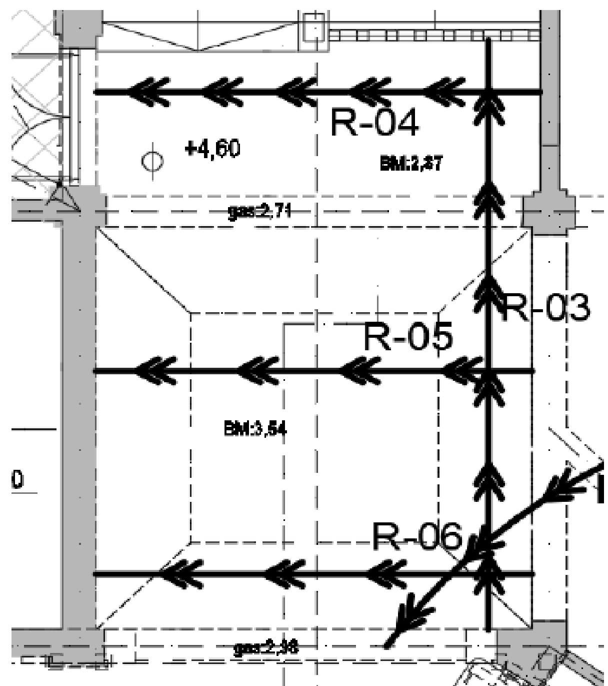
R05. vizsgálati hely – 1. emeleti födémen
A radarszelvény hossza: 4,30 m



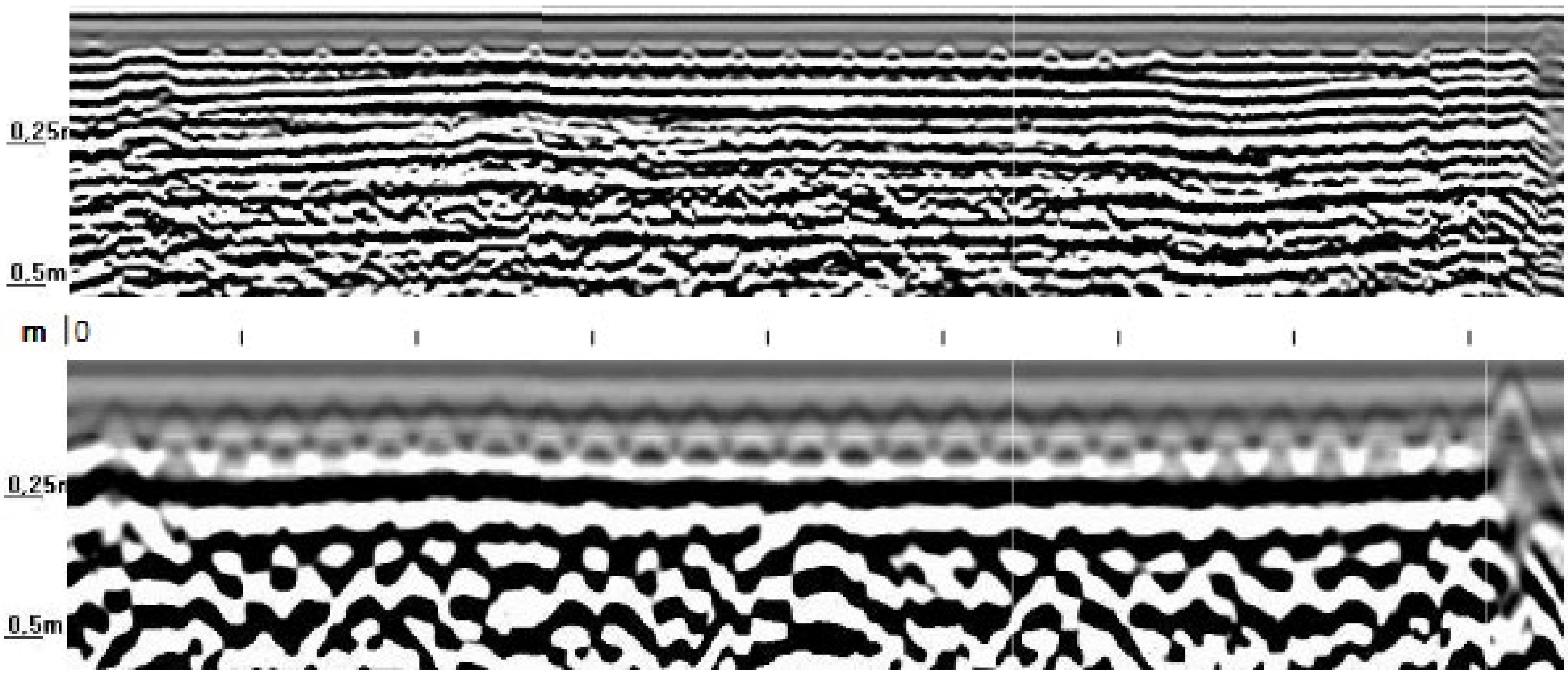
1600 MHz frekvenciás felvétel



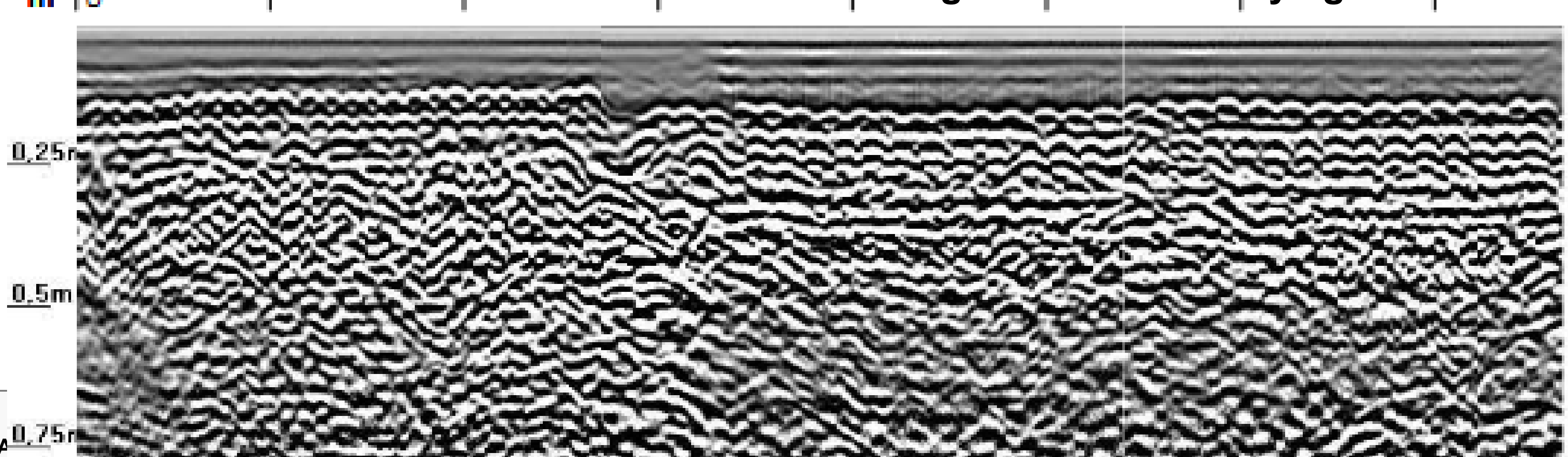
600 MHz frekvenciás felvétel



Radar image of slab with constant thickness

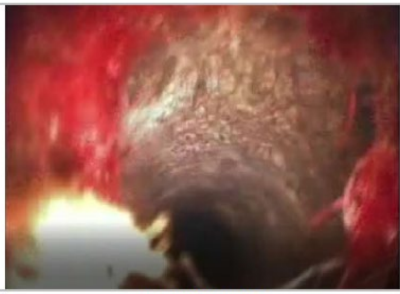


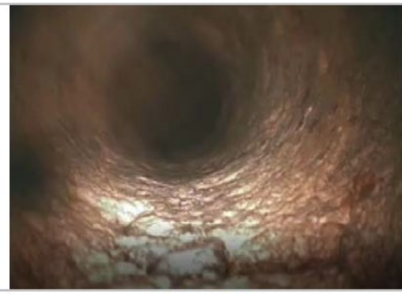
Radar image of slab with varying thickness



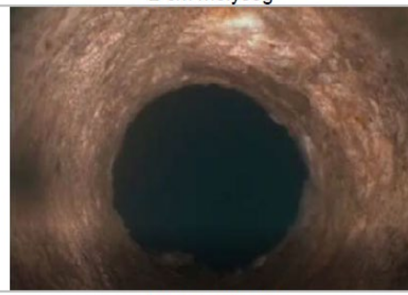
- **Tests with videoendoscopy** **(semi-destructive)**

E30. vizsgálati hely – 1. emelet, födémen keresztül
A fúrt lyuk hossza: 11,3 cm, átmérője: 18 mm

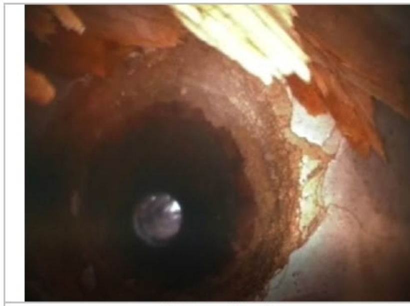

0 cm mélység


2 cm mélység


5 cm mélység


10 cm mélység

E13. vizsgálati hely – padlásszint, falon keresztül
A fúrt lyuk hossza: 30 cm, átmérője: 18 mm


5 cm mélység


25 cm mélység

Megállapítás: A vizsgálat alapján a falvastagság 30 cm, anyaga tégla.

E16. vizsgálati hely – padlásszint, falon keresztül
A fúrt lyuk hossza: 23 cm, átmérője: 18 mm


5 cm mélység

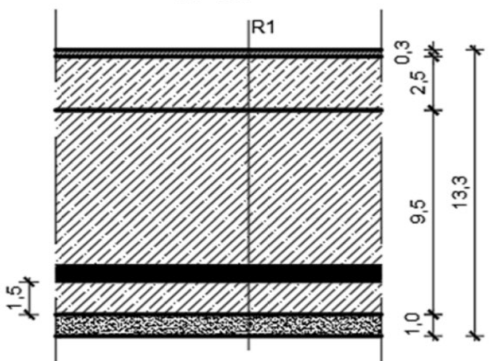

15 cm mélység

Megállapítás: A vizsgálat alapján a falvastagság 23 cm, anyaga beton. 15 cm-nél réteghatár található.

Hely: 2. emelet karzat

Készült E29 jelű videoendoszkópos vizsgálat és 2/13 jelű feltárás alapján.

1-es részlet
M=1:2



R1	
Linóleum	1 rtg
Kiegyenlítő aljzat	2,5 cm
Vasbeton lemez	9,5 cm
Vakolat	1,0 cm

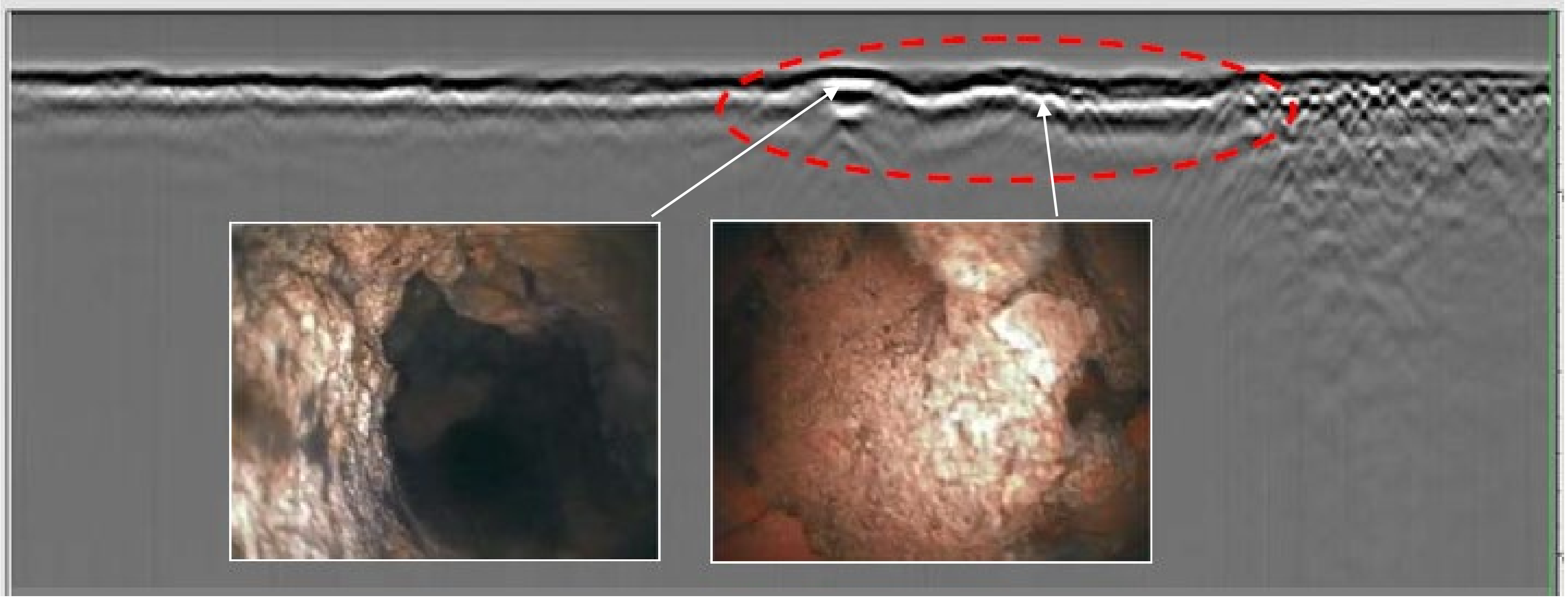
Thickness and layers of RC floors

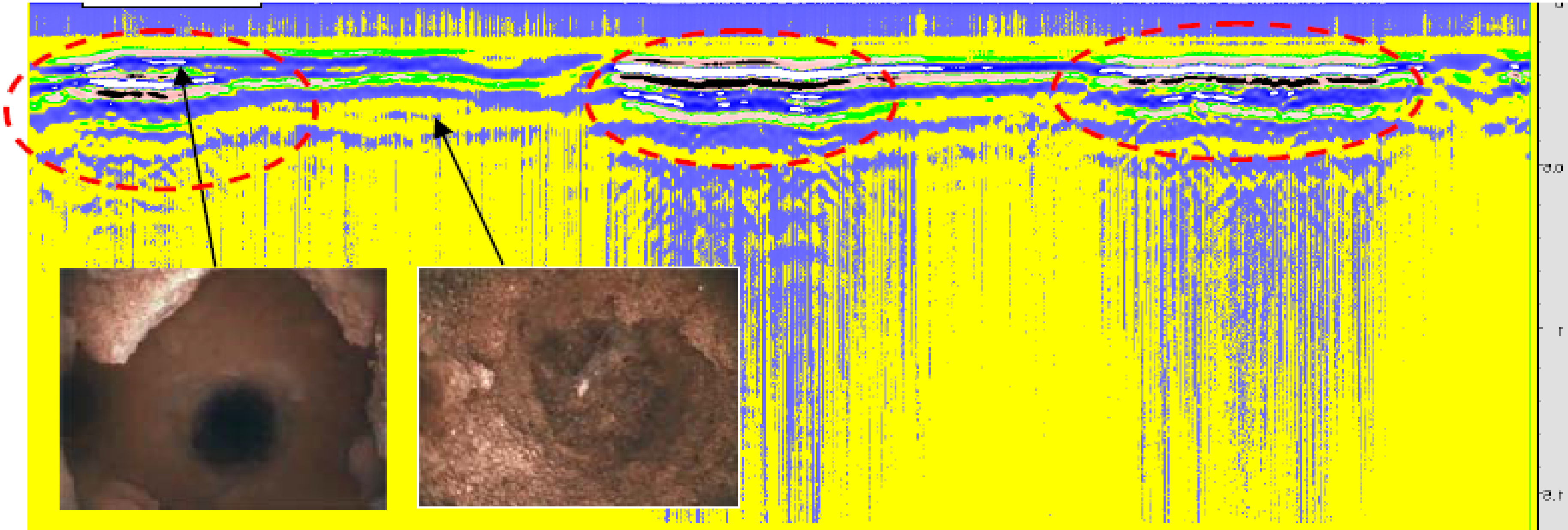
Thickness and layers of walls

Variation of materials

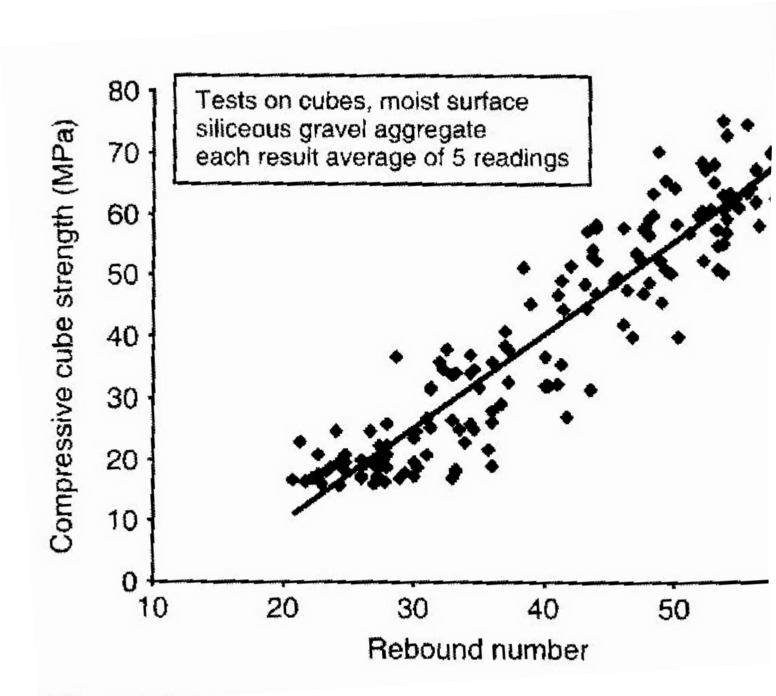
Internal defects

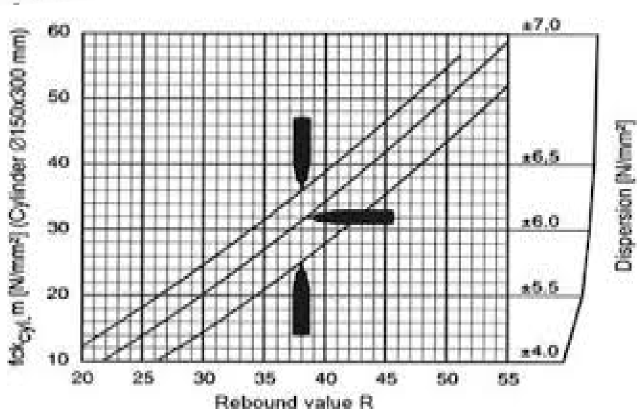
Combination of georadar and endoscopy tests on concrete floor slab





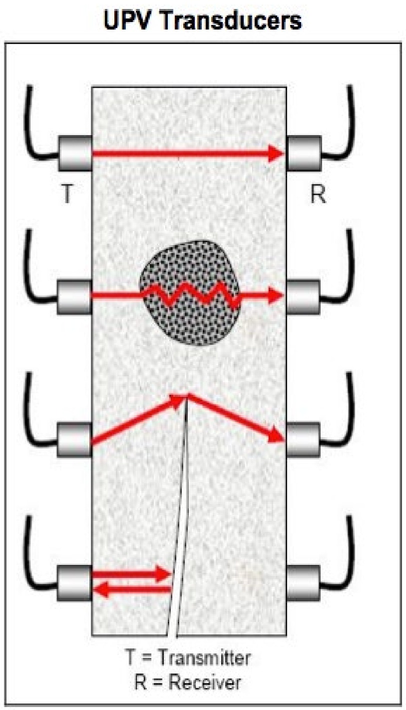
• Tests with rebound hammer (N type)



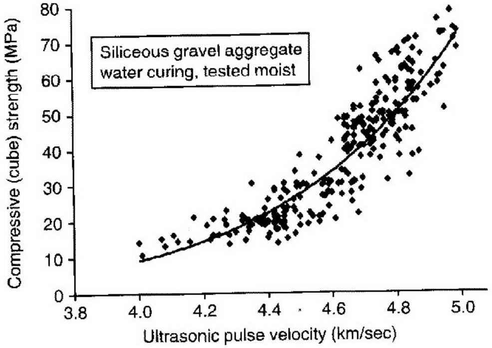


- Estimation of concrete strength

• Ultrasonic test on concrete

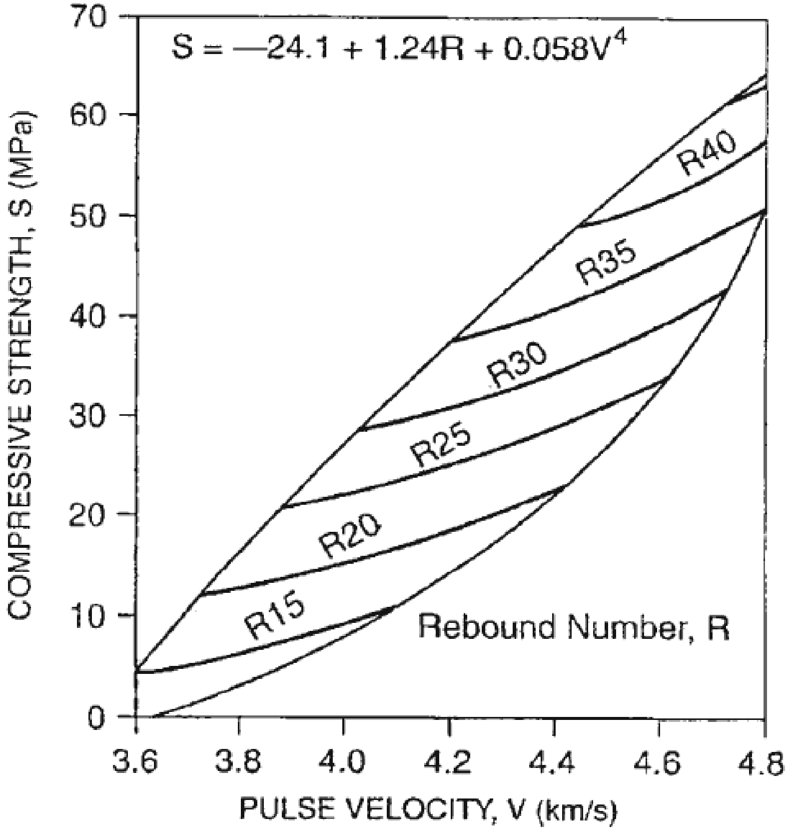


- Strength of concrete
- Voids
- Depth of cracks

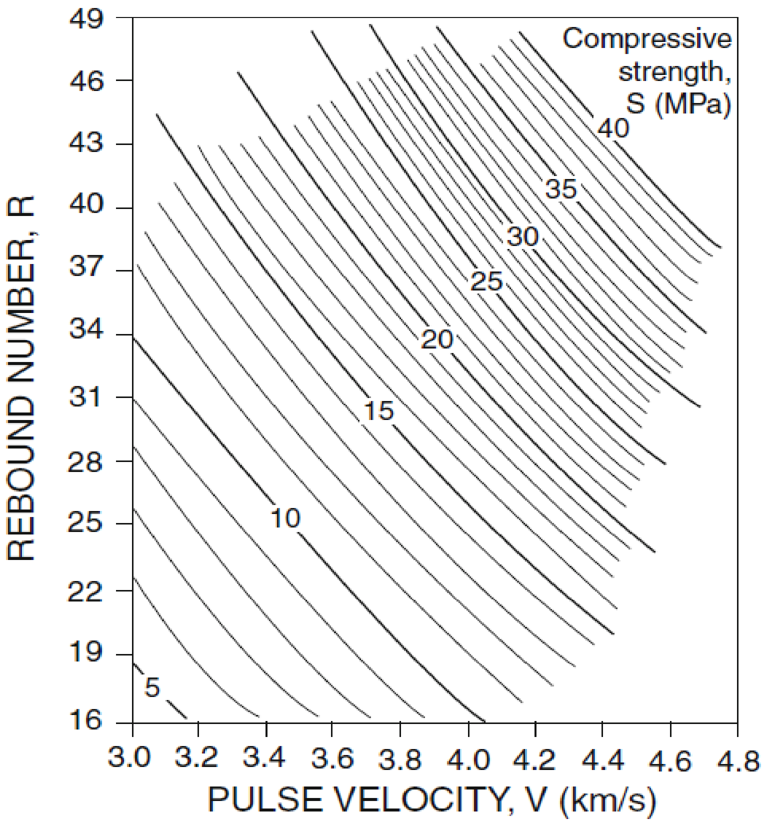


- **Combination of UPV and rebound hammer measurements**

$$f_c = f\,(UPV,R) = a\,UPV^bR^c$$

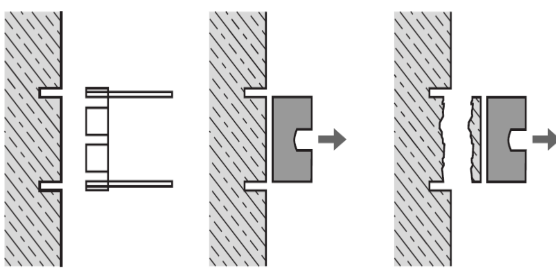


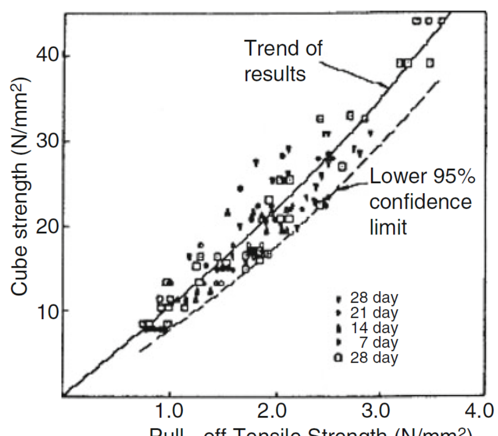
[Australian method IAEA, 2002]



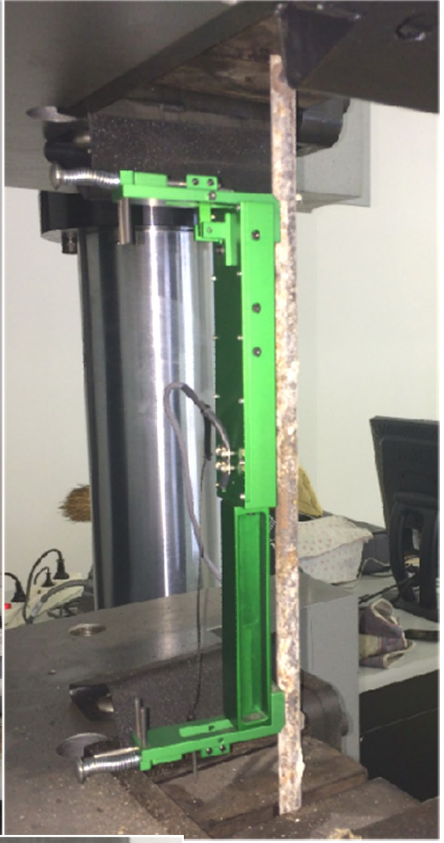
[RILEM Committee TC 43]

- **Pull-off test on concrete surface** (semi-destructive)



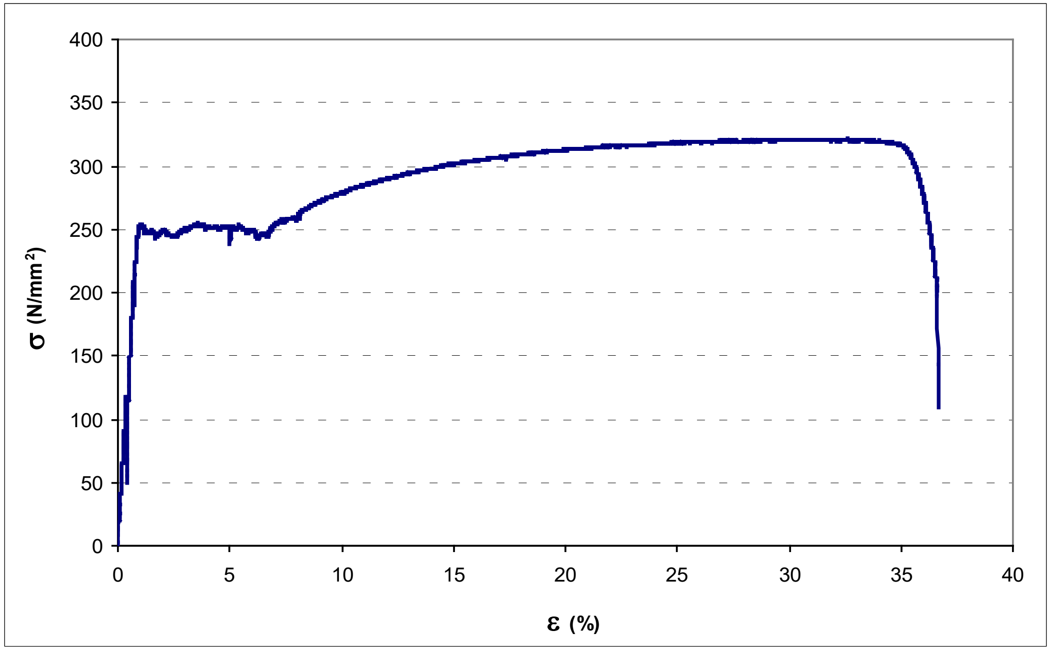


- Strength of concrete
- Pull-off bond strength



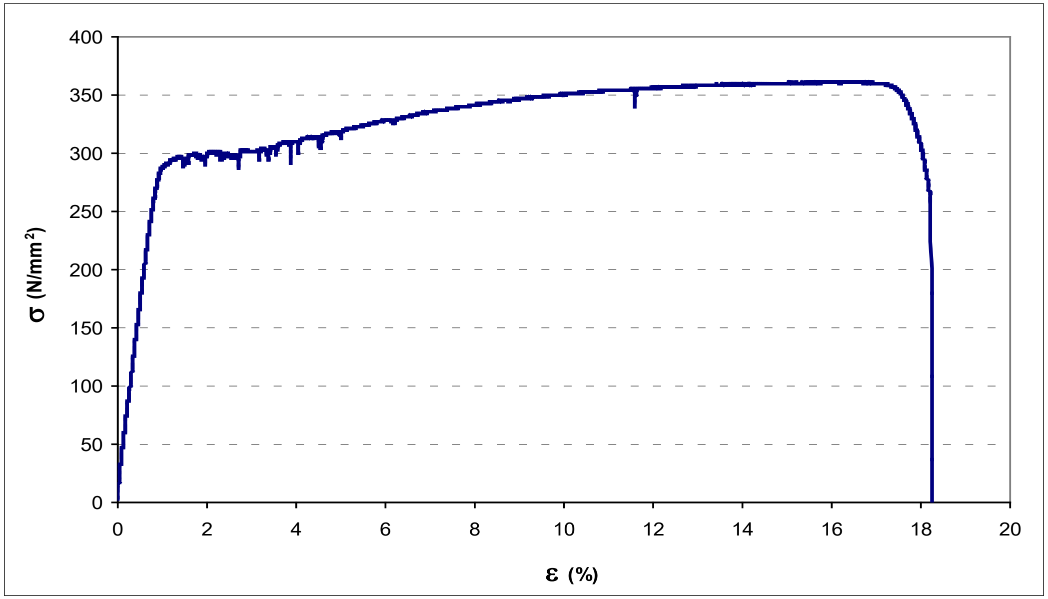
- **Tensile test on reinforcing steel**

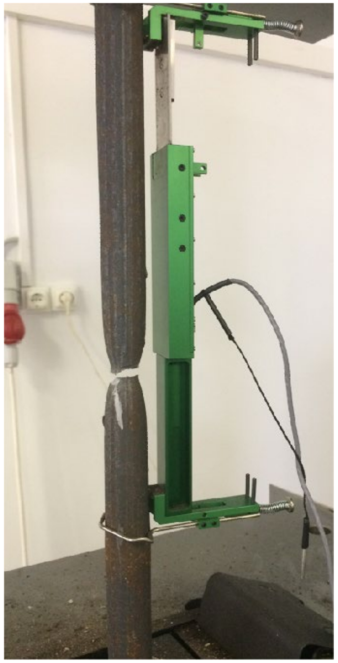

1 cm

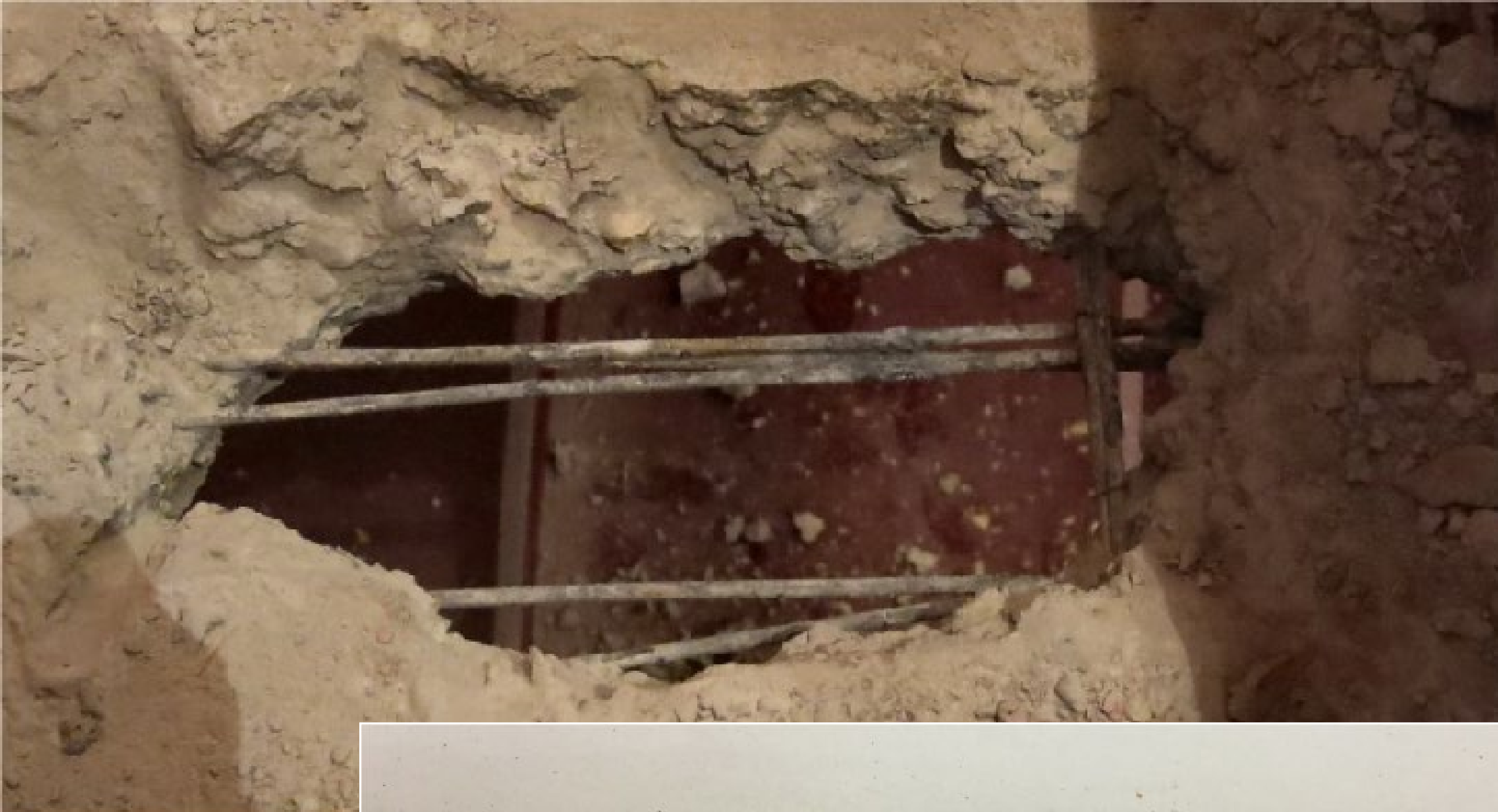


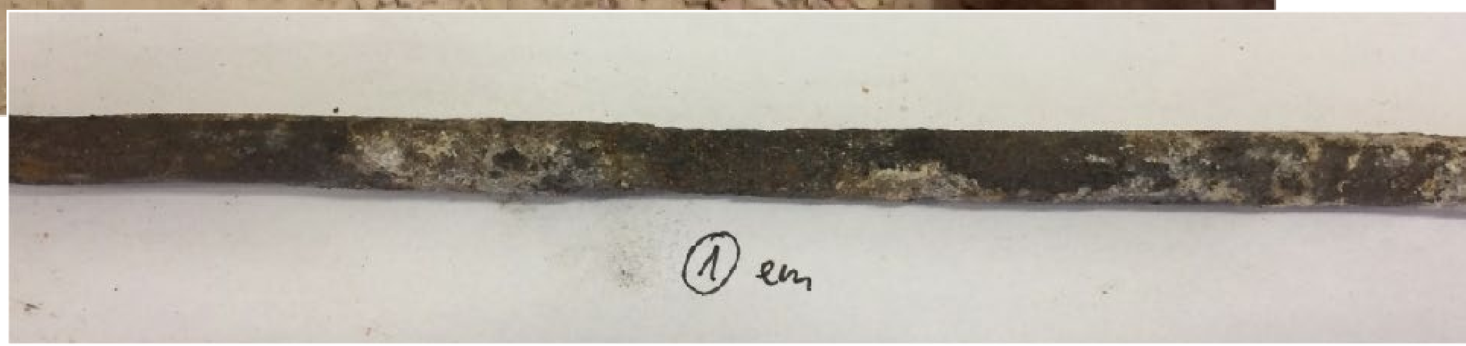
Stress-strain curve of reinforcing steel

- $f_{yk,0.05}$ = 195,4 N/mm²
- Large variability
- High ductility



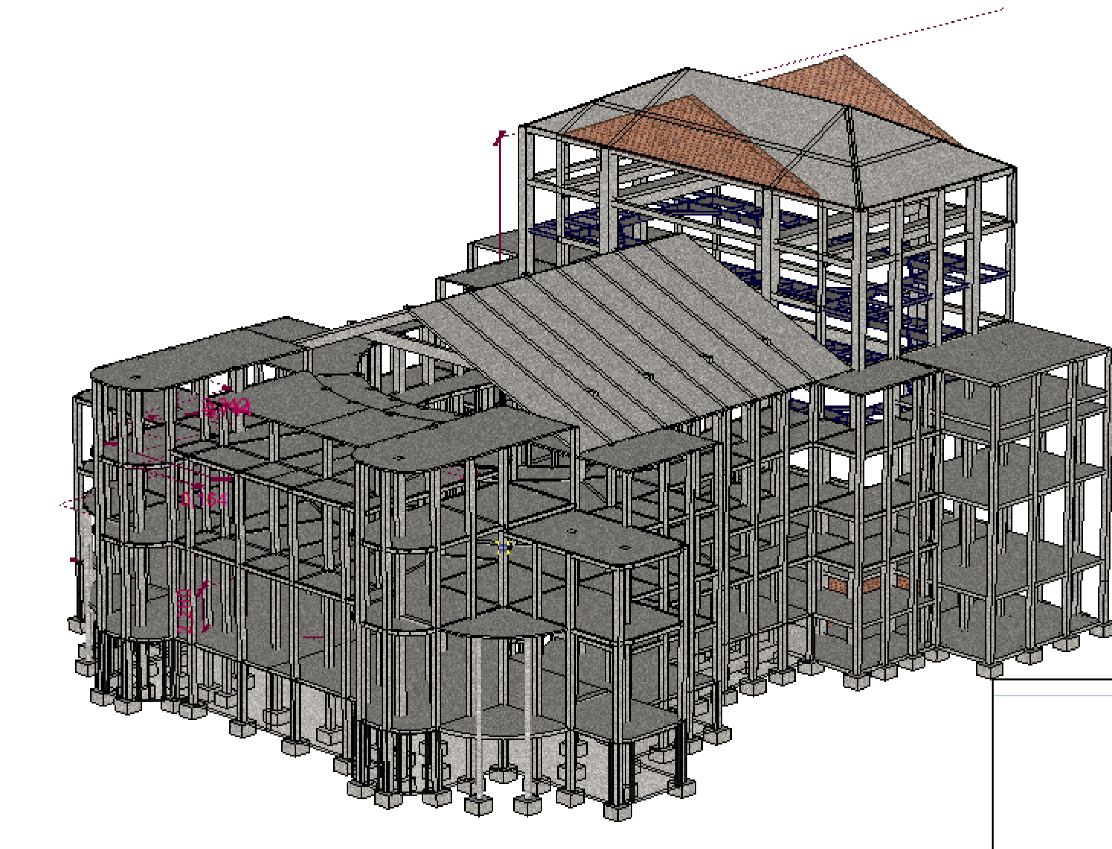


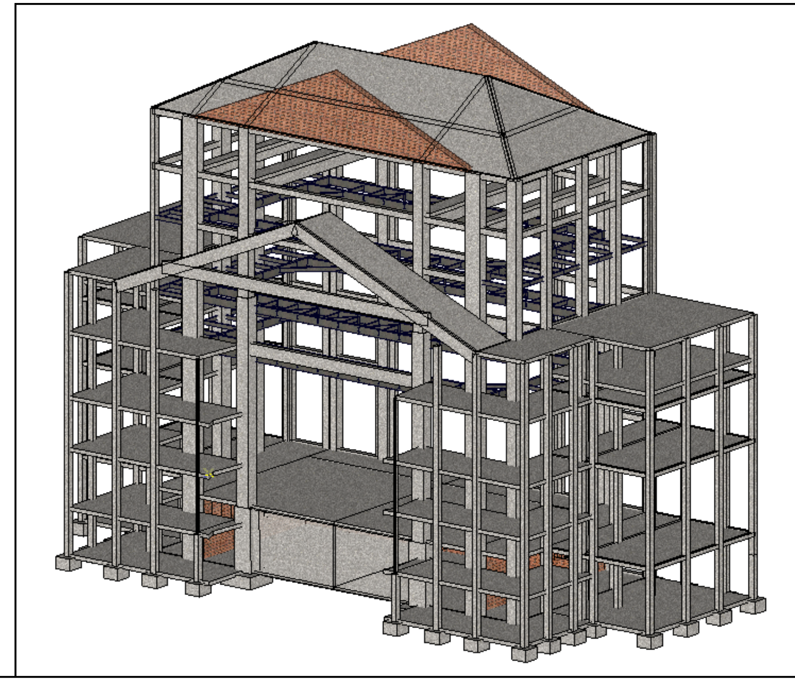



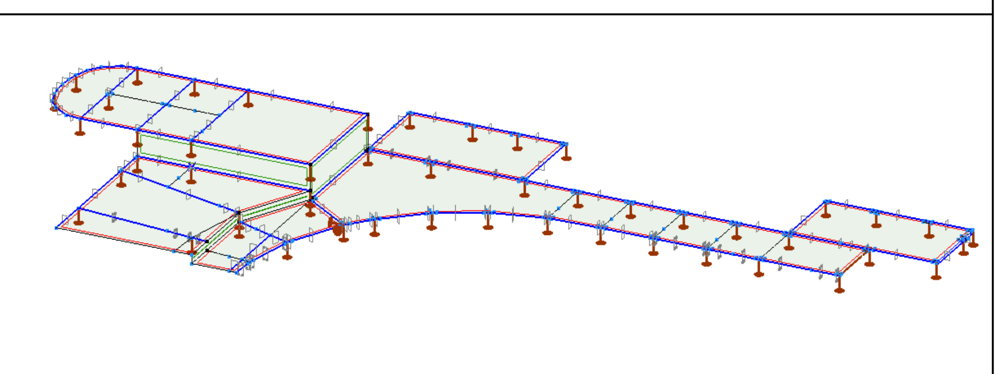

1 cm

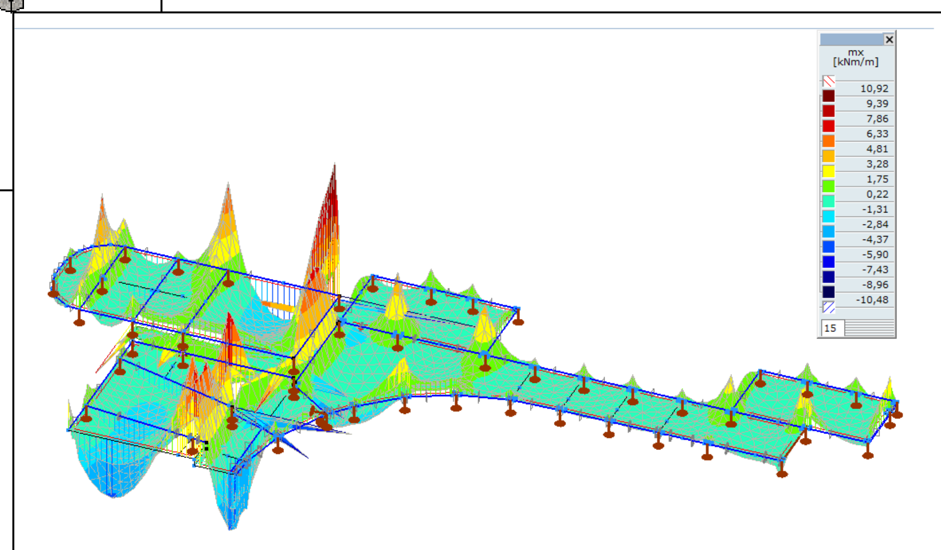
Alapozási szerkezet

Static analysis on 3D FE model










CSIKY GERGELY SZÍNHÁZ

DIAGNOSTICS OF STRUCTURES

LECTURE 09

Assessment and rehabilitation of heritage structures help by combined non-destructive tests – Part3

Zoltán Orbán

University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

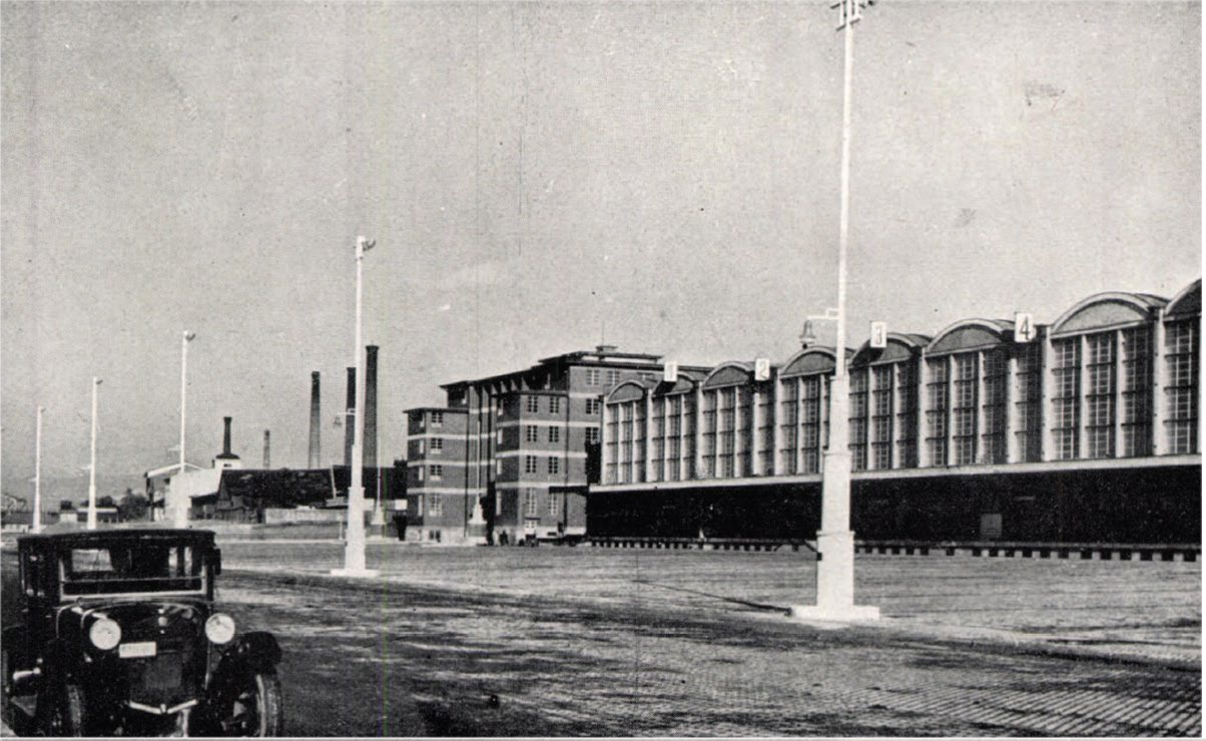
Case Study 3.

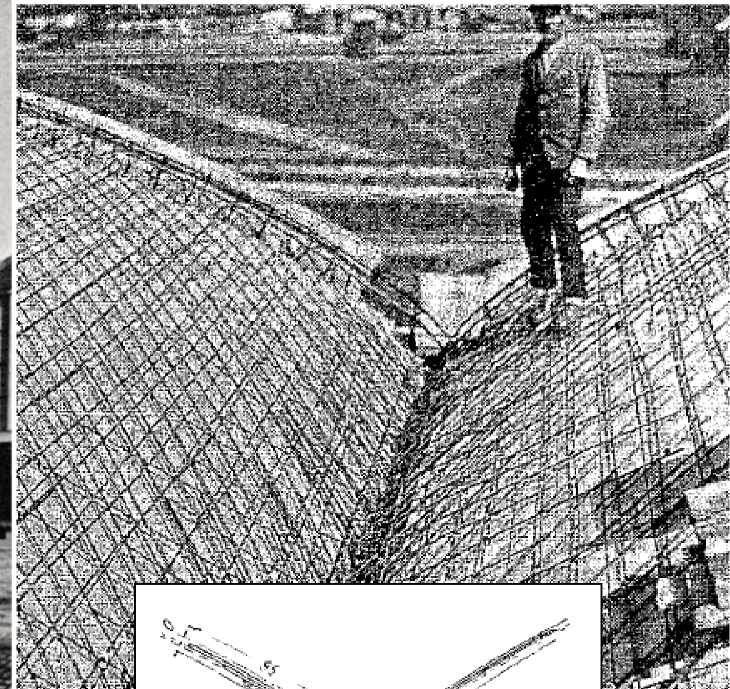
The Great Market Hall in Budapest

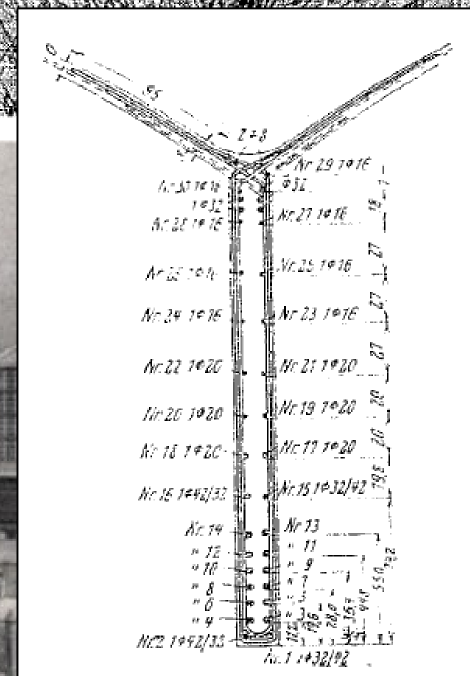
Date of construction: 1930
Designer: Aladár Münnich

234m long, 42m wide

Zeiss–Dywiidag roof system

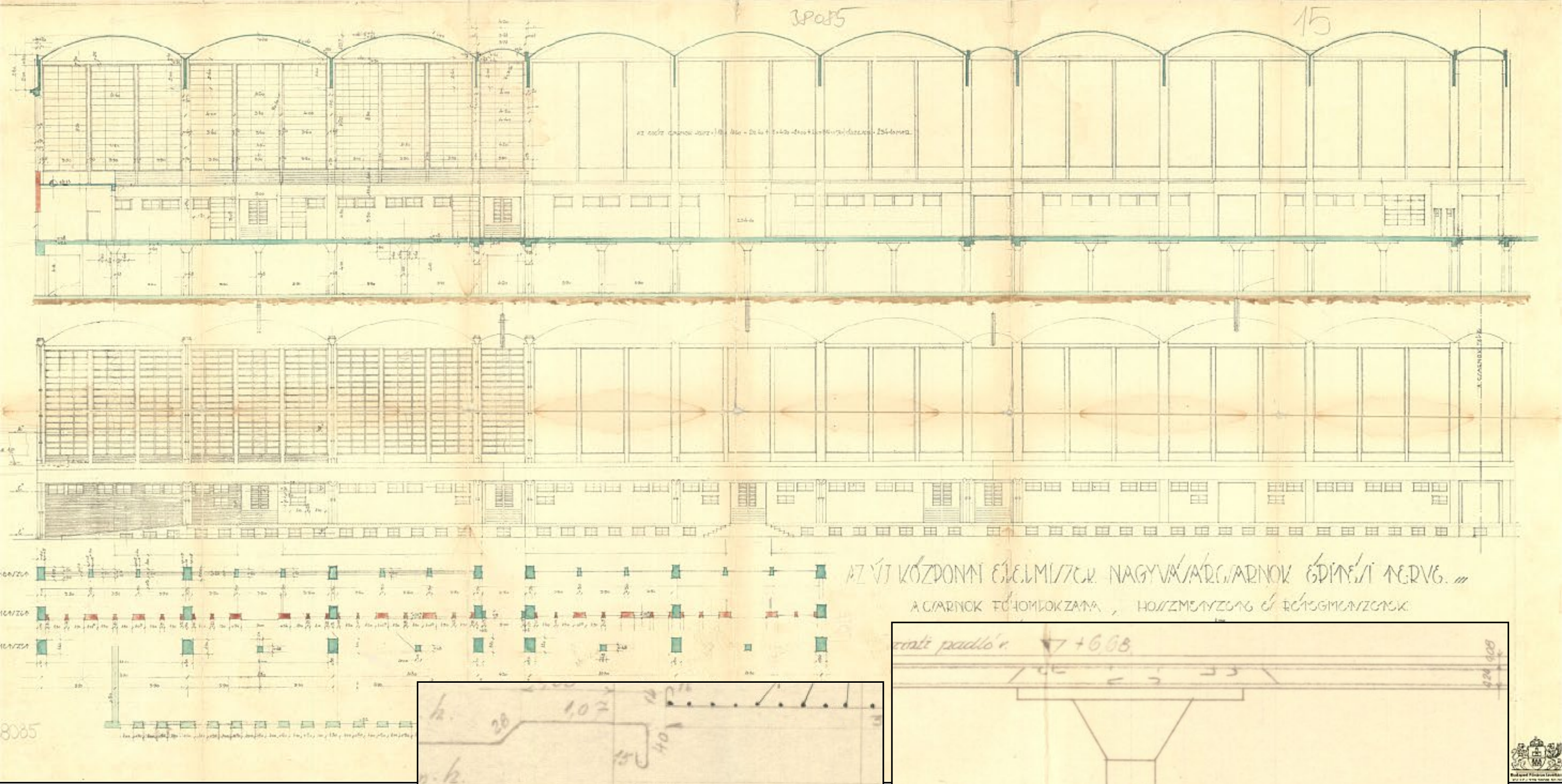


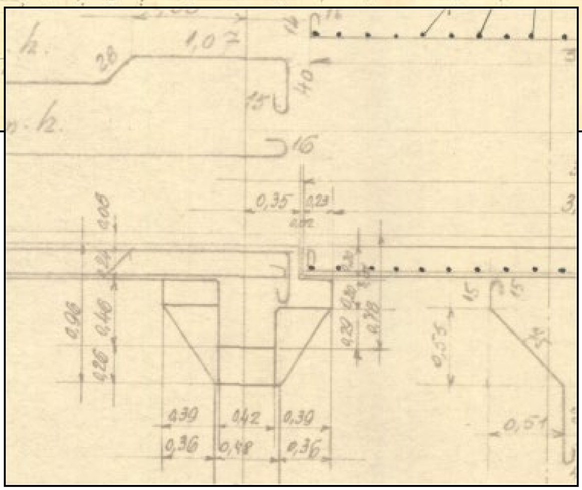


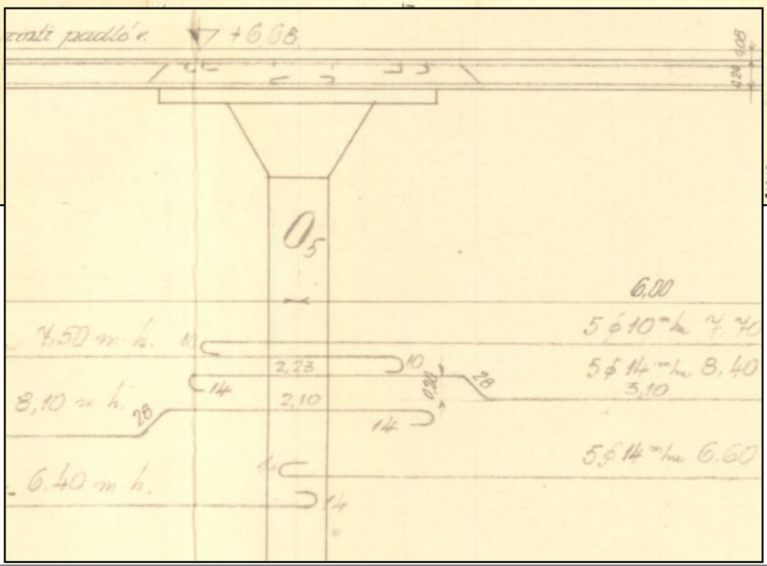


ASSESSMENT AND REHABILITATION OF HERITAGE STRUCTURES HELPED BY COMBINED NDT TESTS

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP







Original drawings from 1930

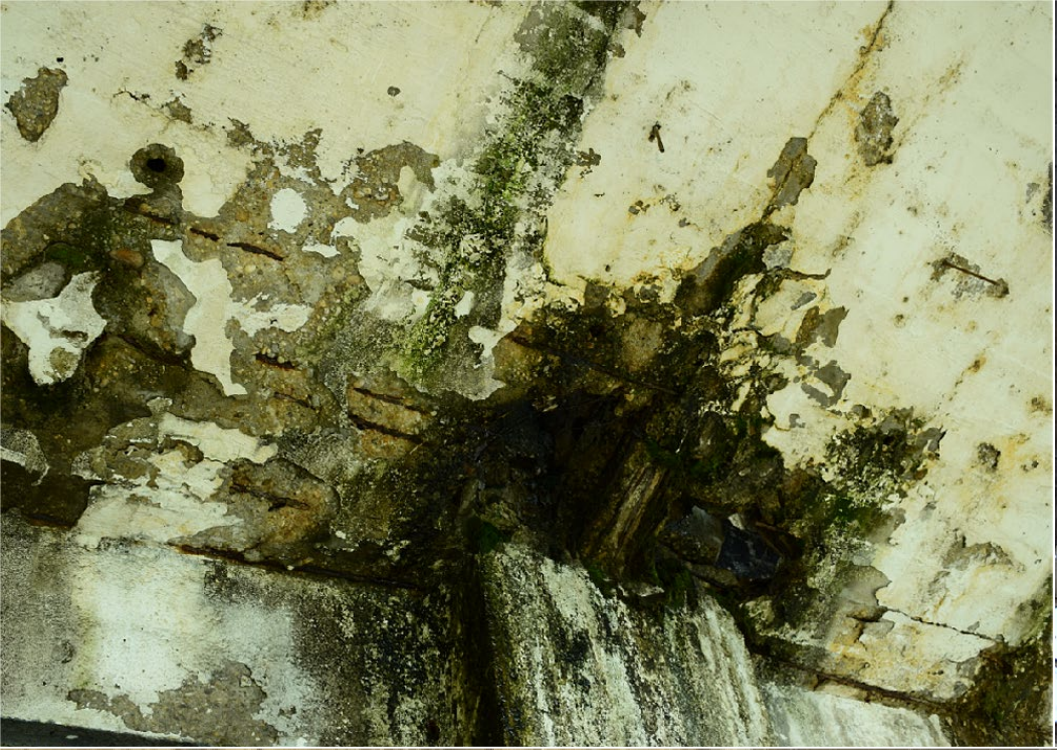

Current condition

ASSESSMENT AND REHABILITATION OF HERITAGE STRUCTURES HELPED BY COMBINED NDT TESTS

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

ASSESSMENT AND REHABILITATION OF HERITAGE STRUCTURES HELPED BY COMBINED NDT TESTS

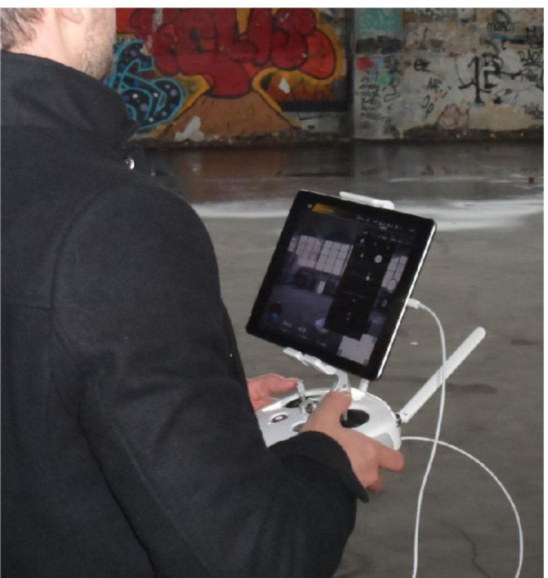
STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP



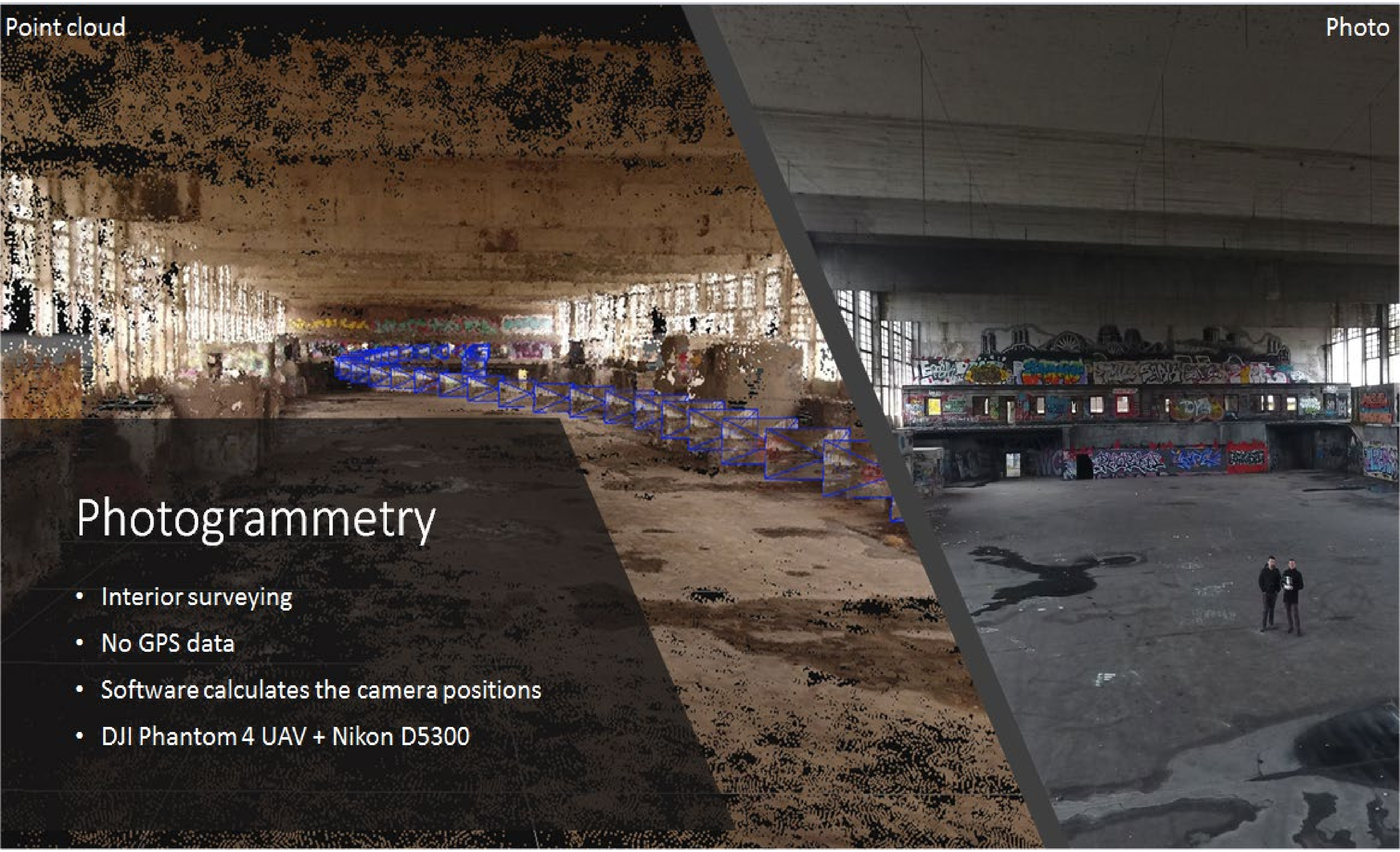
Structural diagnostics

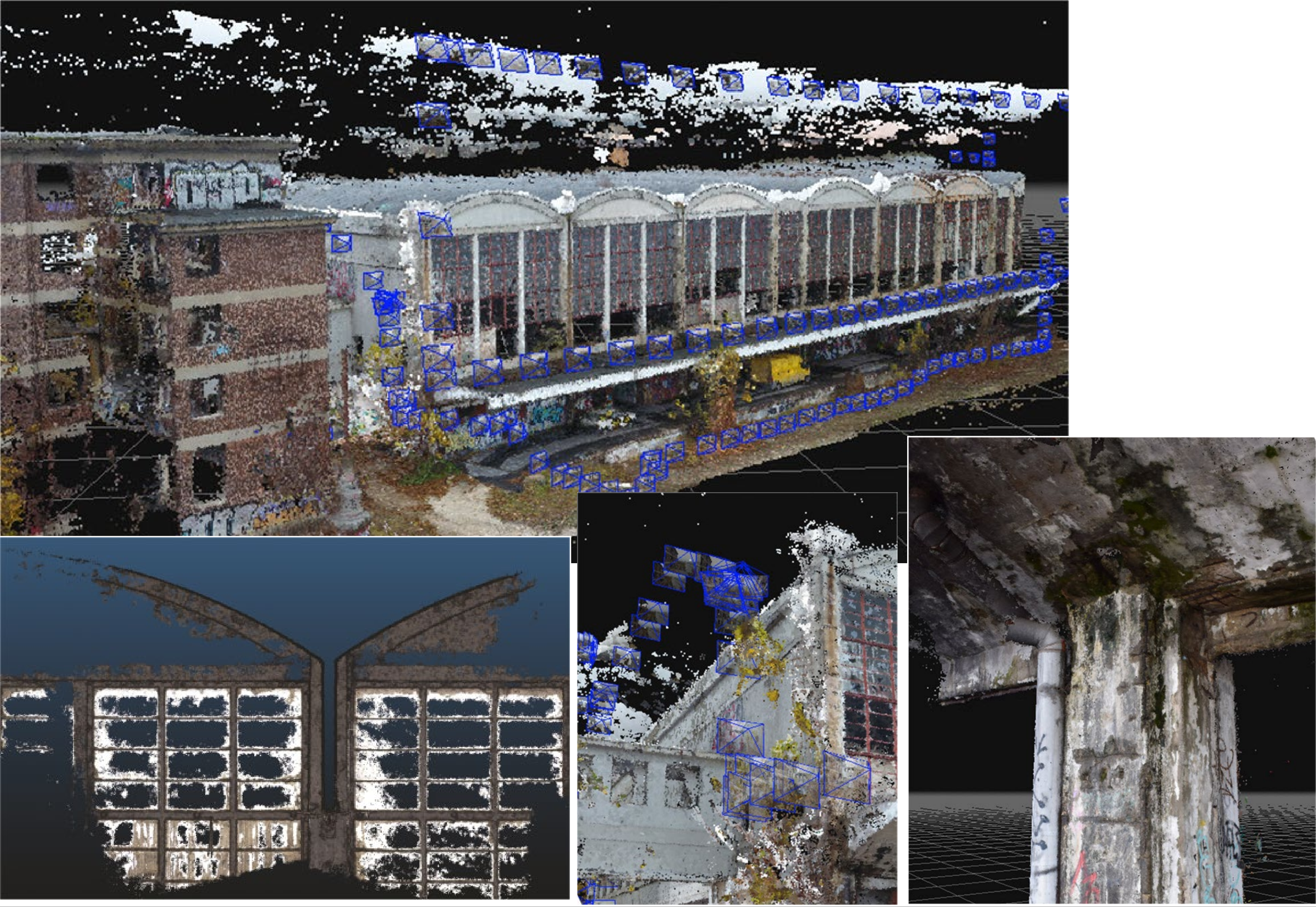
Geometrical survey with 3D laser scanning

Photogrammetry with drones

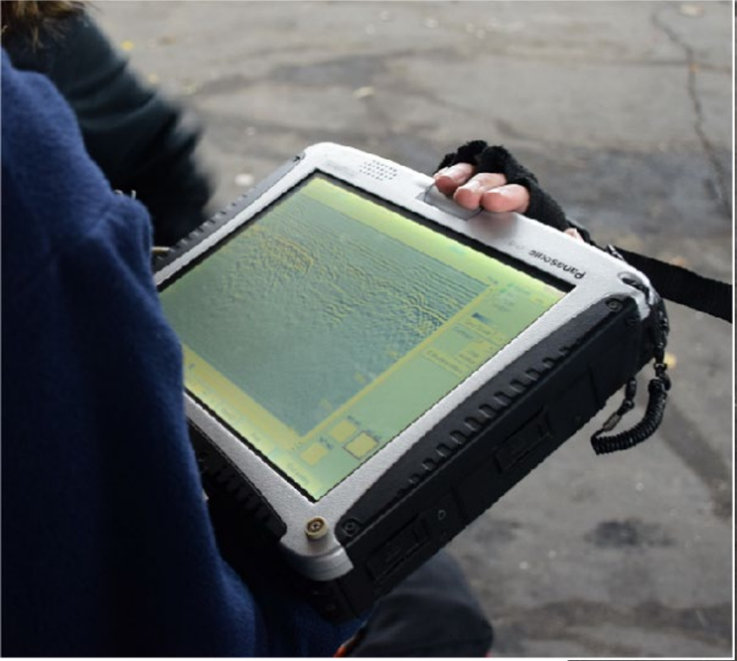


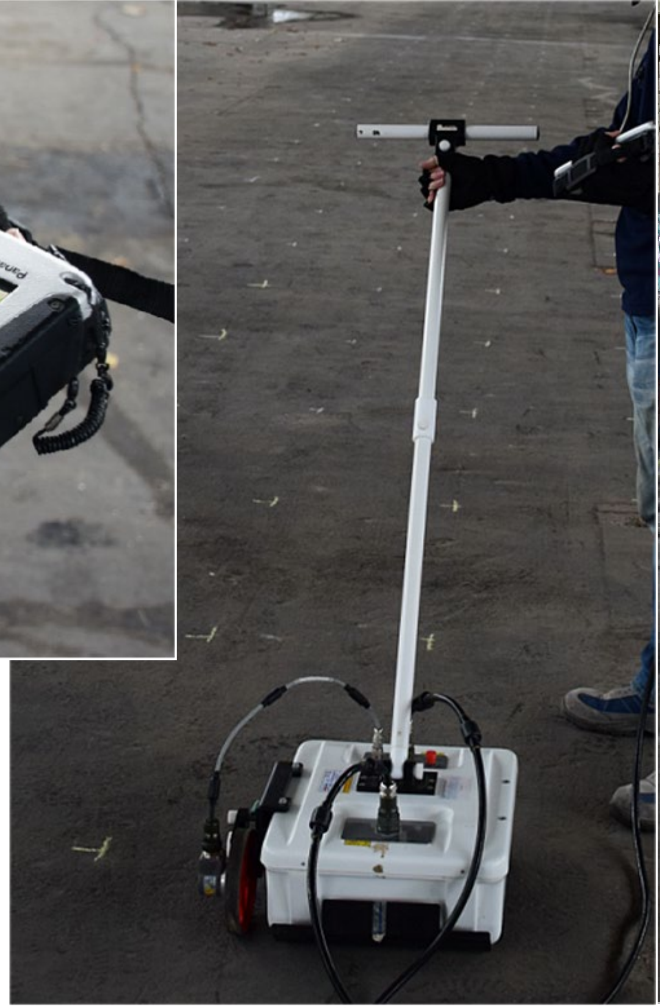
Photogrammetry with drones (point cloud from photo images)



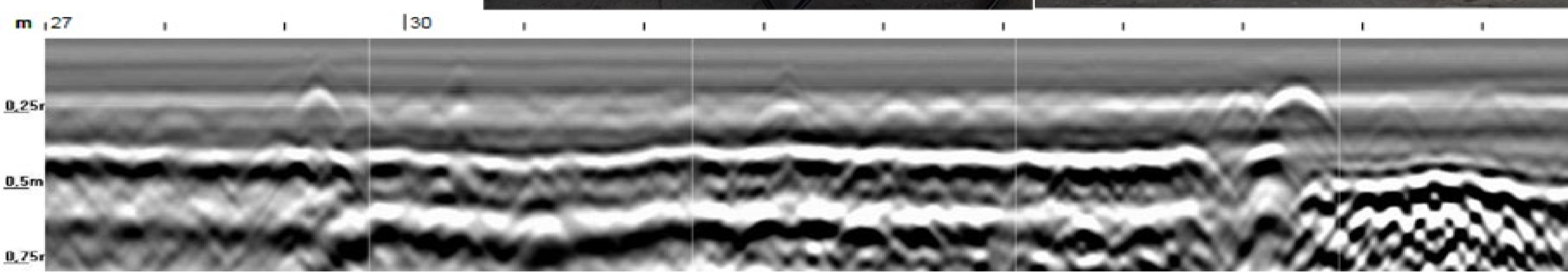


ASSESSMENT AND REHABILITATION OF HERITAGE STRUCTURES HELPED BY COMBINED NDT TESTS



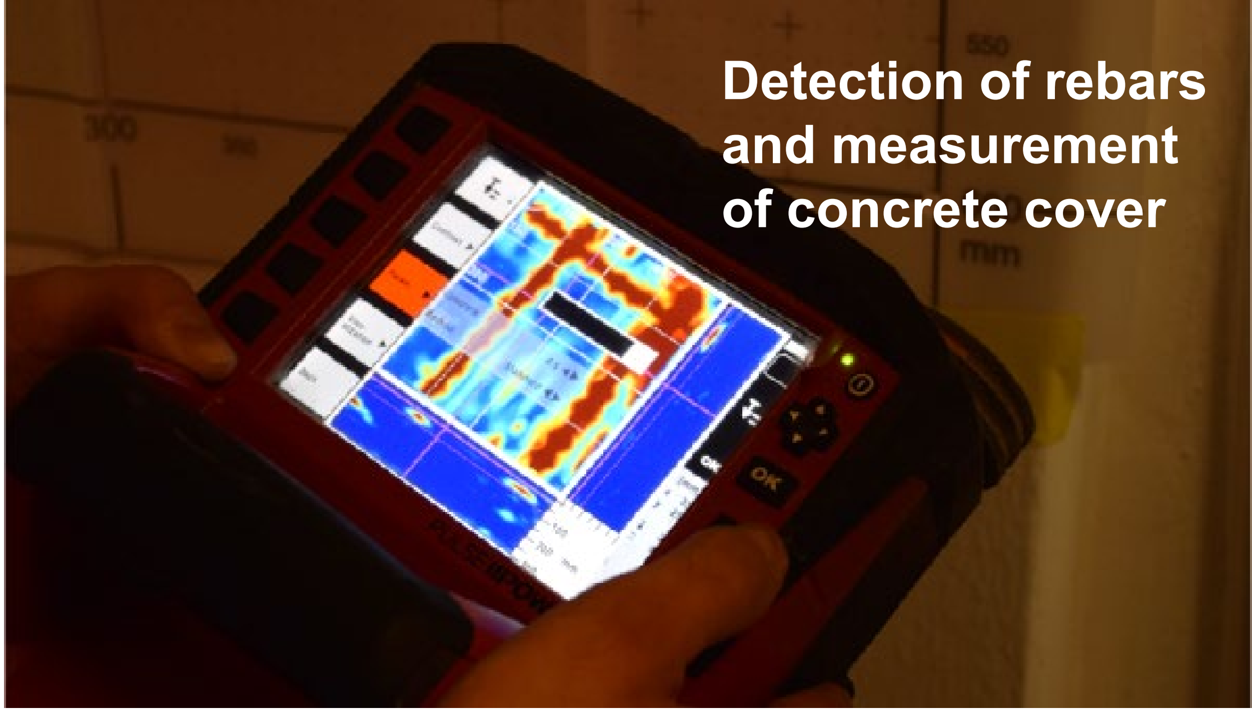


Georadar test




Endoscopy
survey

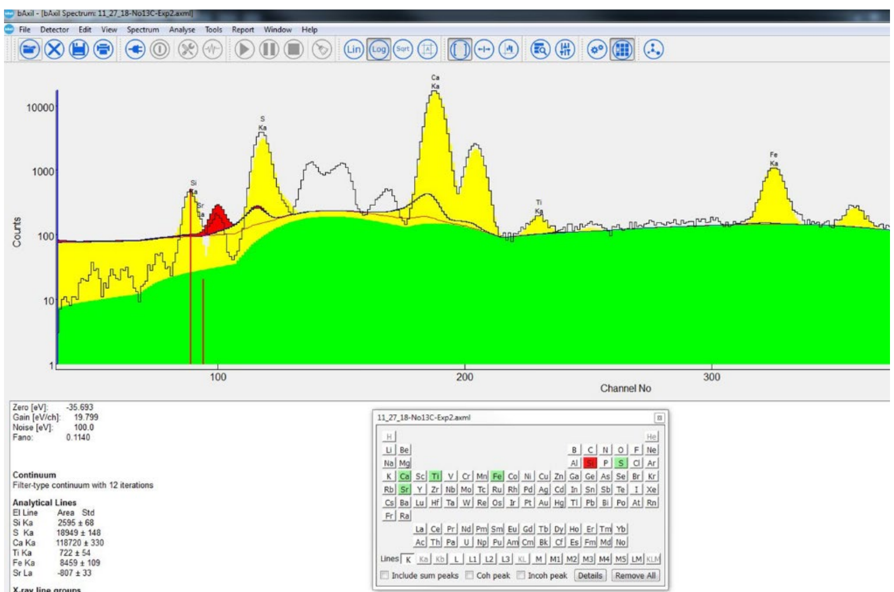

OLYMPUS


Detection of rebars
and measurement
of concrete cover

X-ray fluorescense analysis – elemental analysis

- **OLYMPUS XRF – hand tool**

- **detactable elements:** Mg, Al, Si, P, S, K, Ca, Ti, Mn, V, Cr, Fe, Co, Ni, Cu, Zn, W, As, Pb, Bi, Zr, Mo,–



Spectra of 2. salt deposited surface measurement

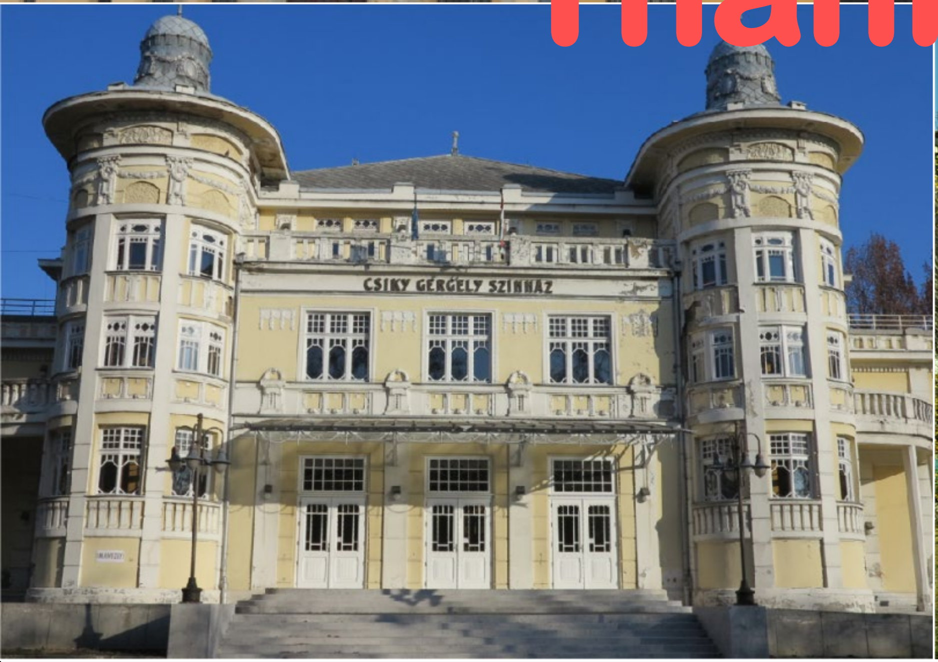
Conclusions

- Assessment of heritage structures is a cyclic process in which the preliminary assessment is often supplemented by subsequent detailed investigations and analysis.

- The combination of test methods can improve the accuracy of estimation of properties and help reduce time to obtain the required parameters for analysis.

- A well chosen combination of NDT methods can contribute to improved assessment of heritage structures and helps prepare rehabilitation.

Thank you!



DIAGNOSTICS OF STRUCTURES

LECTURE 10

Mapping foundations with NDT methods
(CASE STUDY)

Zoltán Orbán

University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Testing foundations with NDT methods

Significance

- Condition, material and depth of foundations are often unknown
- It is important when foundation damages are suspected or when increase in loading is expected
- Survey and testing of foundations with other methods can be more expensive

Objectives

- Survey the integrity of foundations
- Determine the geometry and material of foundations
- Provide data for foundation assessment

Available methods

- Borehole radar method (single-hole, cross-hole)
- Parallel seismic method
- Borehole sonic method
- Cross-borehole sonic tomography
- Dynamic foundation response method

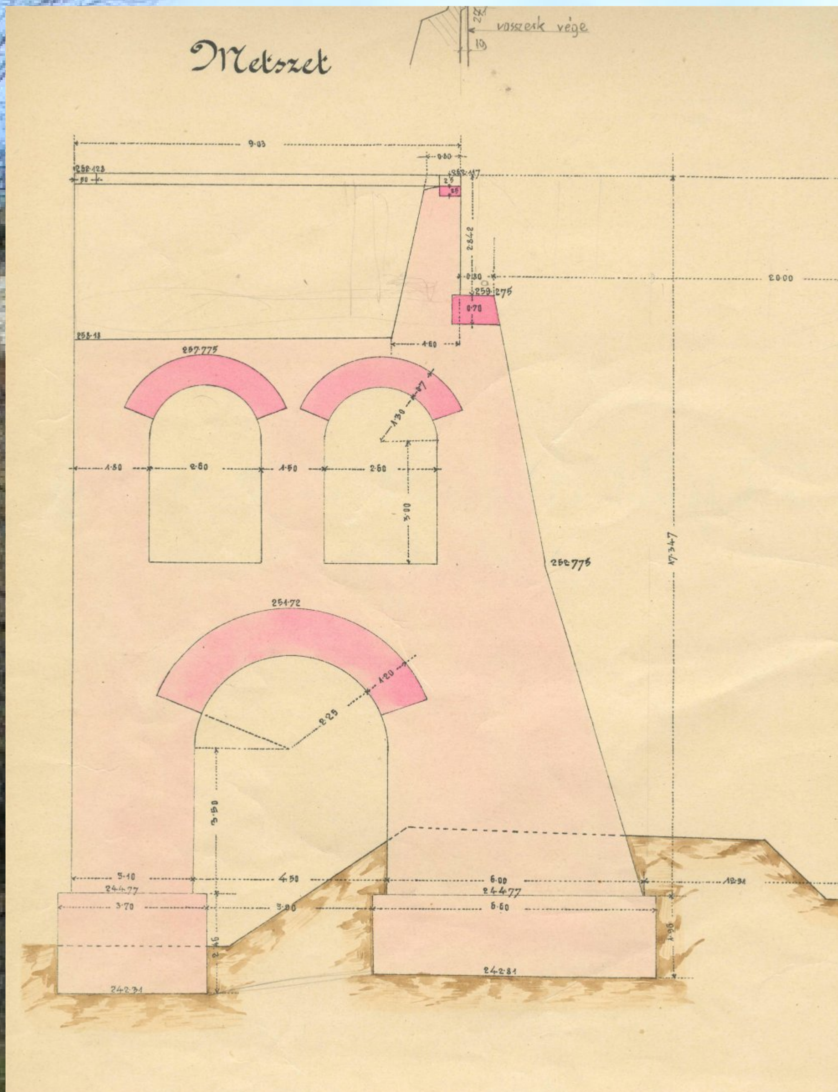
Field tests (case study)

- Survey of the foundation of the Rátót viaduct (Hungary)
- Survey of the foundation of a stone arch in Eplény (Hungary)

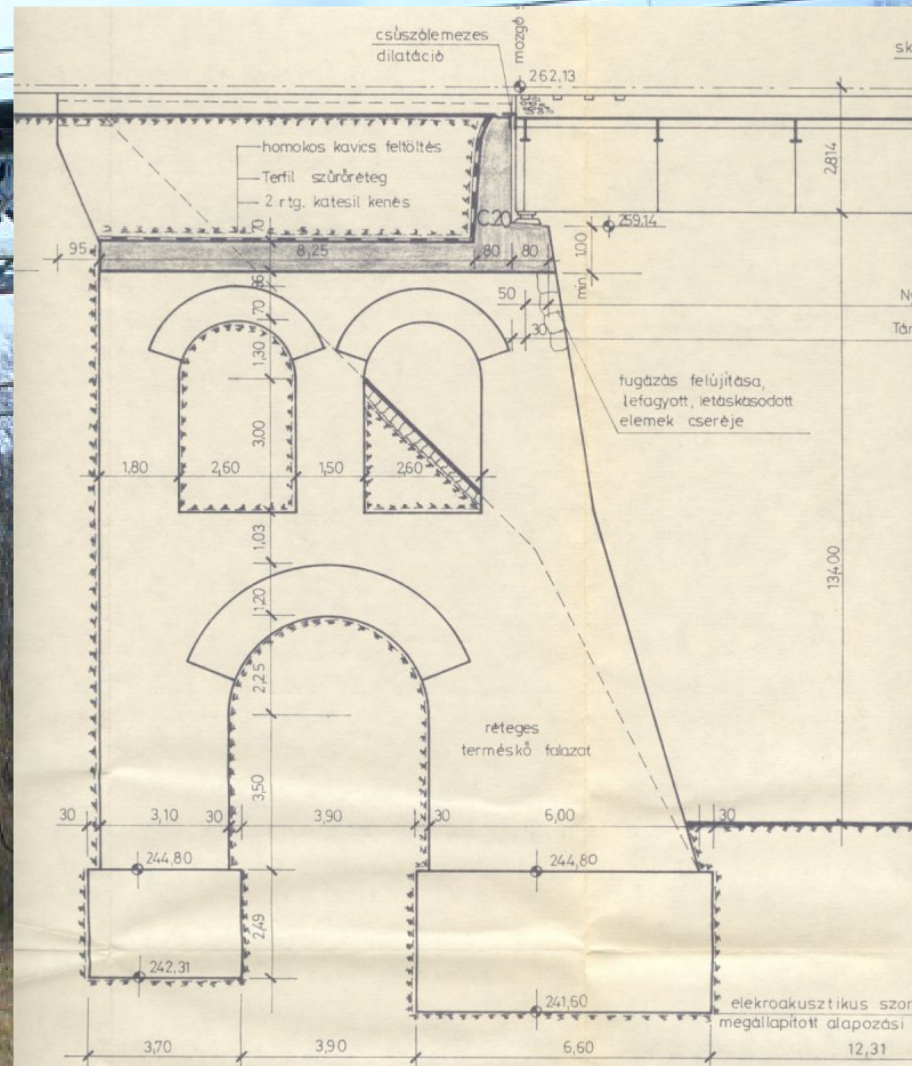
Methods used in case study

- Borehole radar method
- Parallel seismic method

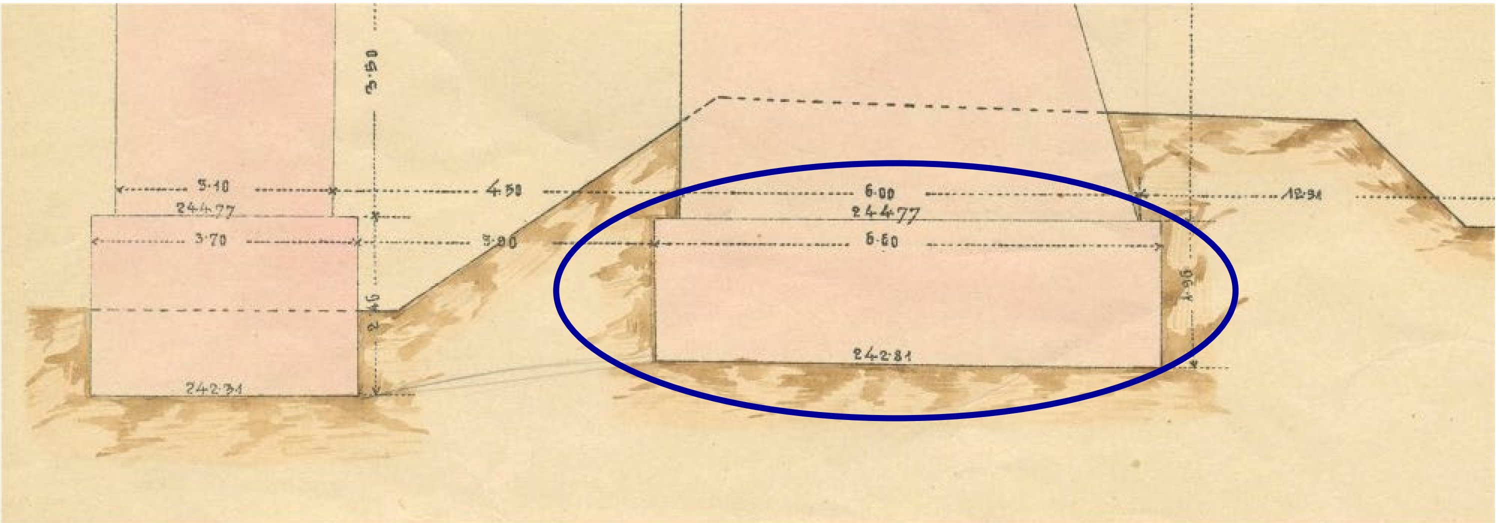
Field tests on a masonry abutment



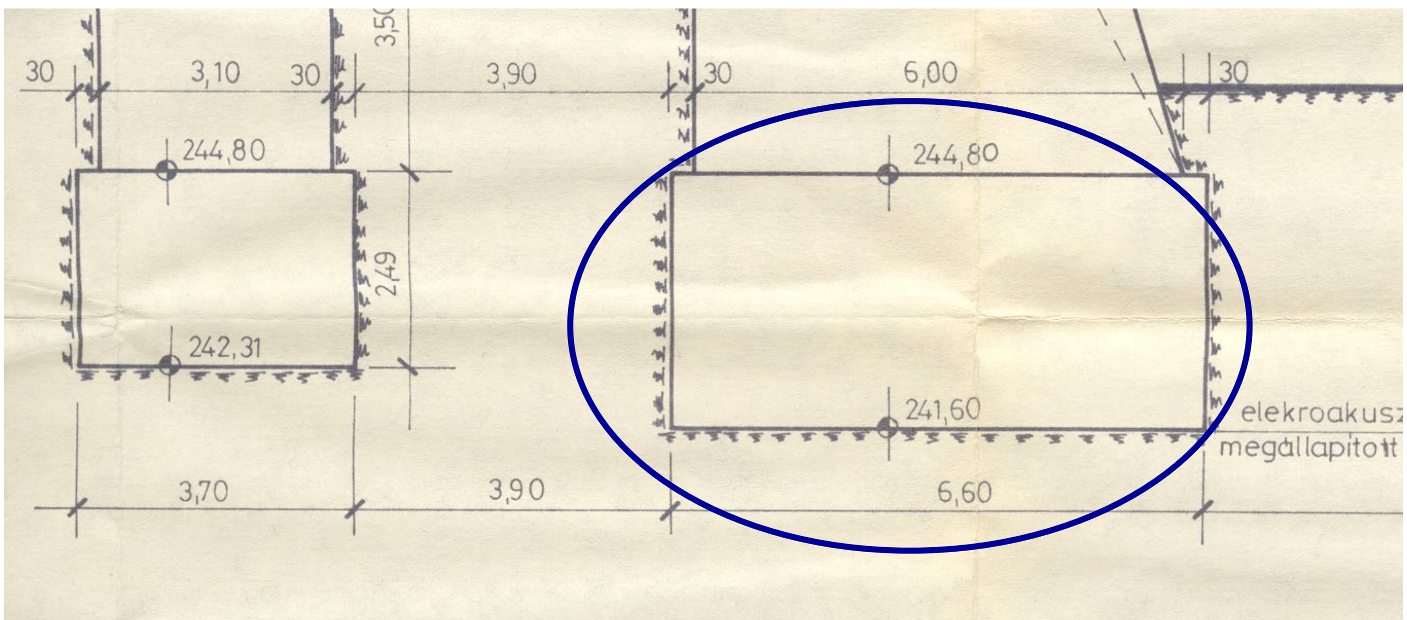
Original plan



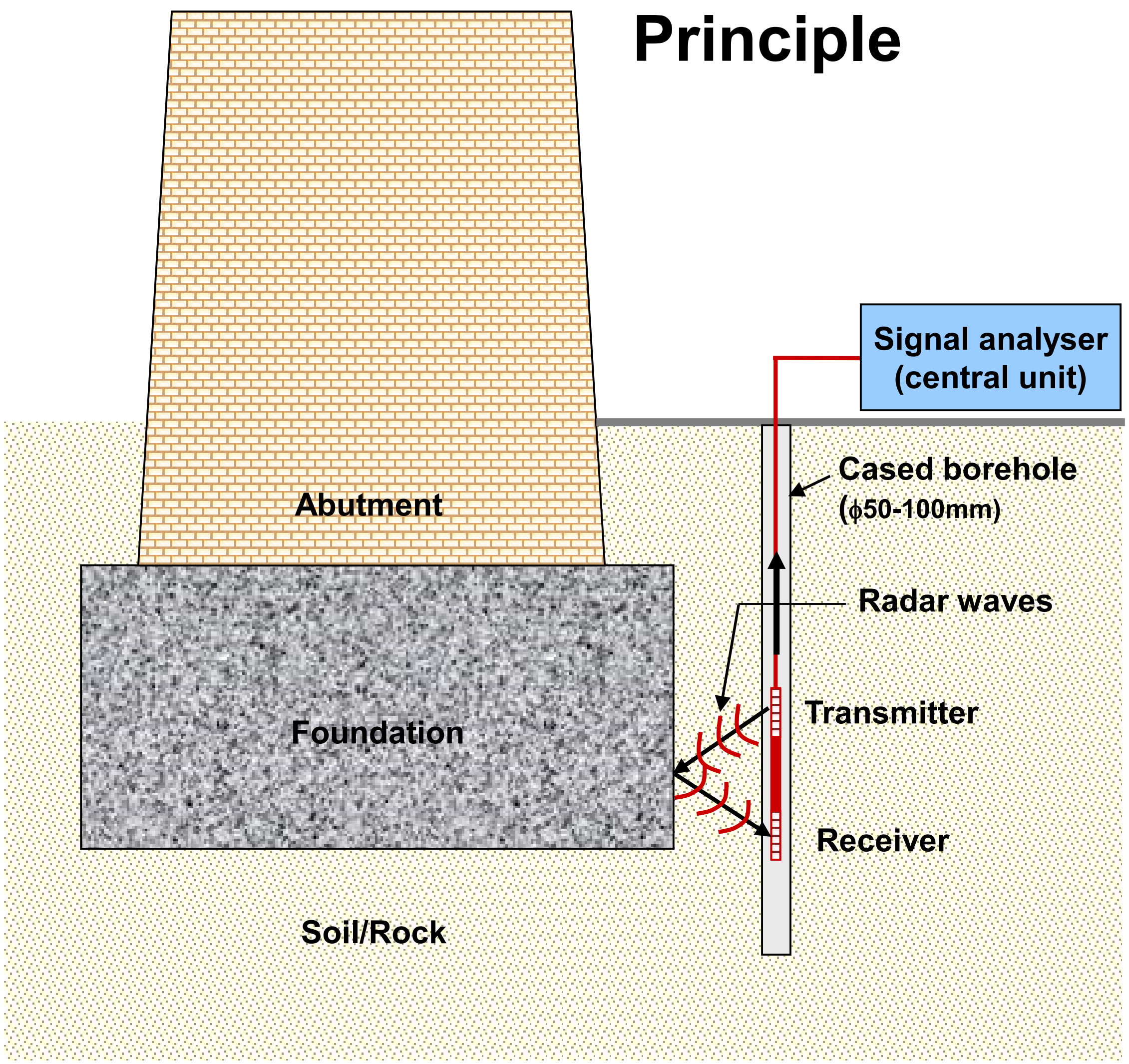
Reconstruction plan
(by later survey)



What is the real foundation depth and geometry?



Tests with the borehole radar method



Steps

Step 1: drilling

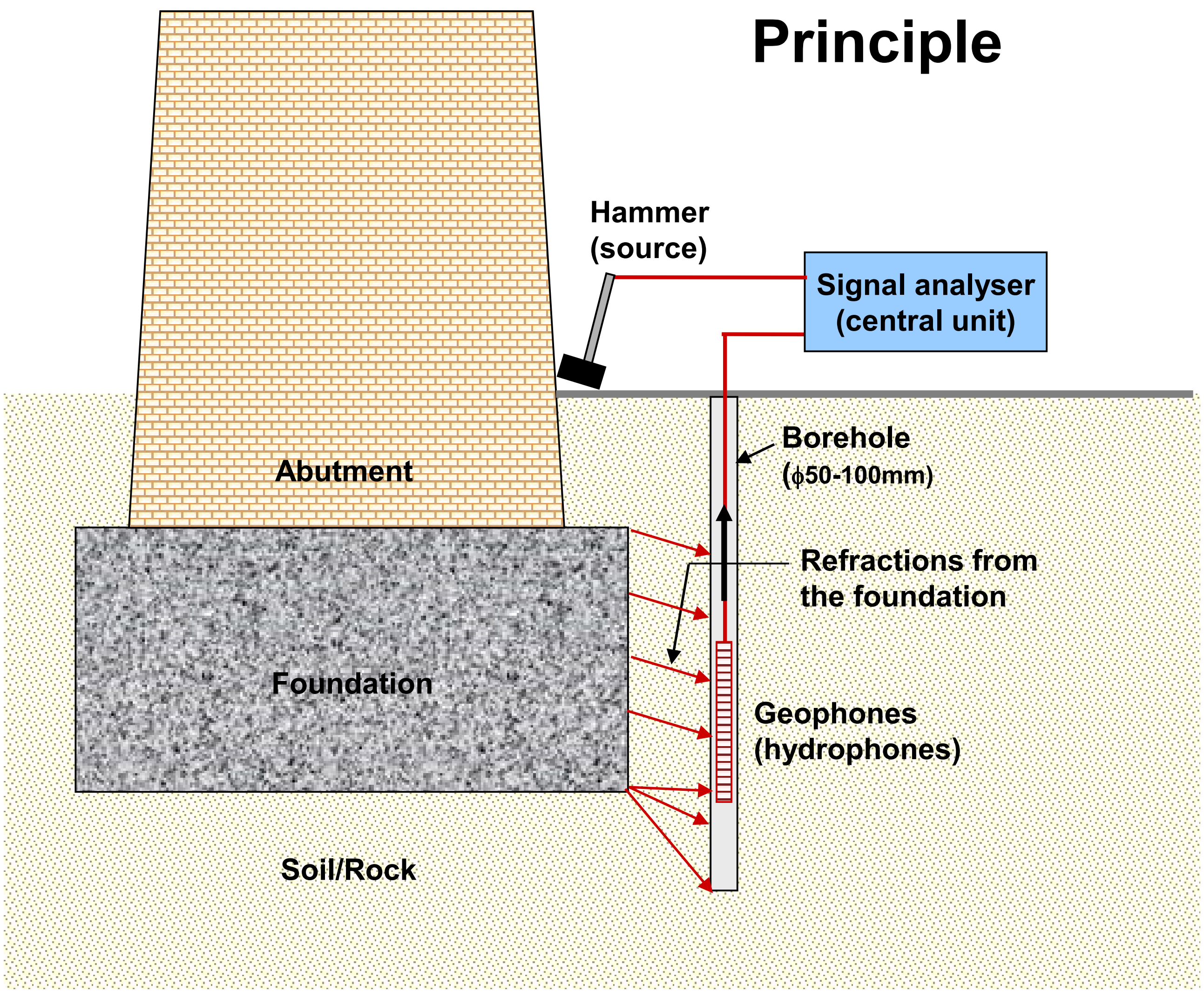
Step 2: removal and analysis of soil

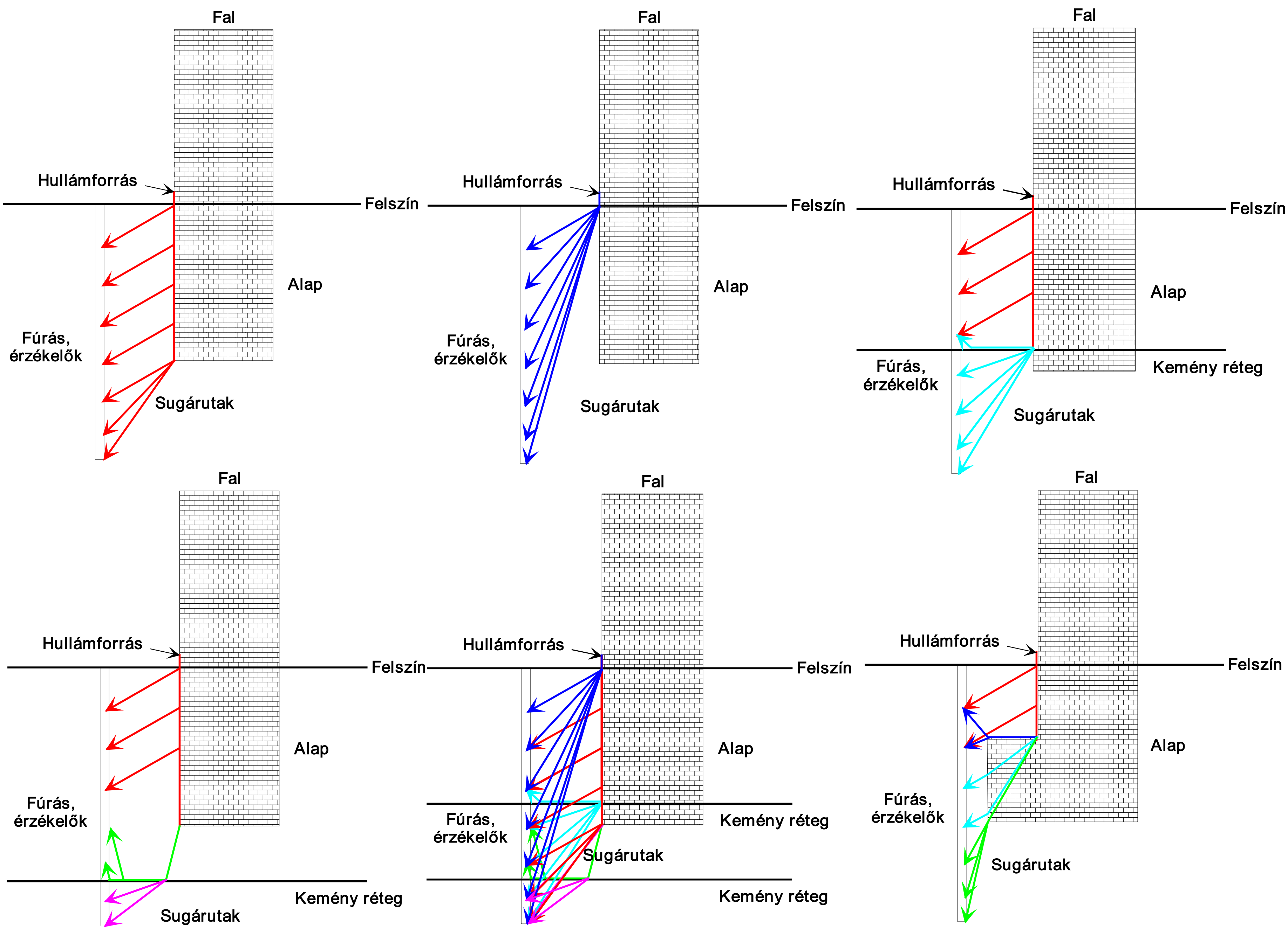
Step 3: Casing with PVC tube


Step 4: Test with borehole radar


Radar equipment with central unit
SIRveyor

Tests with the parallel seismic method




Fal
Hullámforrás
Felszín
Alap
Fúrás, érzékelők
Sugárutak
Fal
Hullámforrás
Felszín
Alap
Fúrás, érzékelők
Sugárutak
Fal
Hullámforrás
Felszín
Alap
Kemény réteg
Fúrás, érzékelők
Sugárutak
Fal
Hullámforrás
Felszín
Alap
Fúrás, érzékelők
Kemény réteg
Sugárutak
Fal
Hullámforrás
Felszín
Alap
Kemény réteg
Fúrás, érzékelők
Sugárutak
Kemény réteg
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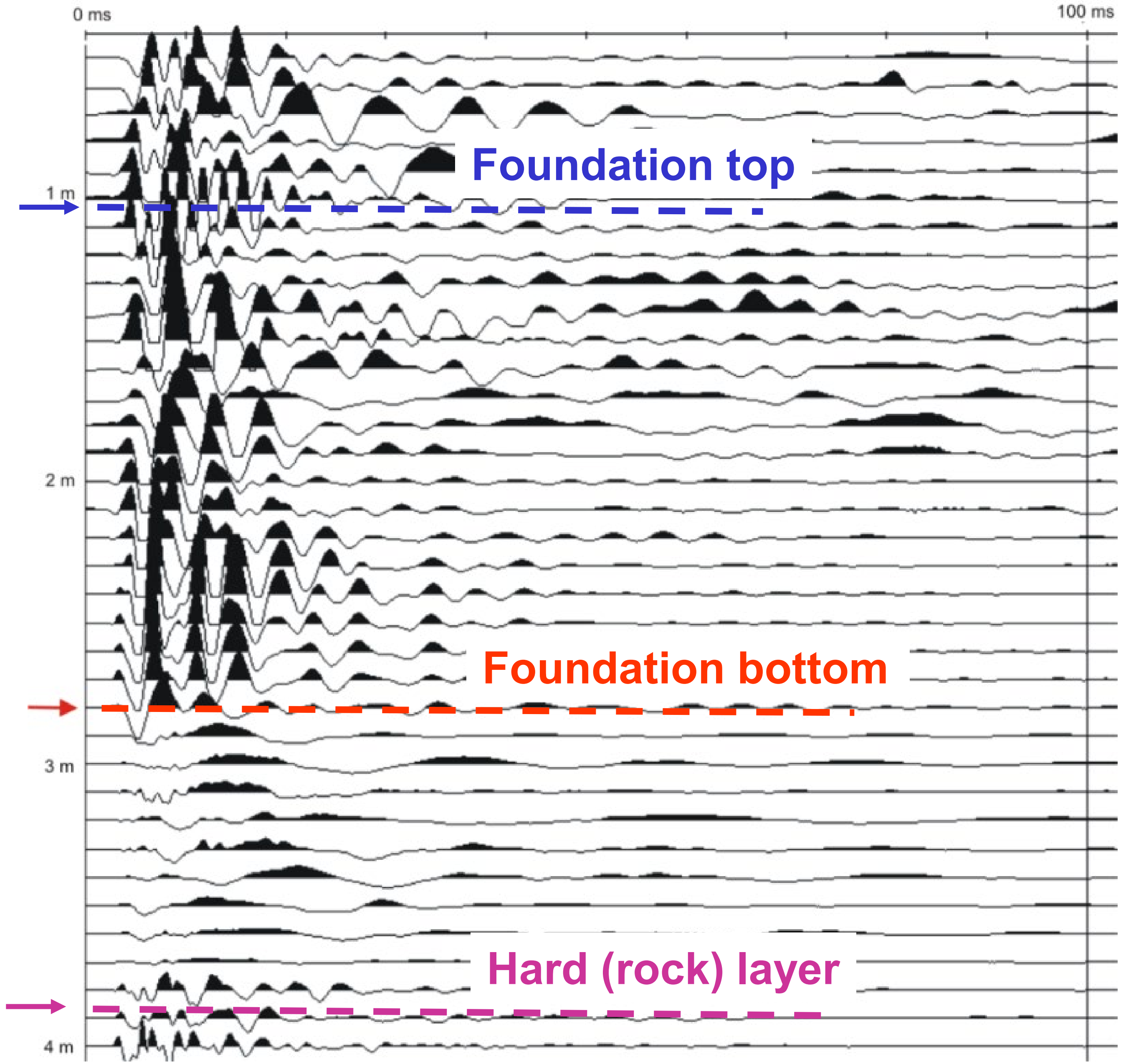
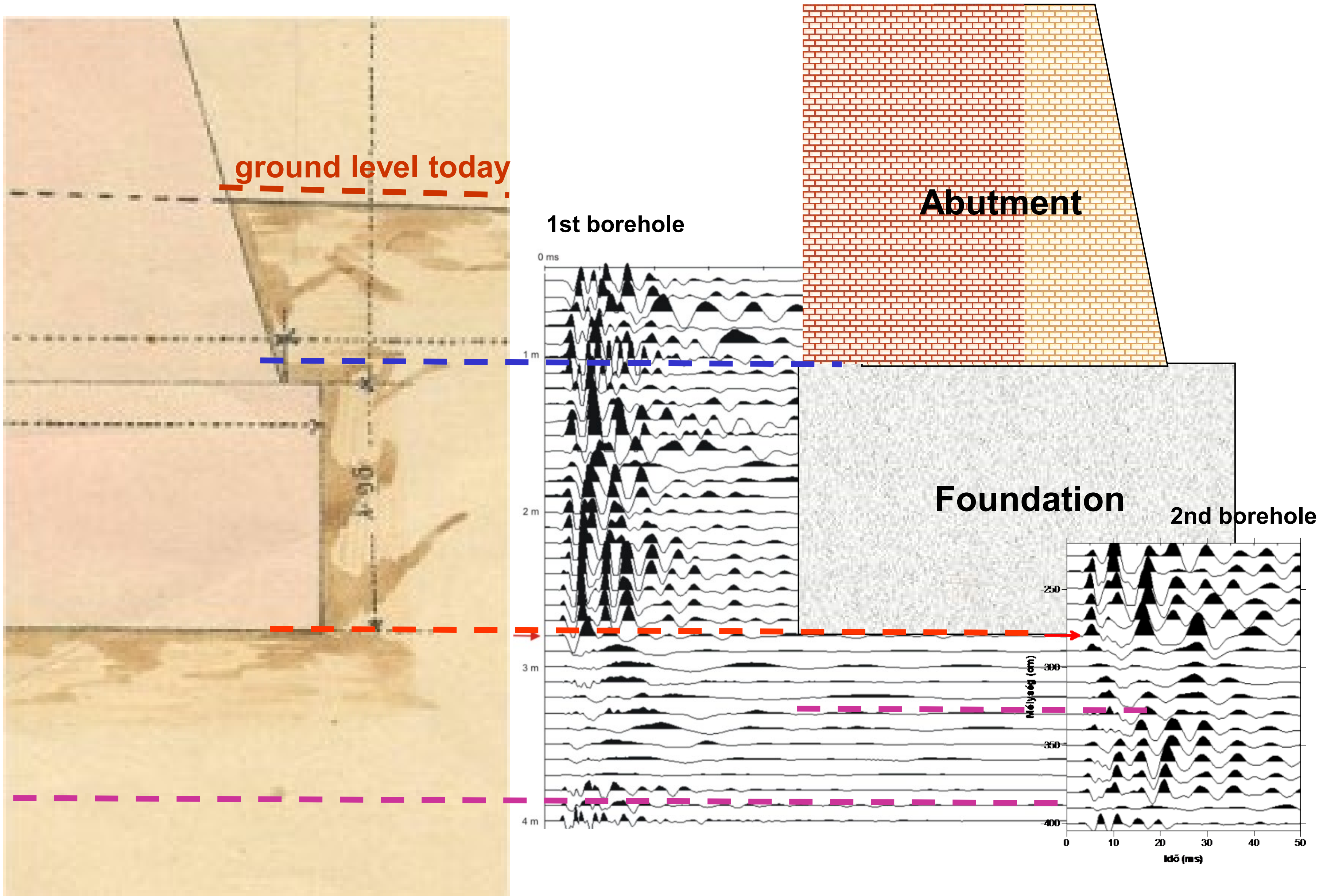
Felszín
Alap
Fúrás, érzékelők
Sugárutak



0 ms
100 ms
1 m
2 m
3 m
4 m
Foundation top
Foundation bottom
Hard (rock) layer



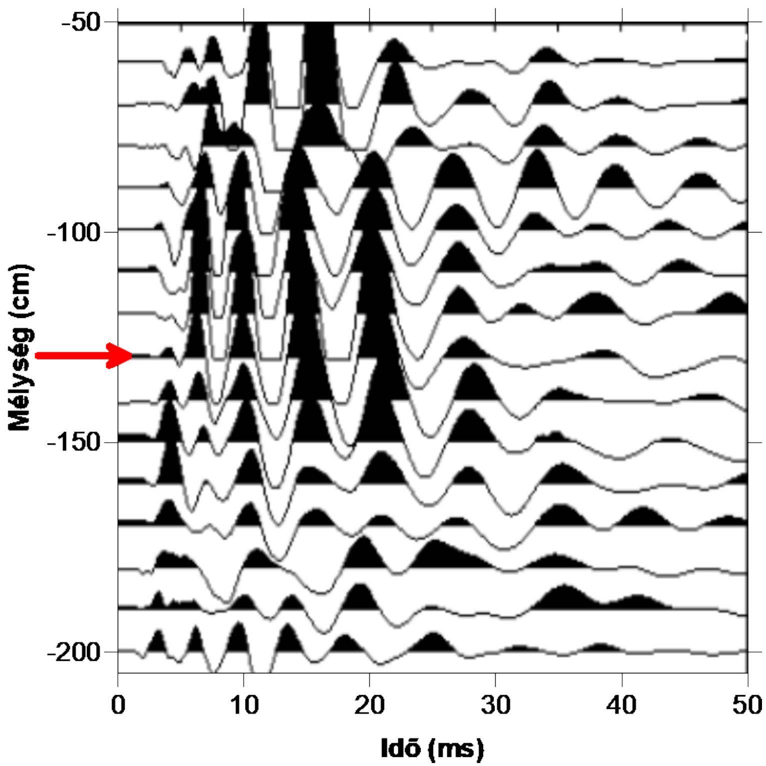
ground level today
1st borehole
Abutment
Foundation
2nd borehole
0 ms
1 m
2 m
3 m
4 m
-250
-300
-350
-400
Mélység (cm)
0
10
20
30
40
50
Idő (ms)

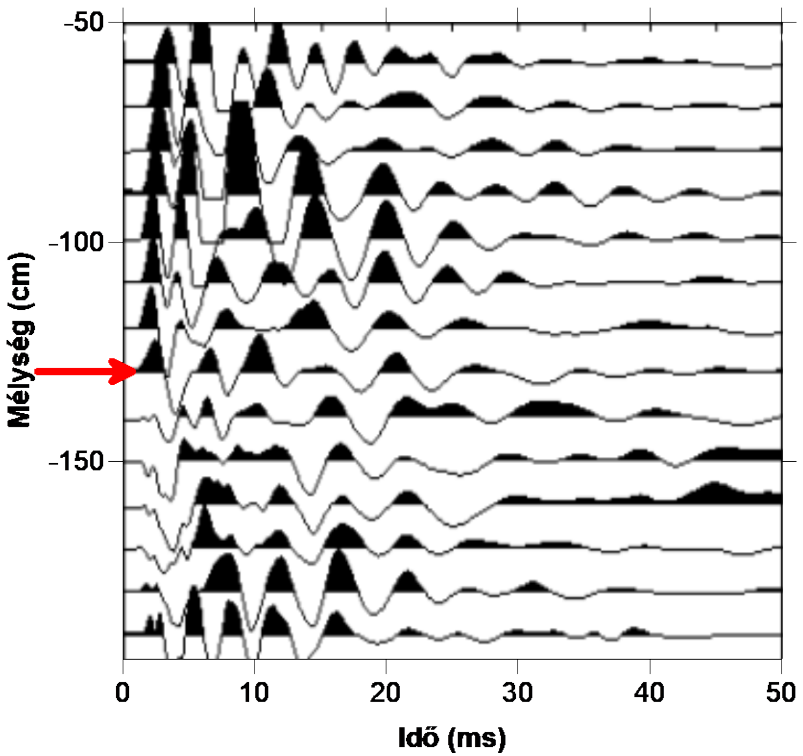
Field tests on a stone arch bridge

Tests with the borehole radar method

Tests with the parallel seismic method

Results


-50
-100
-150
-200
Mélység (cm)
0
10
20
30
40
50
Idő (ms)


-50
-100
-150
Mélység (cm)
0
10
20
30
40
50
Idő (ms)

COMPARISON

The borehole radar method	The parallel seismic method

Advantages

- Relatively quick and inexpensive
- Can accurately determine the depth of foundations

Limitations

- Accuracy depends on the distance of the borehole to the foundation and on soil properties

- Requires a PVC-cased borehole
- Not applicable in electrical conductive environment (clayey soil, high moisture content)

- Traffic may disturb the measurement

DIAGNOSTICS OF STRUCTURES

LECTURE 11

NDT of Danube bridge pier

(CASE STUDY)

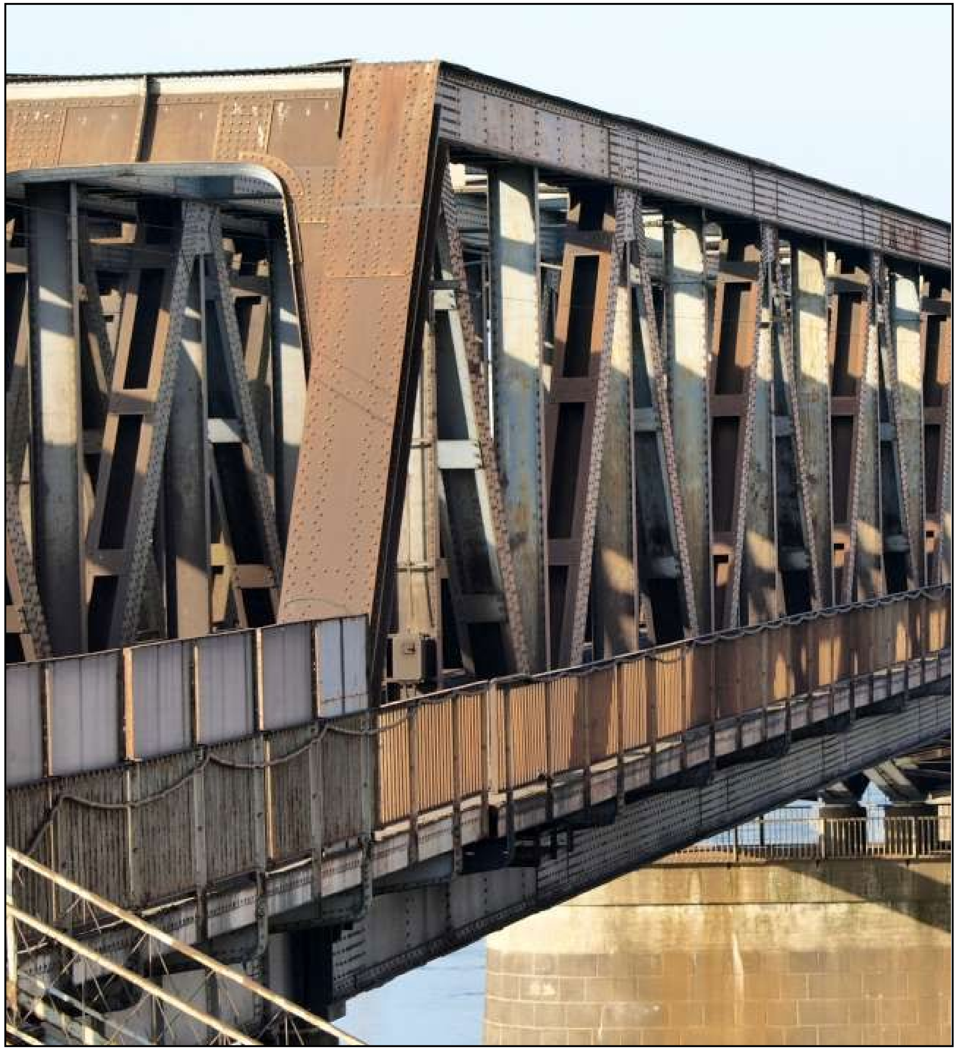
Zoltán Orbán

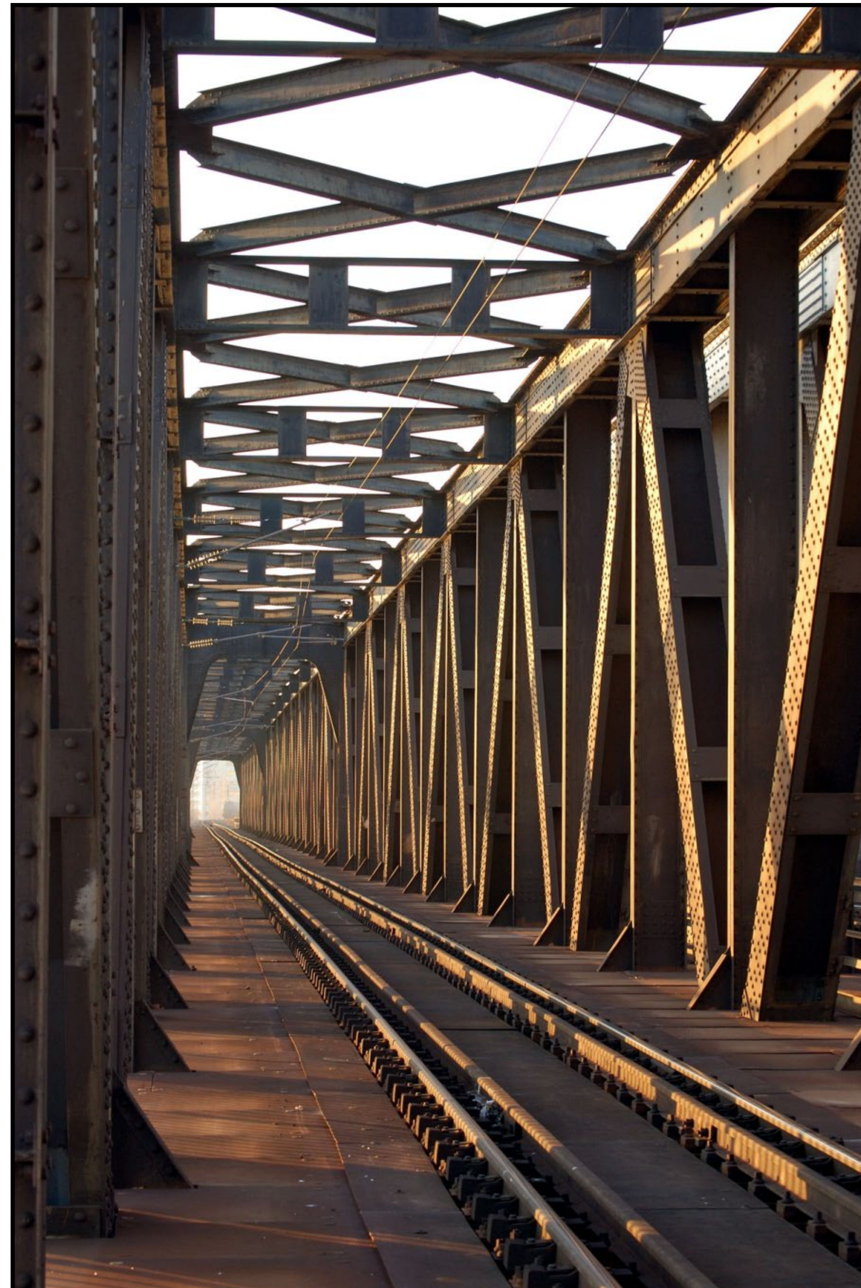
University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

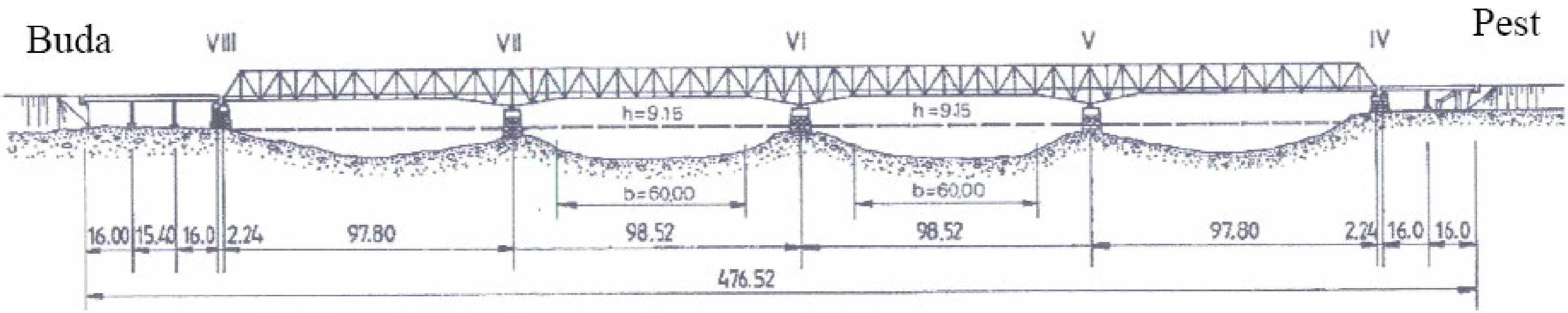
STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Non-Destructive Testing of a Danube bridge piers

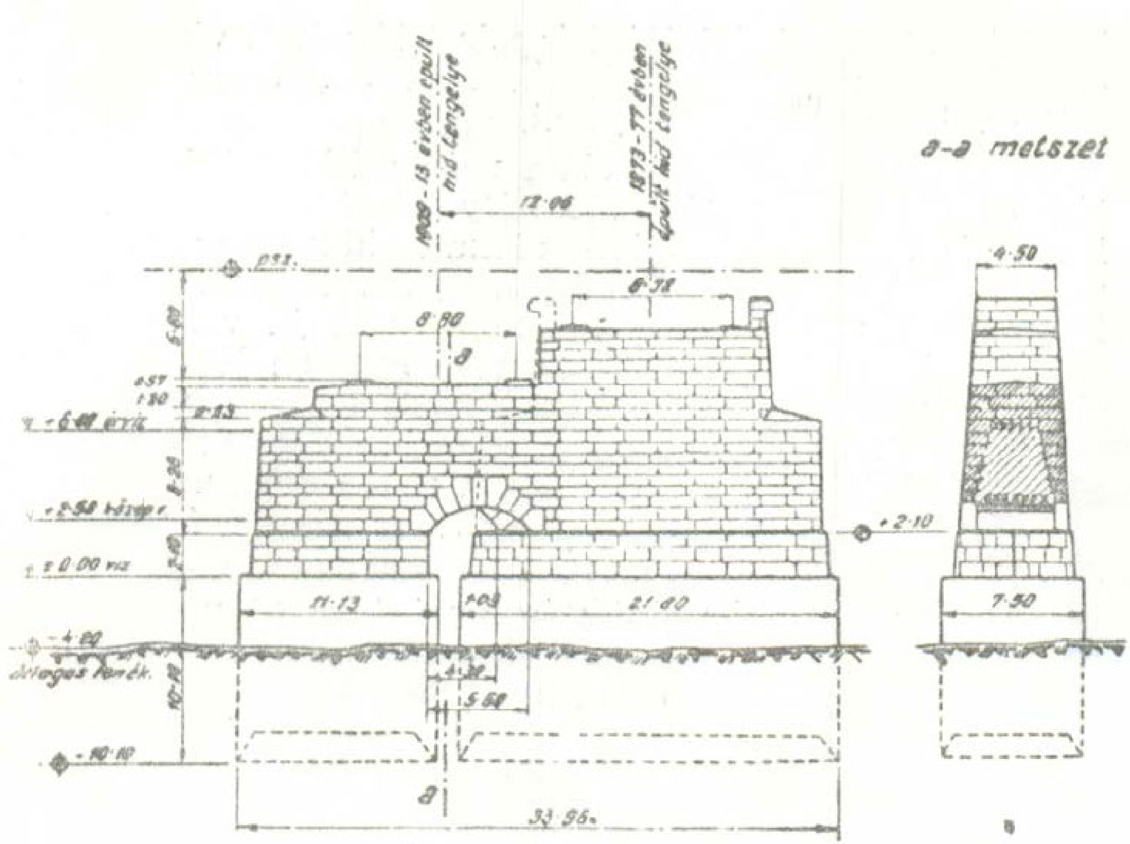
Case study





Original drawings, 1877



Reconstruction works, 1911 and 1945

Uncertain quality of infill

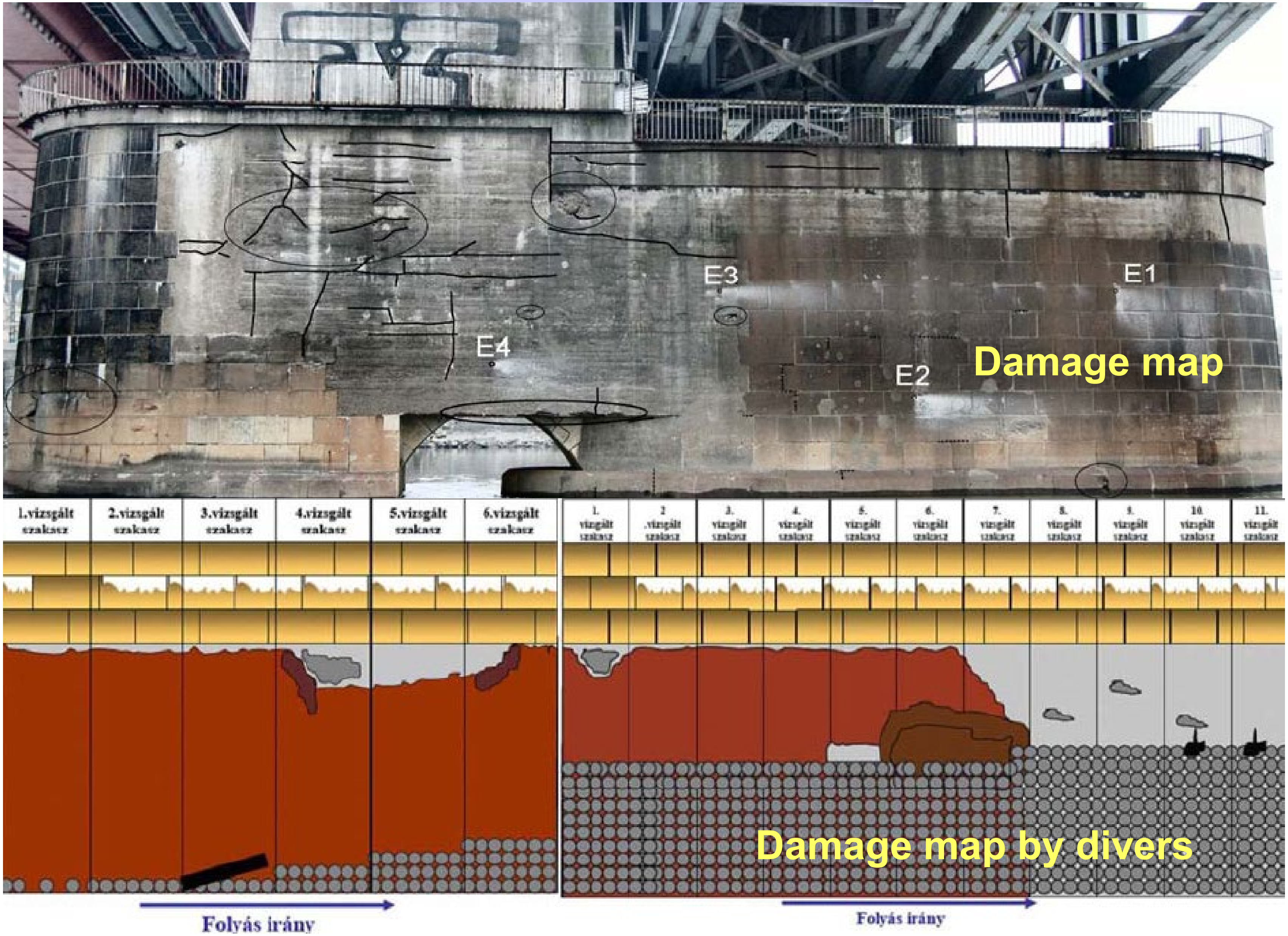
Deterioration of outer masonry

Deterioration of outer masonry

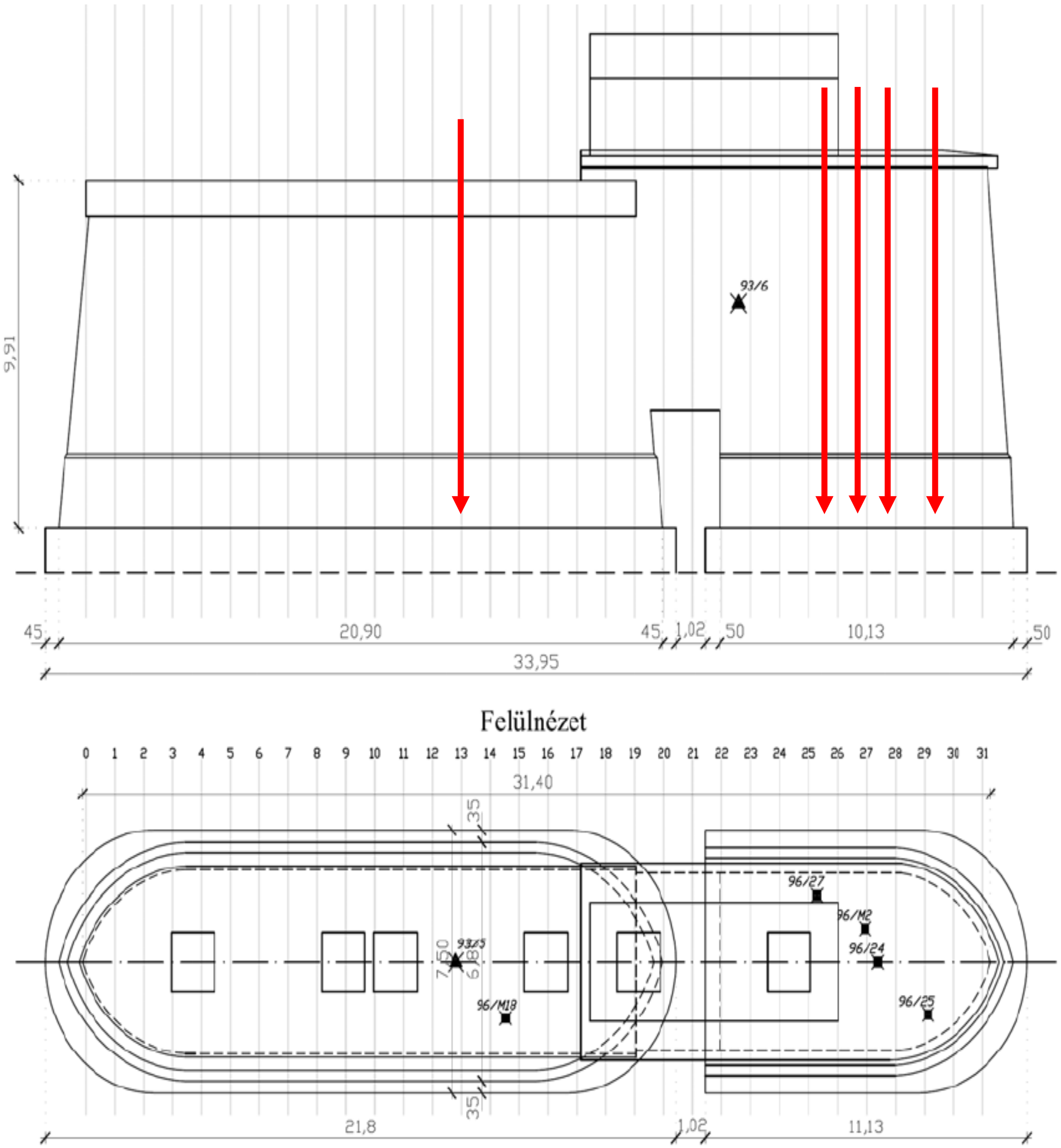
Accident in Austria

Krems, Austria
2002

Visual investigation

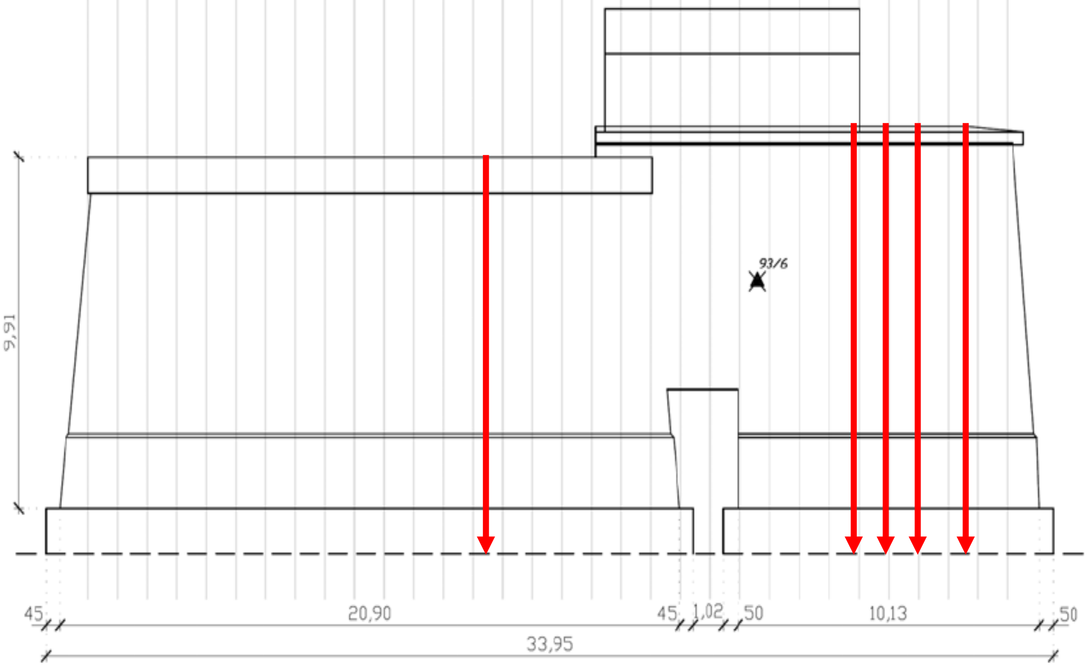


Vertical coring

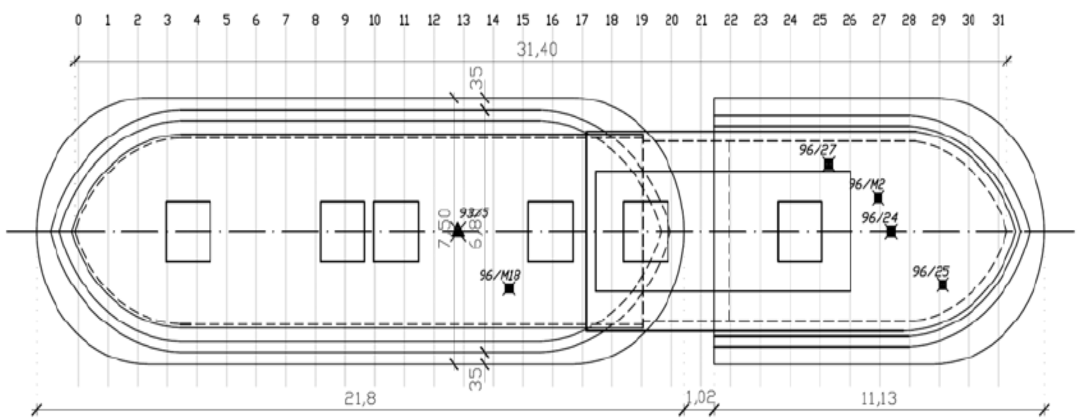


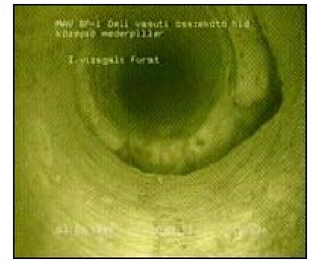
Vertical coring

Vertical boroscopy



Felülnézet





20, - 10,52 m

21, - 10,77 m

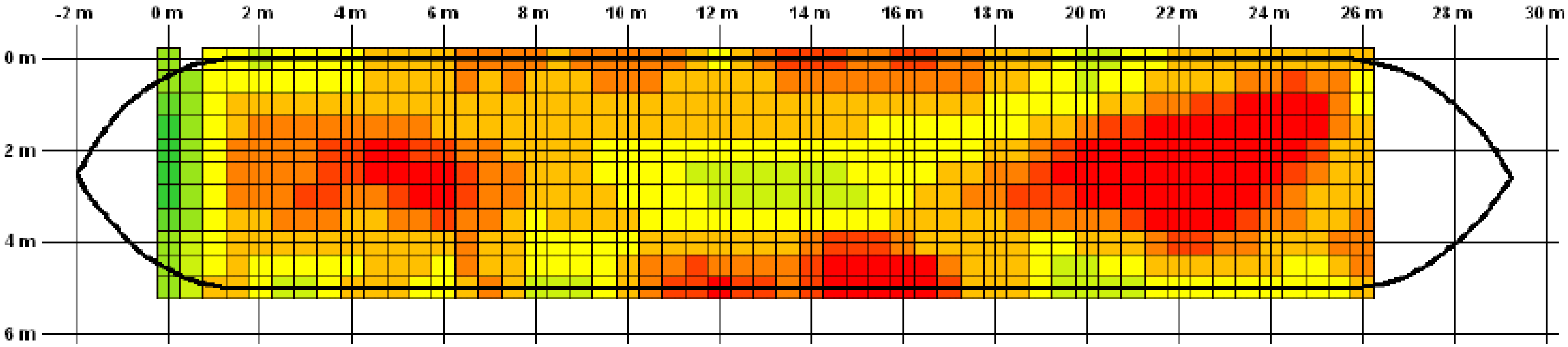
23. - 11,80 m

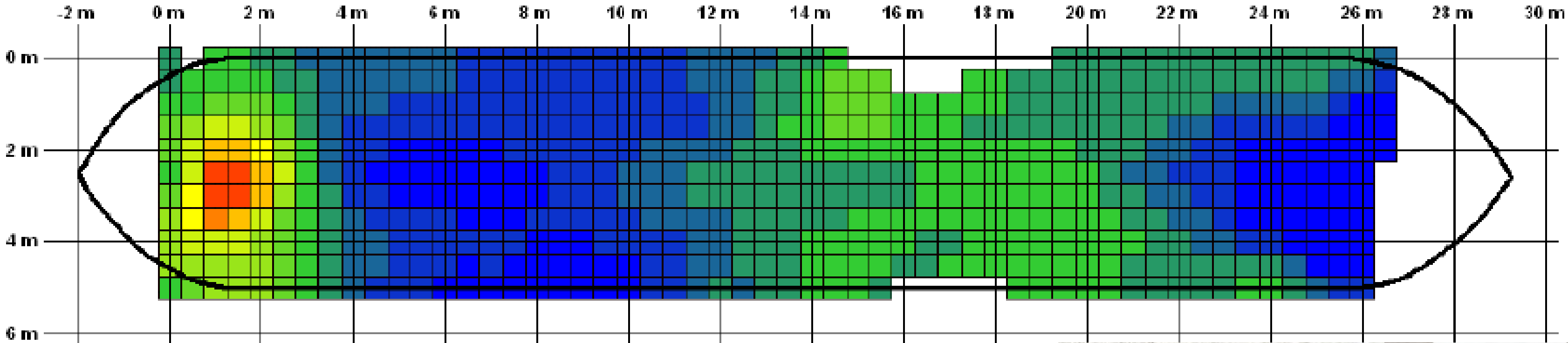
24, - 12,05 m

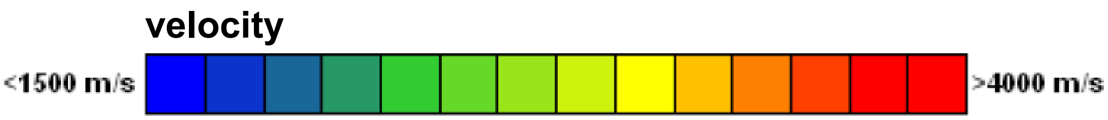
29, - 14,78 m

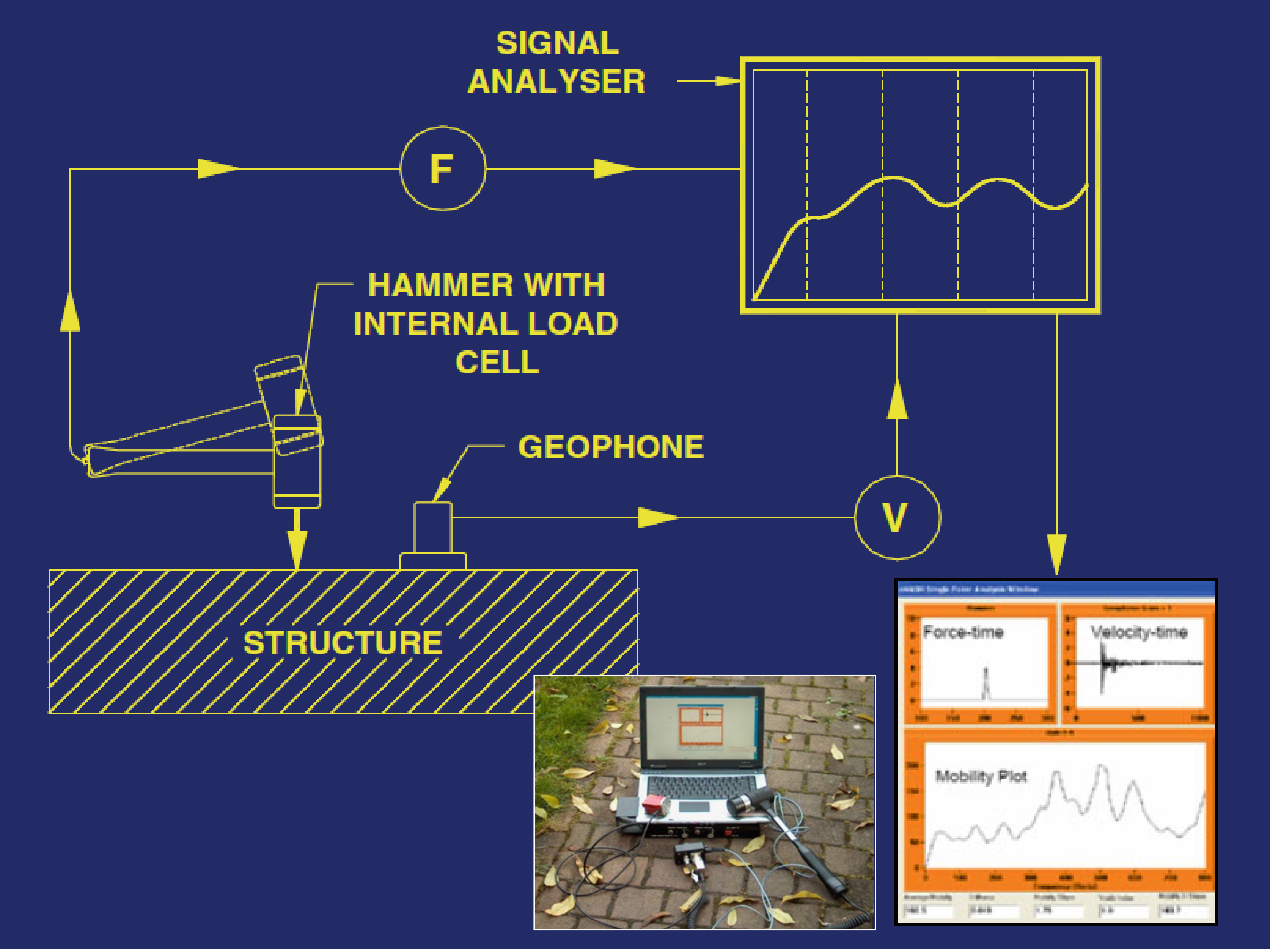
30, - 14,79 m

Seismic tomography



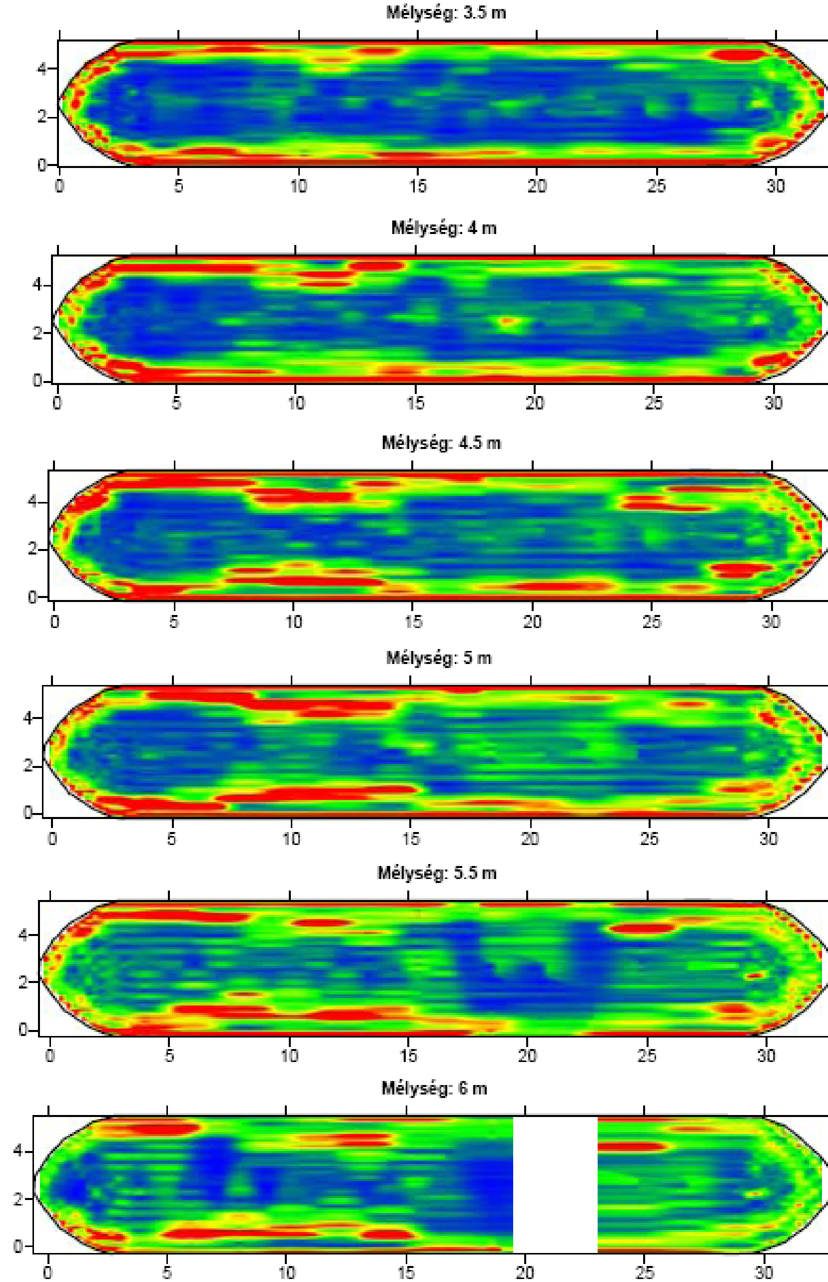




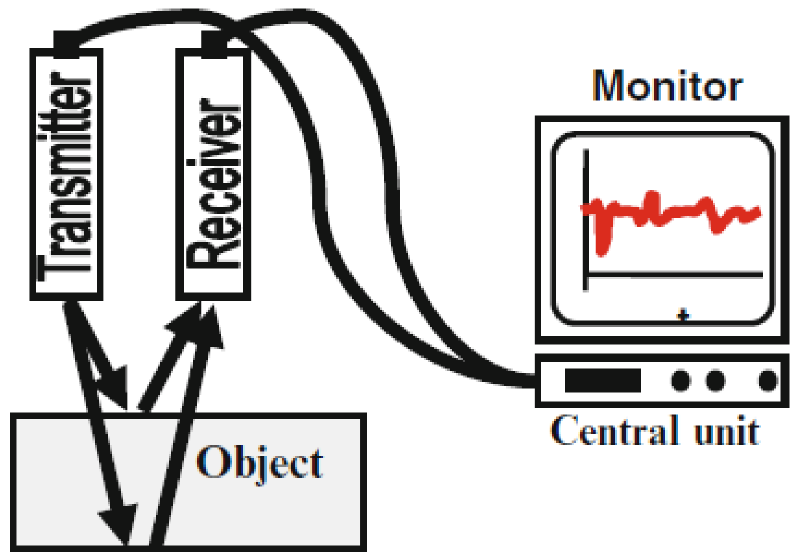


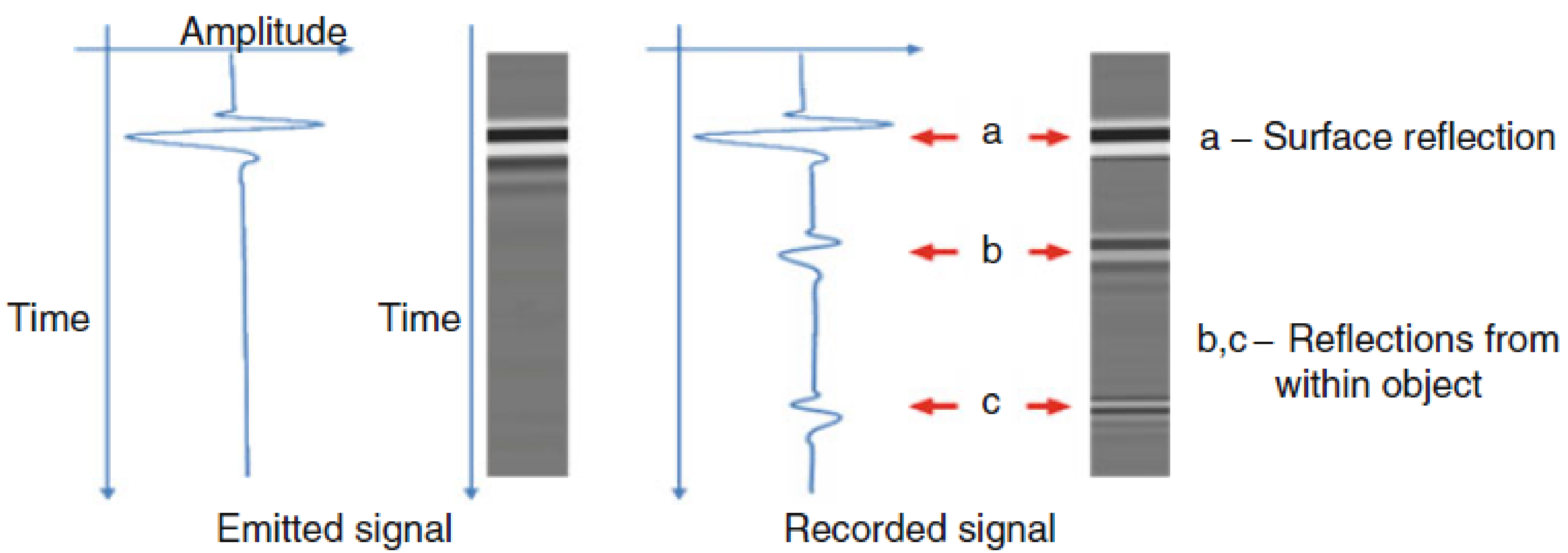
SIGNAL
ANALYSER
F
HAMMER WITH
INTERNAL LOAD
CELL
GEOPHONE
V
STRUCTURE
Force-time
Velocity-time
Mobility Plot

Georadar test

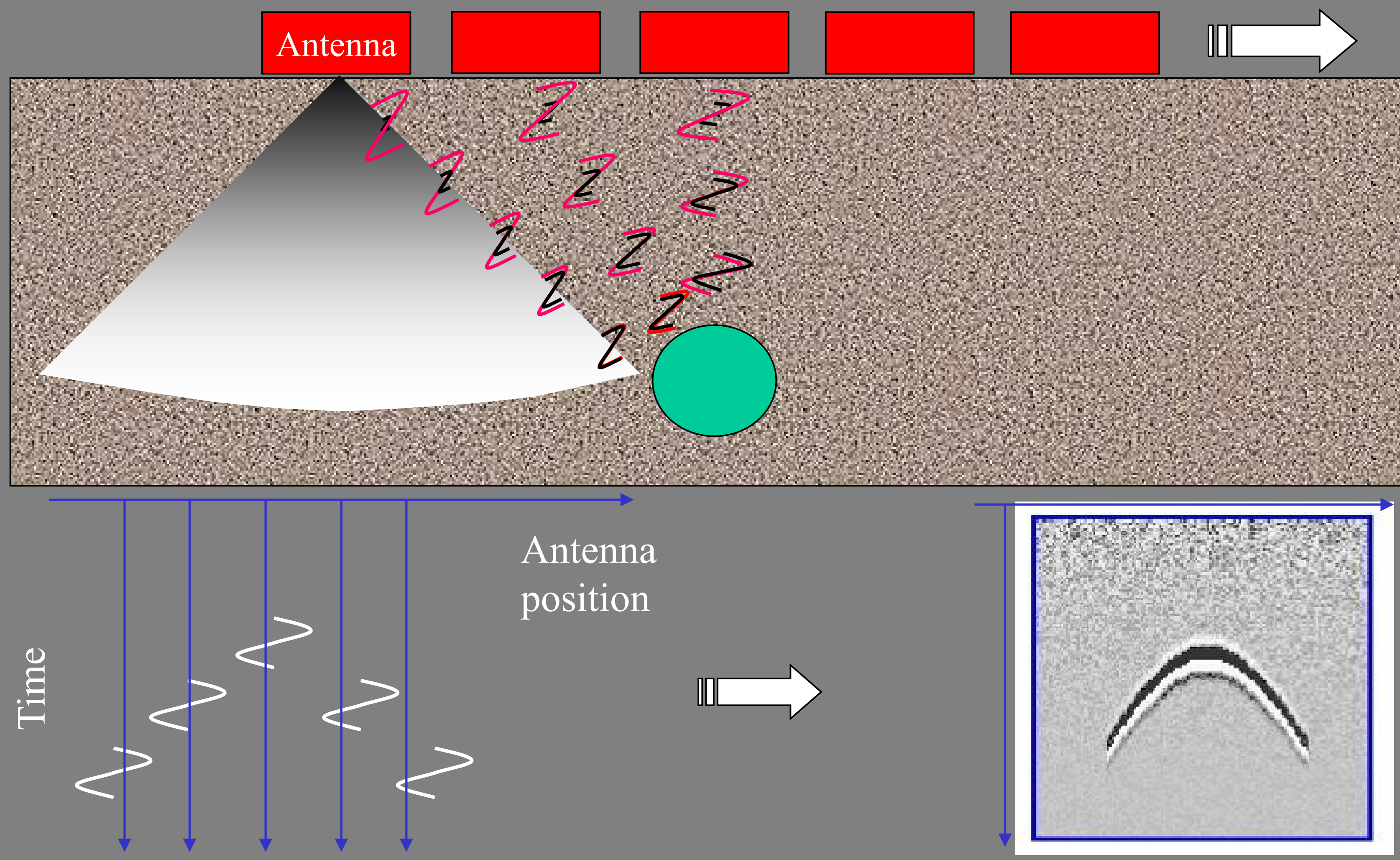


Principle of GPR

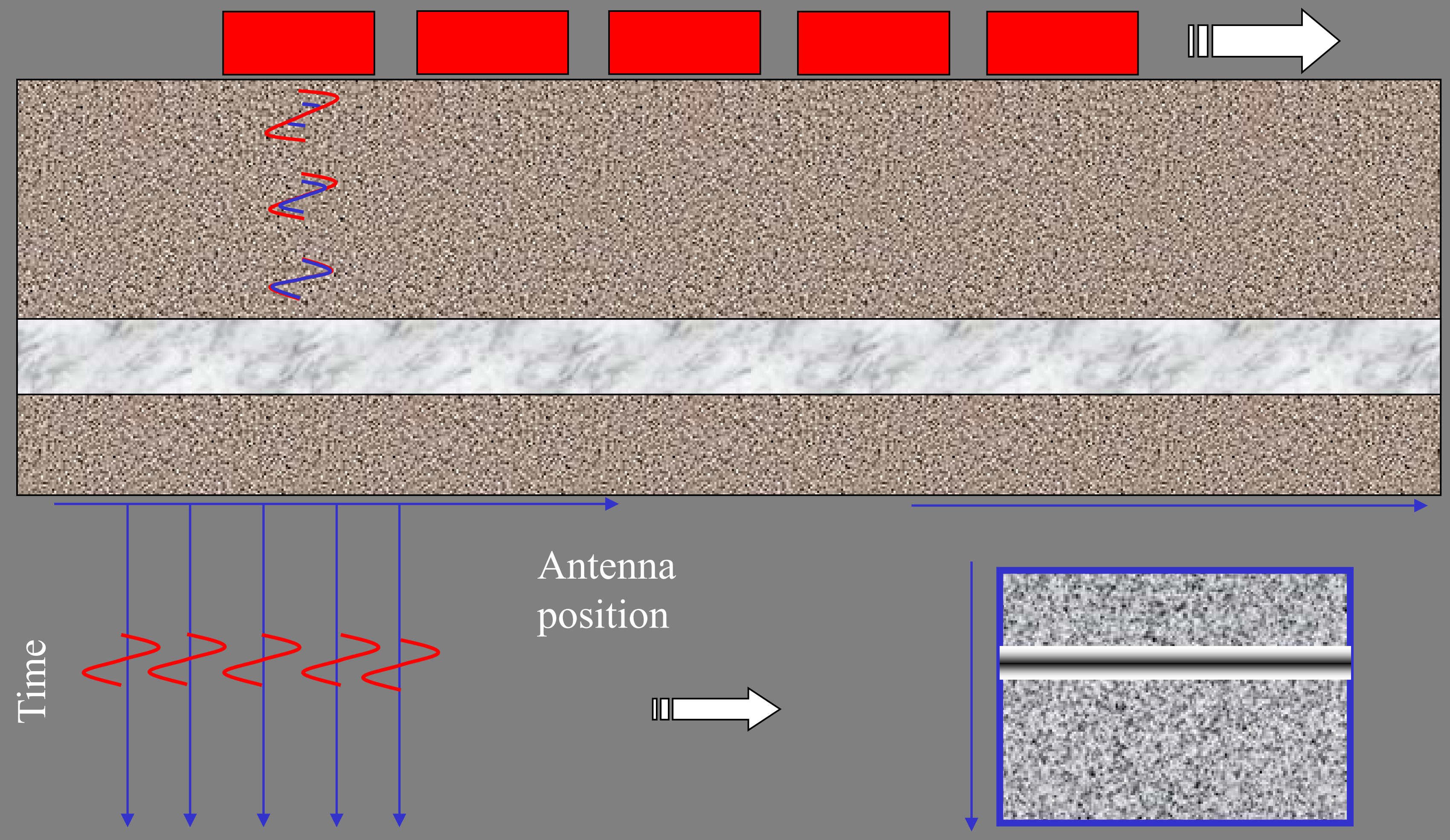




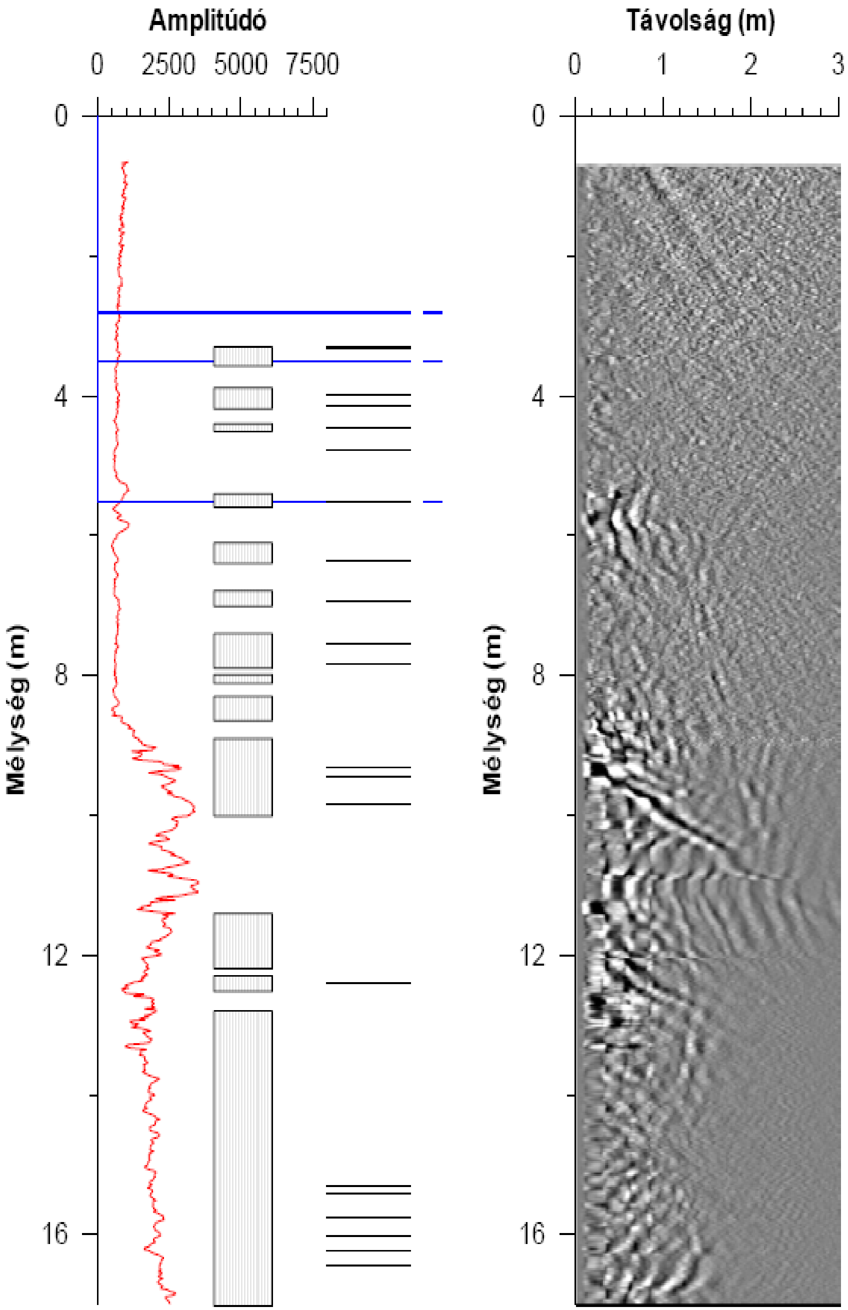
Principle of georadar

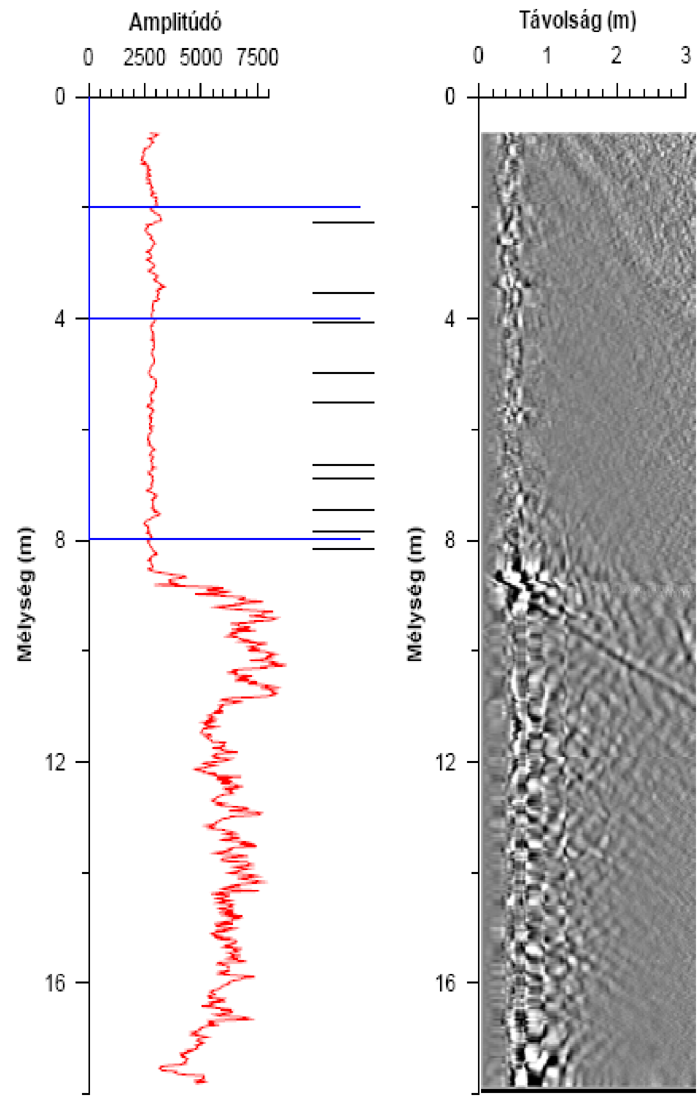


Principle of georadar



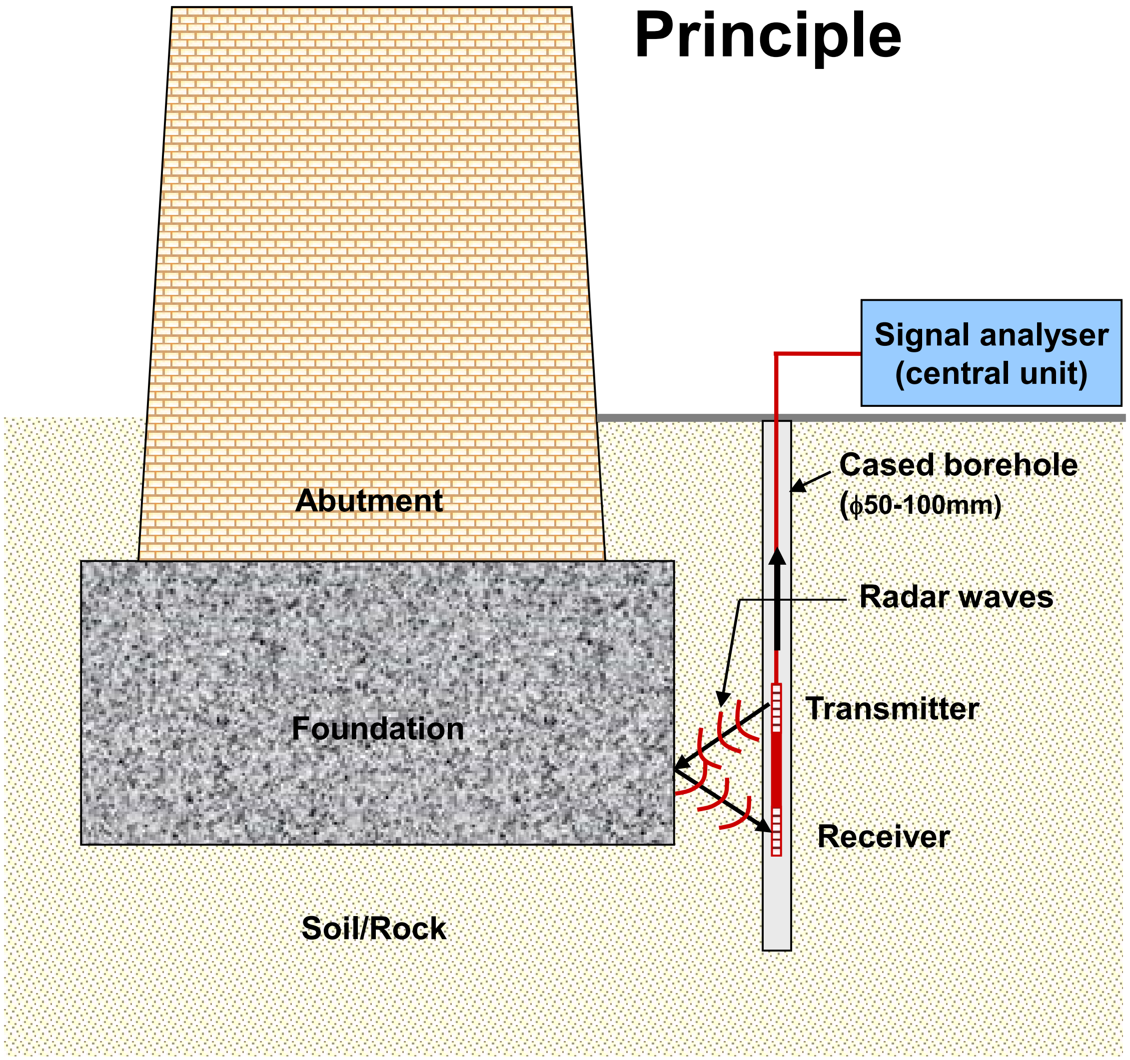
Test with borehole radar

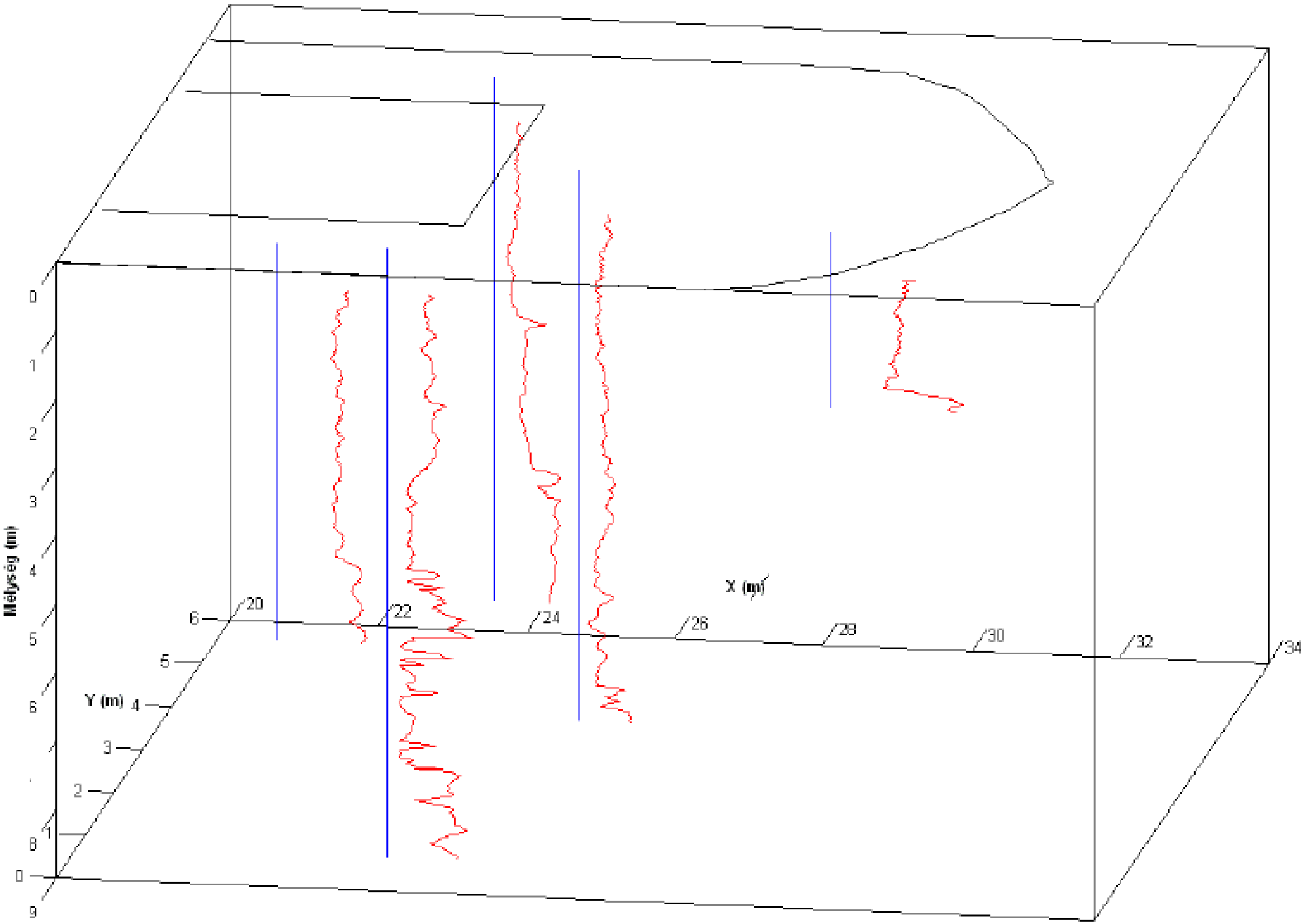




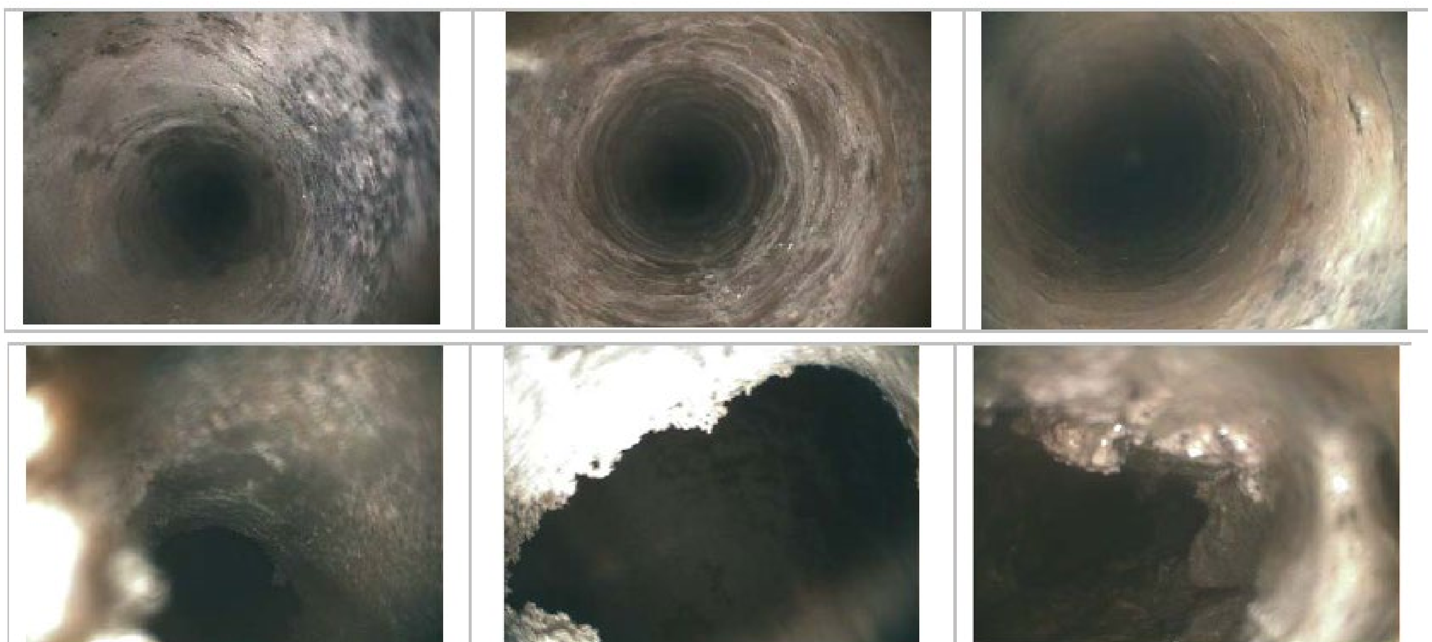
Tests with the borehole radar method

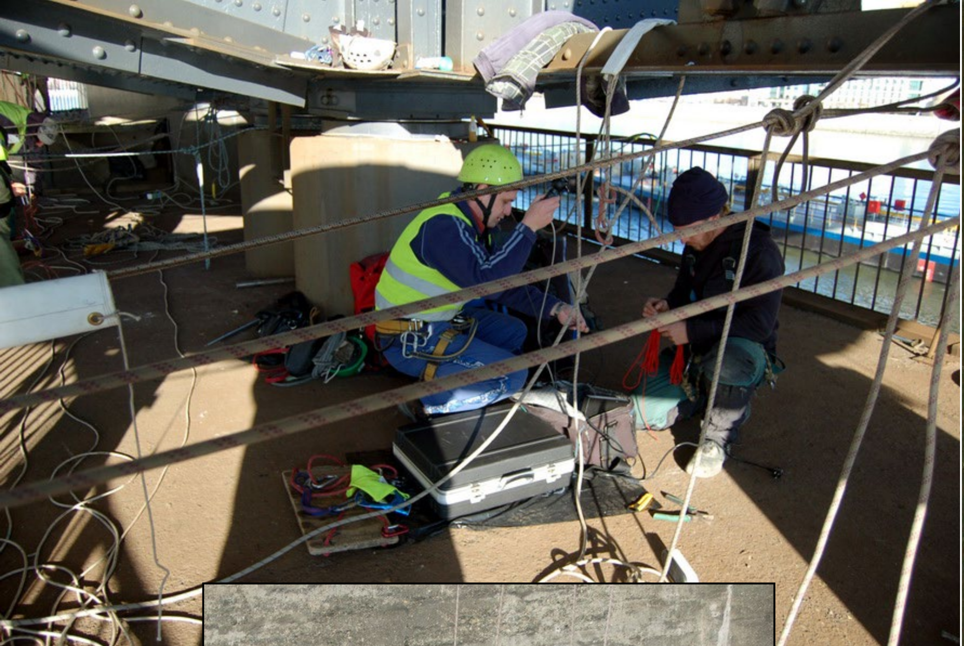
Principle

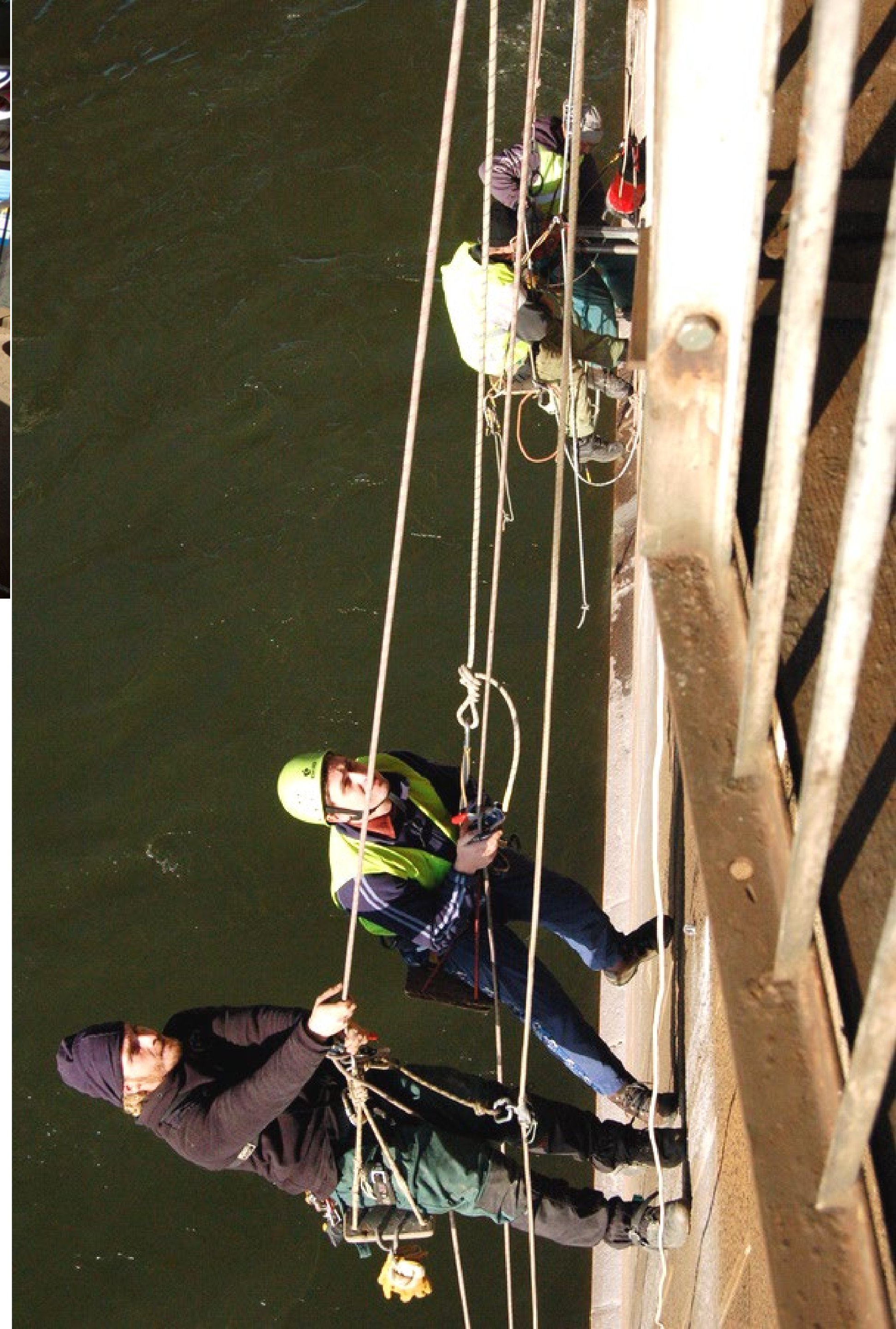



Mélység (m)
0
1
2
3
4
5
6
8
9
Y (m)
0
1
2
3
4
5
6
X (m)
20
22
24
26
28
30
32
34

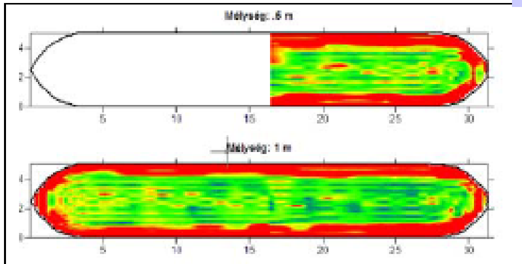
Video endoscopy /horizontal/



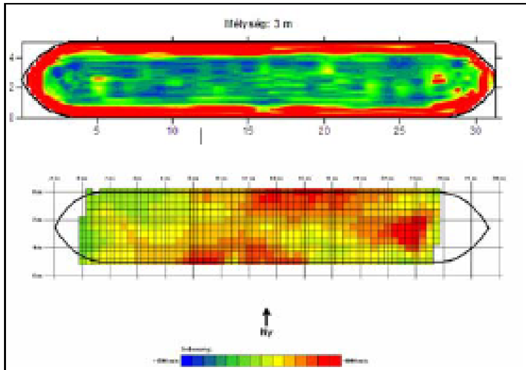




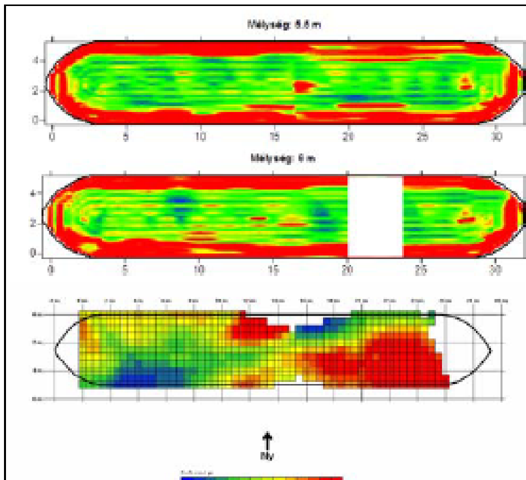
Comparison of NDT test results



A pillér felső 1-1,5 méterének jellemző képe (georadar)

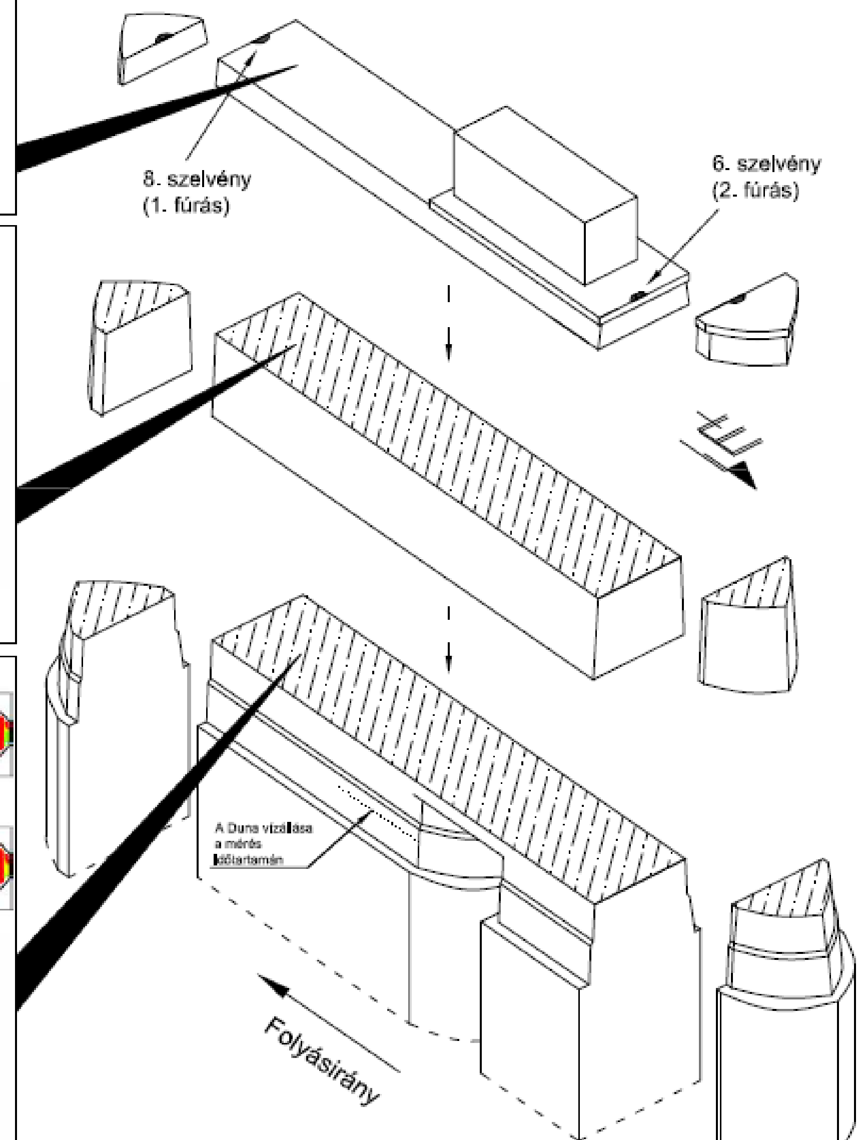


A pillér 1,5 - 4,5 méterének jellemző képe (georadar, szeizmikus tomográfia)



A pillér 5,0 méter alatti jellemző képe (georadar, szeizmikus tomográfia)

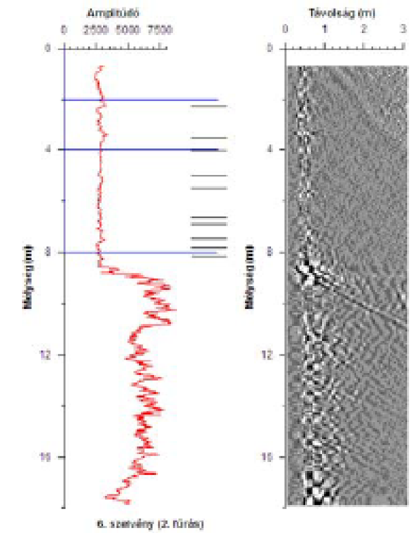
A Déli Vasúti Összekötő Híd VI.számú pillérének szerkezete a geofizikai vizsgálatok alapján



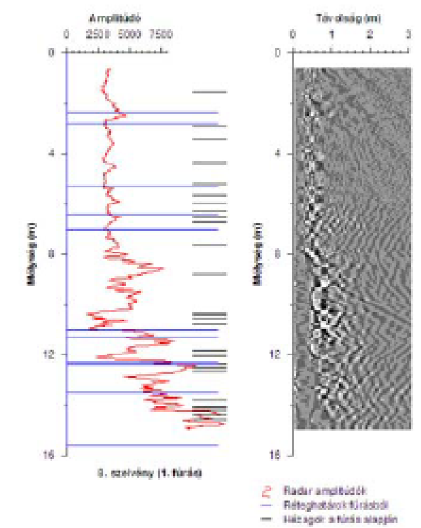
2.2 melléklet

A lyukradaros vizsgálat eredményei

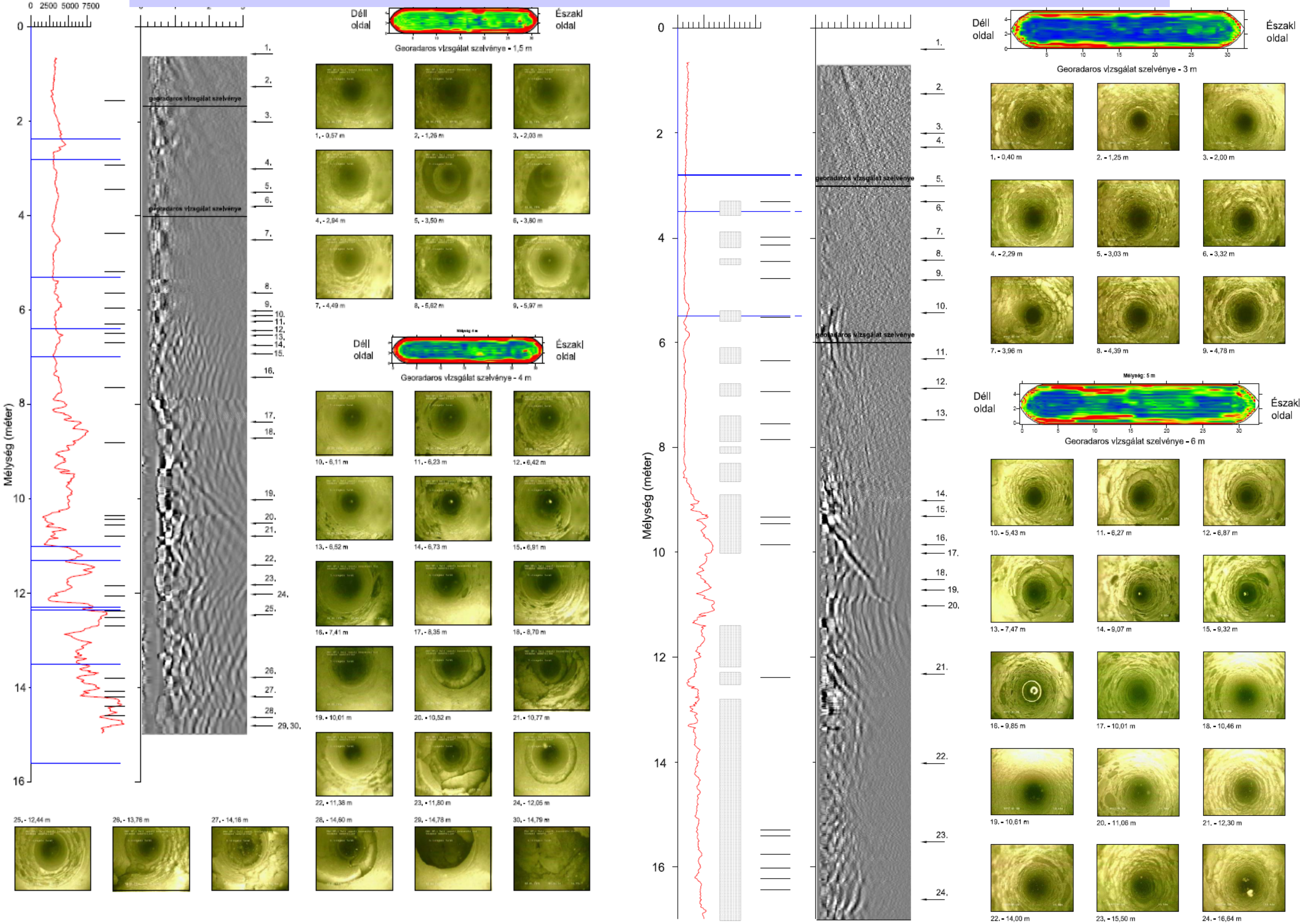
6. szelvény (2. fúrás)



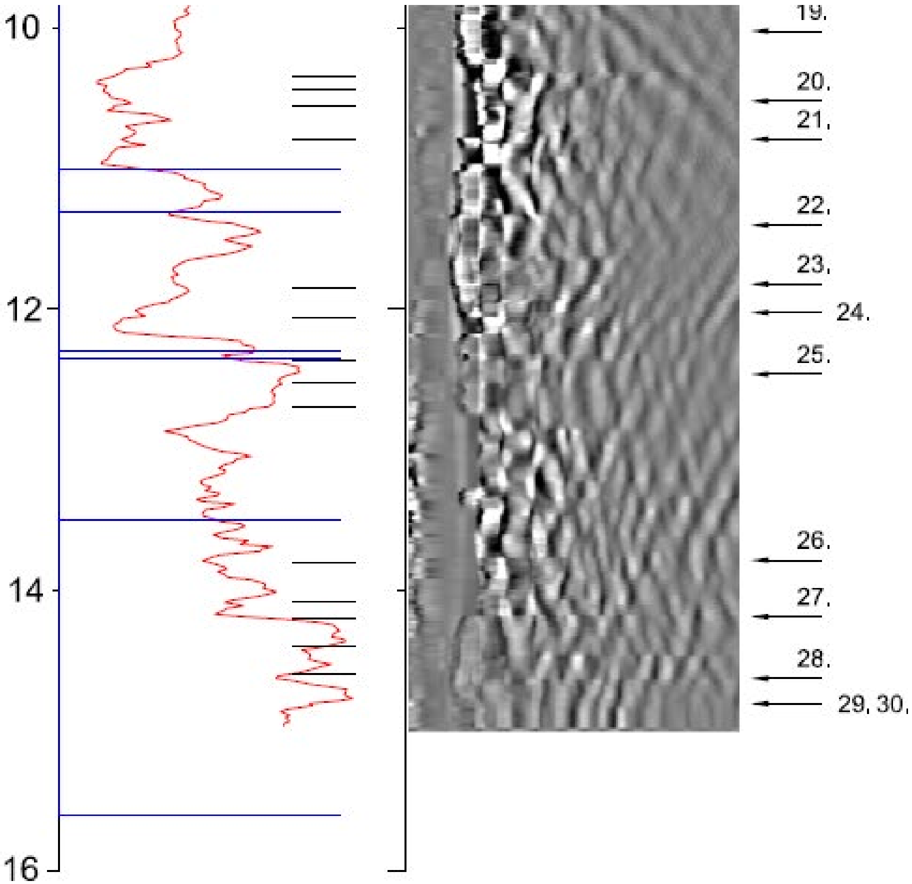
8. szelvény (1. fúrás)



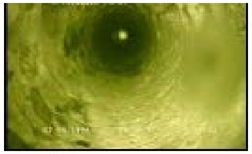
Comparison of NDT and boroscopy test results

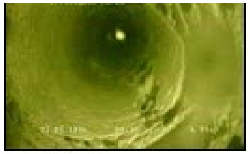


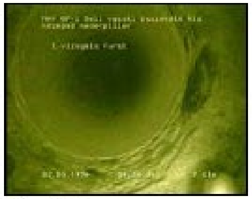
Comparison of NDT and boroscopy test results



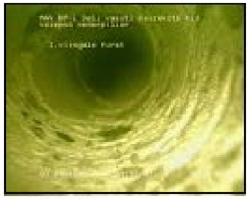

13. - 6,52 m


14. - 6,73 m

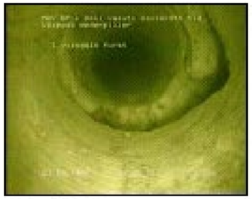

15. - 6,91 m

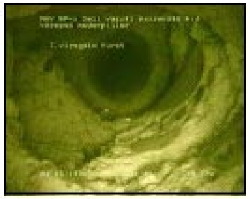

16. - 7,41 m

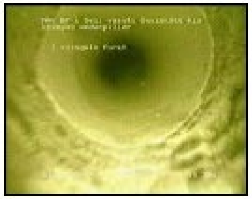

17. - 8,35 m


18. - 8,70 m


19. - 10,01 m


20. - 10,52 m


21. - 10,77 m

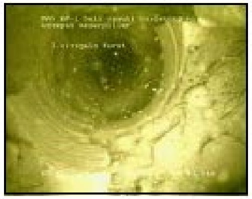

22. - 11,38 m


23. - 11,80 m


24. - 12,05 m

25. - 12,44 m


26. - 13,76 m

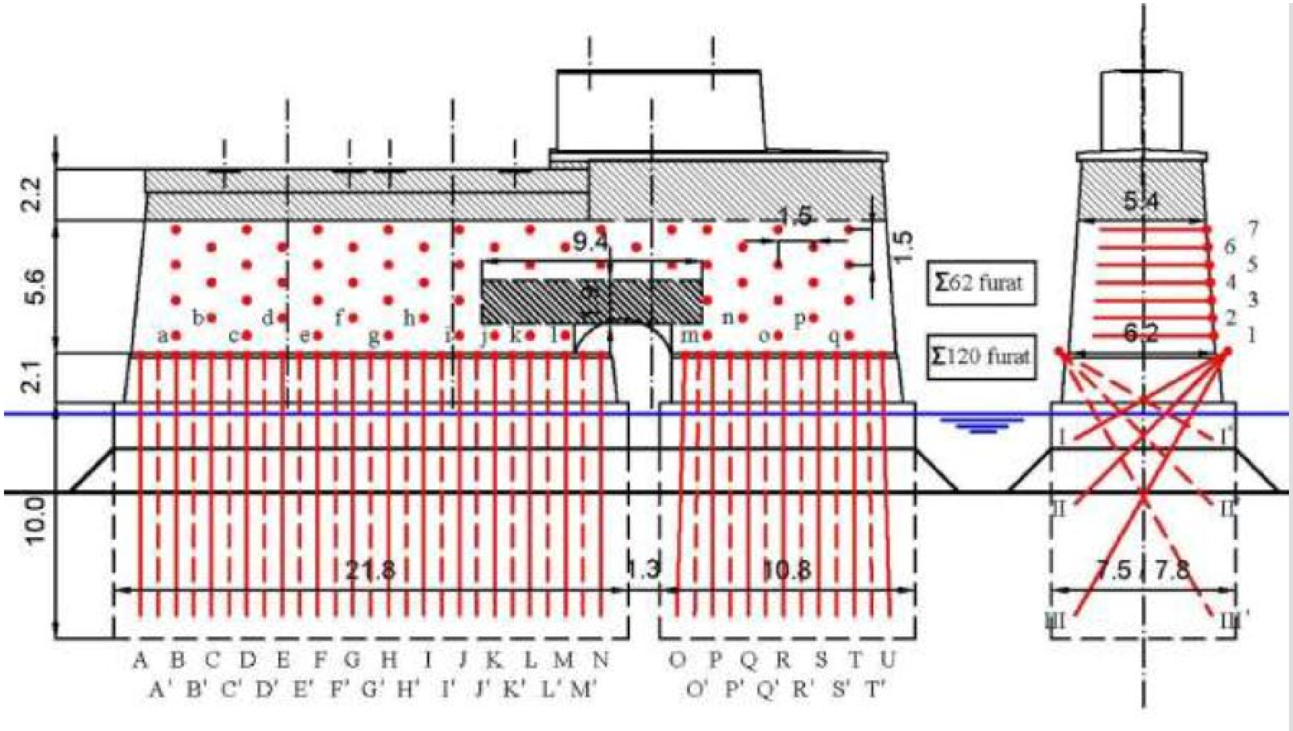

27. - 14,16 m


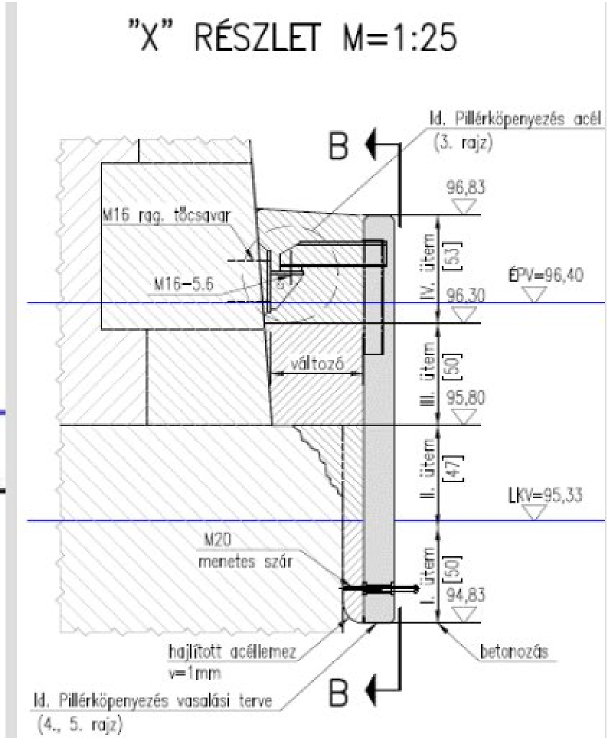
28. - 14,60 m


29. - 14,78 m


30. - 14,79 m


Repair solution





Repair solution

DIAGNOSTICS OF STRUCTURES

LECTURE 12

Condition assessment of historic constructions

(CASE STUDIES)

Zoltán Orbán
University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

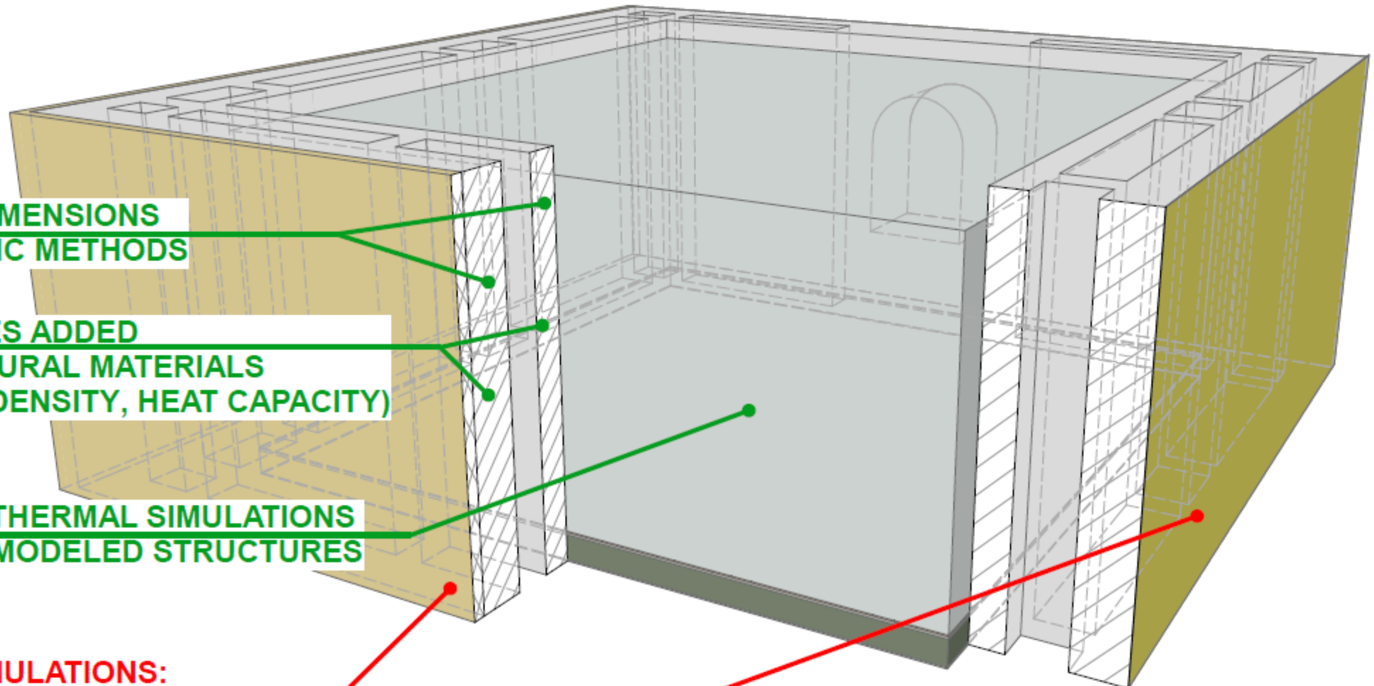
STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Holistic Rehabilitation of Historic Buildings

- **ARCHITECTURAL ASPECTS** (new function, indoor comfort, aestetics, preservation of architectural heritage)
- **STRUCTURAL ASPECTS** (load bearing capacity, serviceability, stability, **earthquake resistance**)
- **ENERGY EFFICIENCY** (energy analysis, compatible insulations)

Complex Analysis of Buildings

Structural analysis based on diagnostics + Energy analysis



1 ACCURATE STRUCTURAL DIMENSIONS REVEALED WITH DIAGNOSTIC METHODS

2 REAL PHYSICAL PROPERTIES ADDED TO THE IDENTIFIED STRUCTURAL MATERIALS (THERMAL CONDUCTIVITY, DENSITY, HEAT CAPACITY)

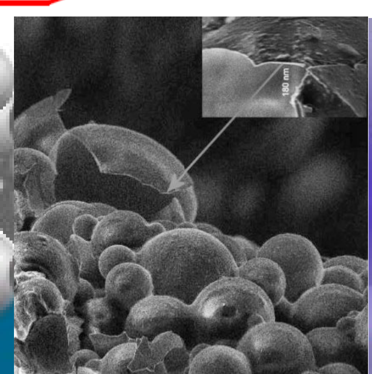
3 ZONE ELEMENT USED FOR THERMAL SIMULATIONS ALL DATA OBTAINED FROM MODELED STRUCTURES

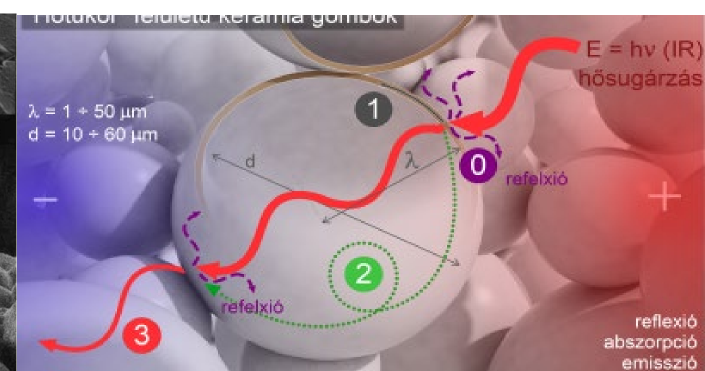
BASED ON THE ENERGY SIMULATIONS:

4 SUGGESTED CONVENTIONAL INSULATION

SUGGESTED NANOTECHNOLOGY INSULATION

Insulation with nano-technology

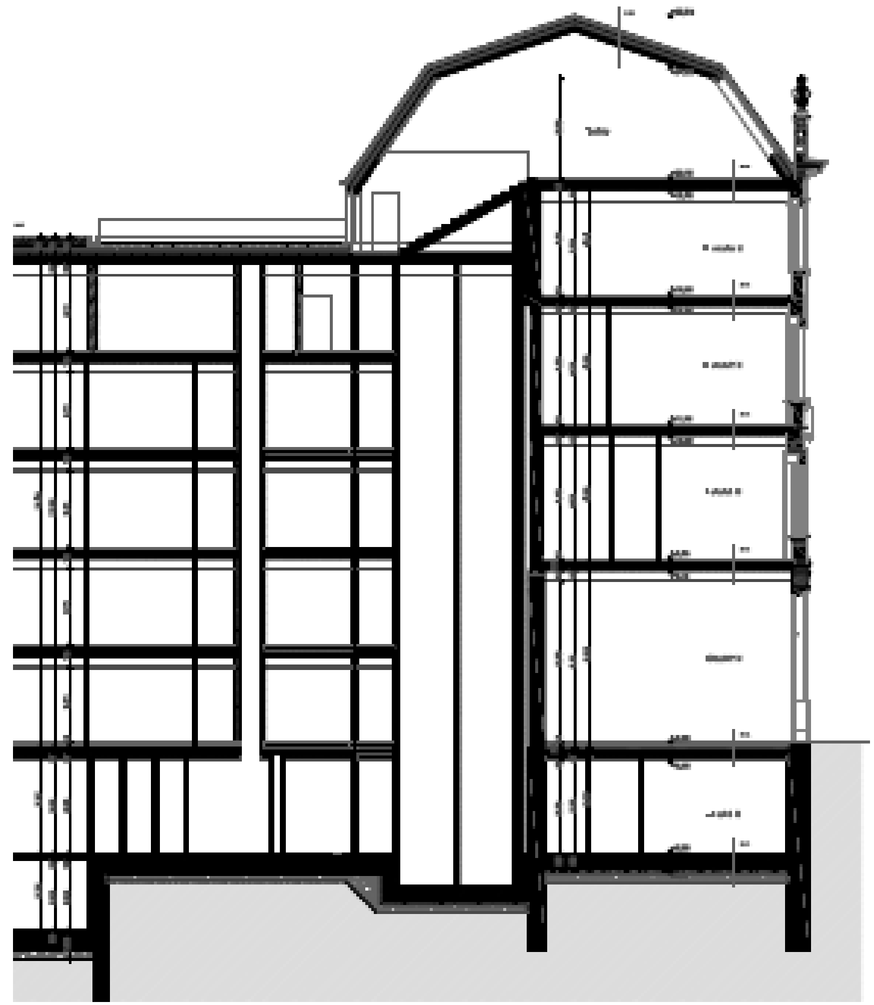




CASE STUDY 1 - Condition assessment of historic building

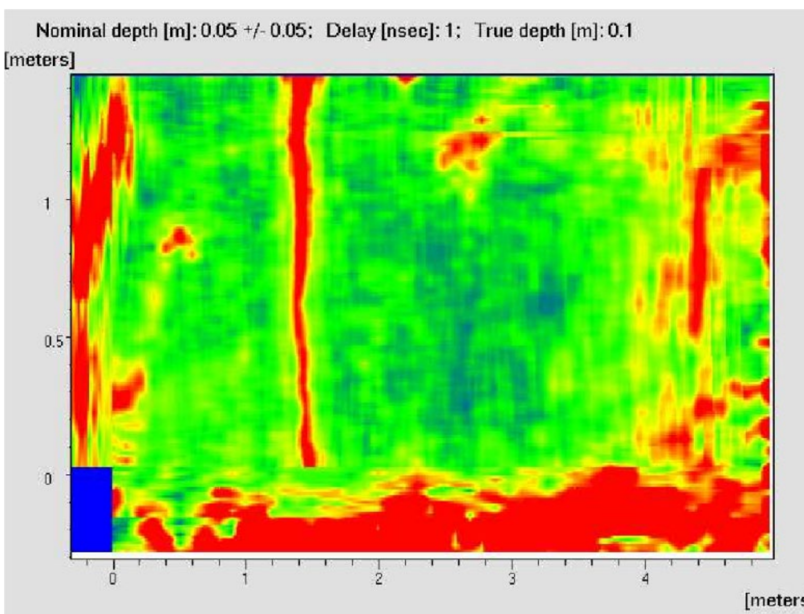
original

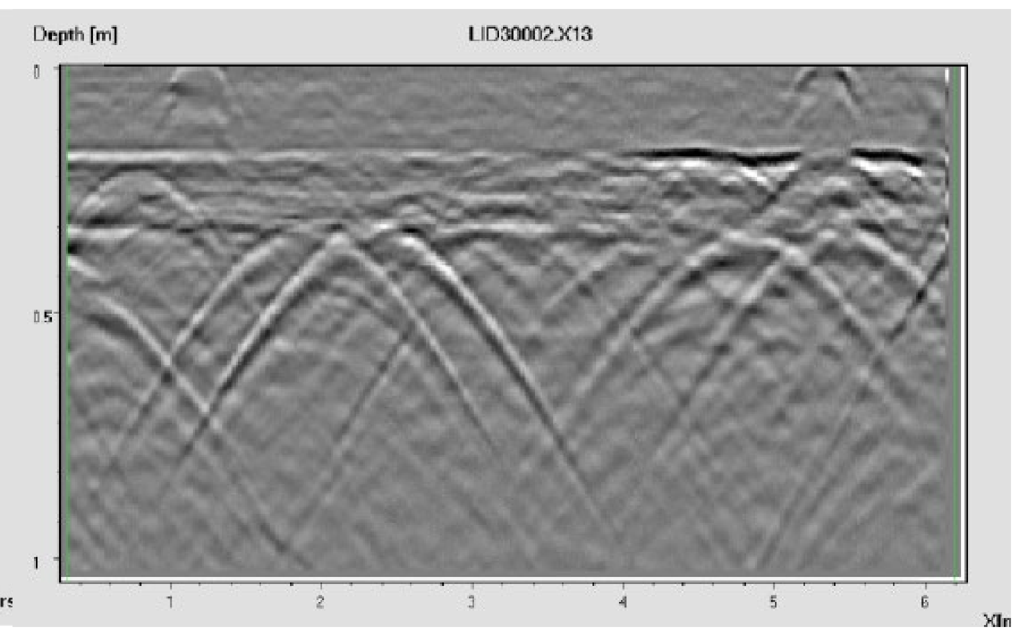
planned reconstruction



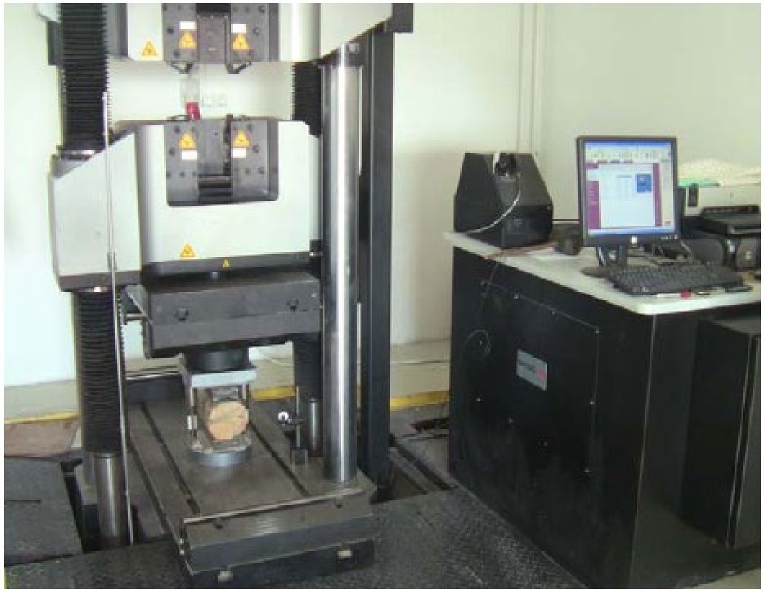
Static analysis including seismic assessment

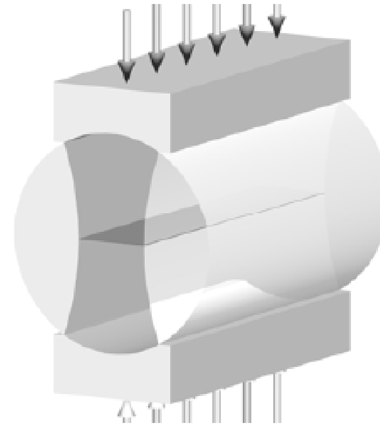
Testing the dimensions and homogeneity of masonry walls with NDT

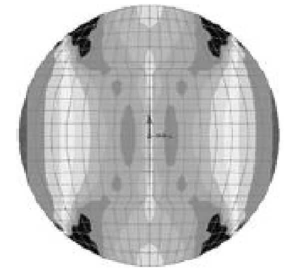


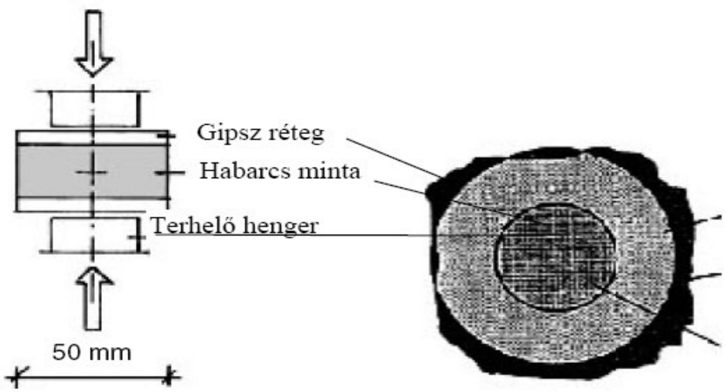


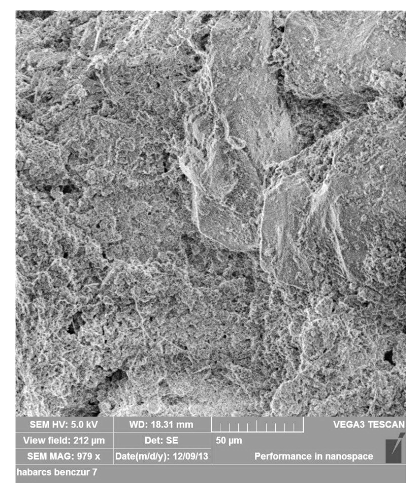
Testing material characteristics on cored samples



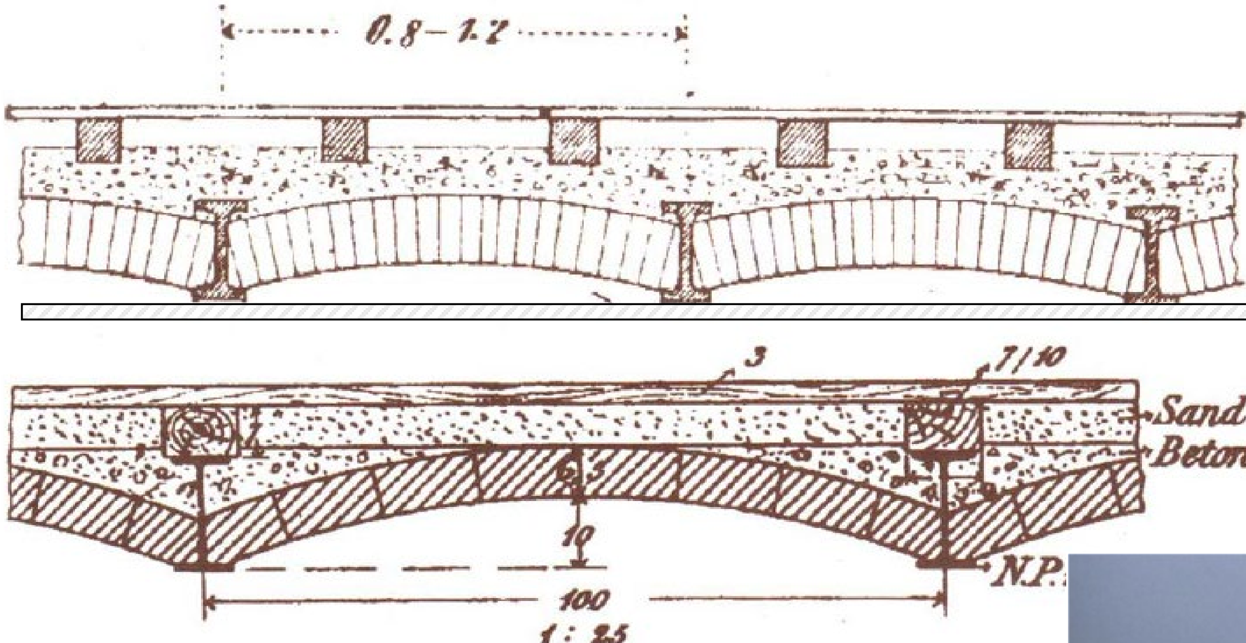




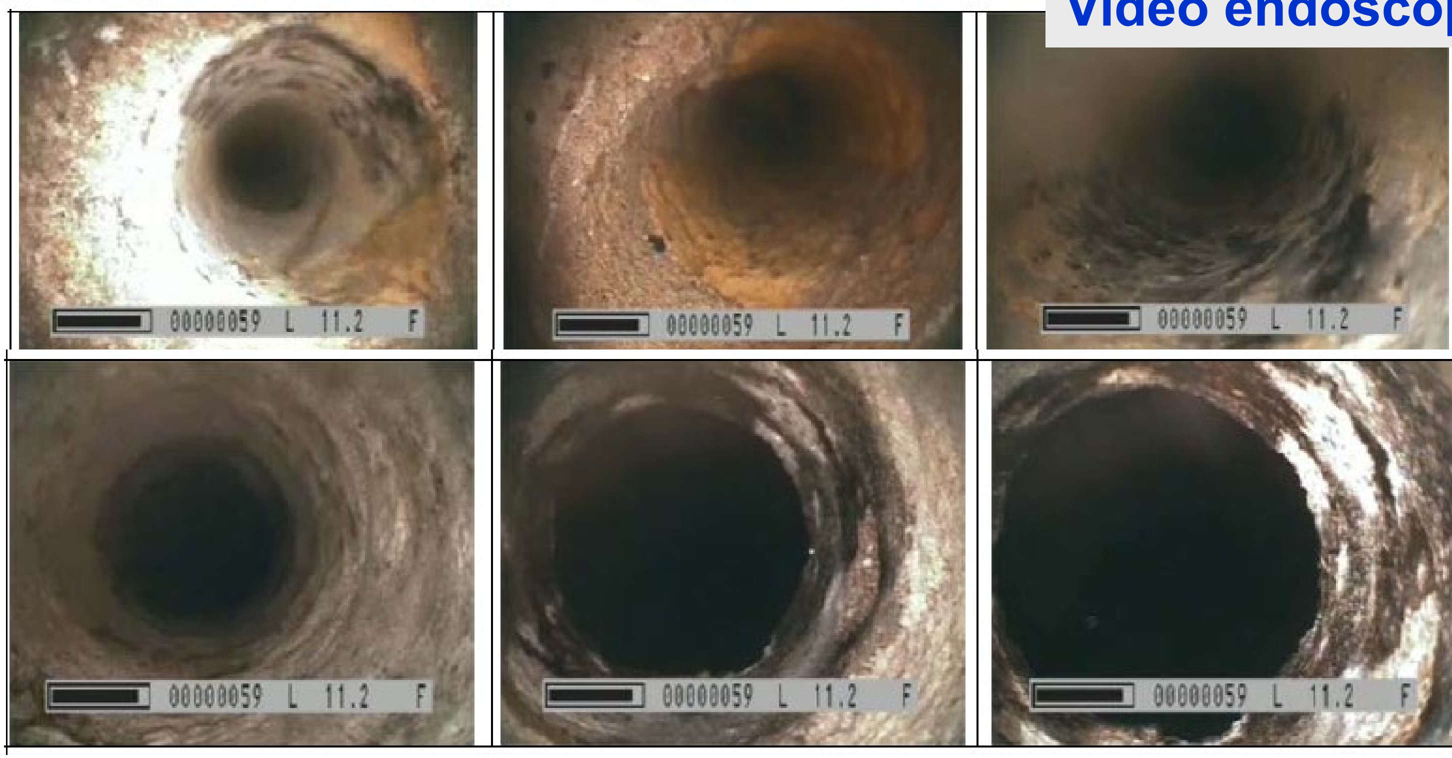




Testing the structure and condition of floors with NDT

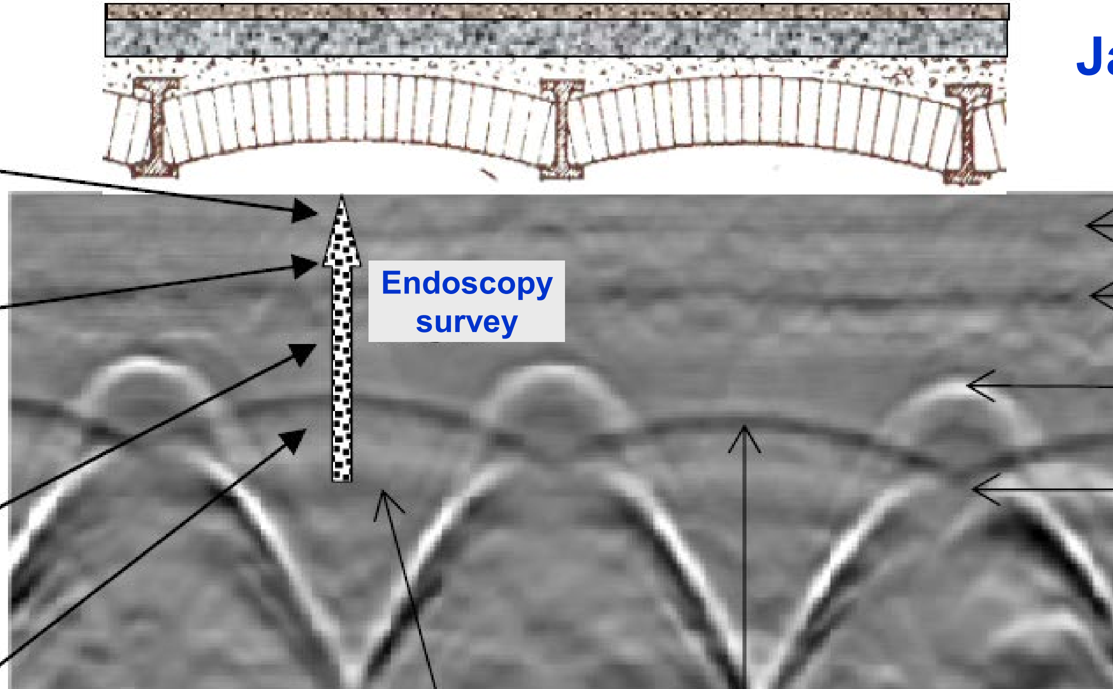


Video endoscopy survey



Jack-arch floor

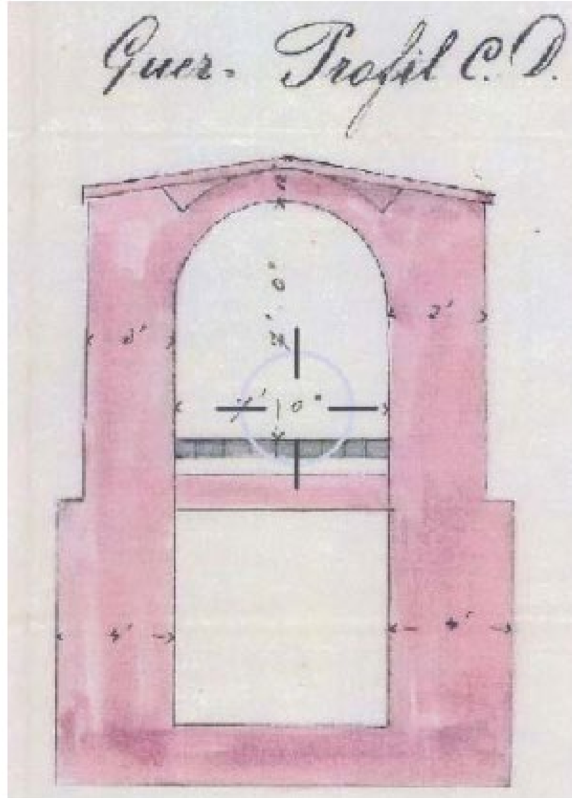
EF/F2 endoszkópos vizsgálat

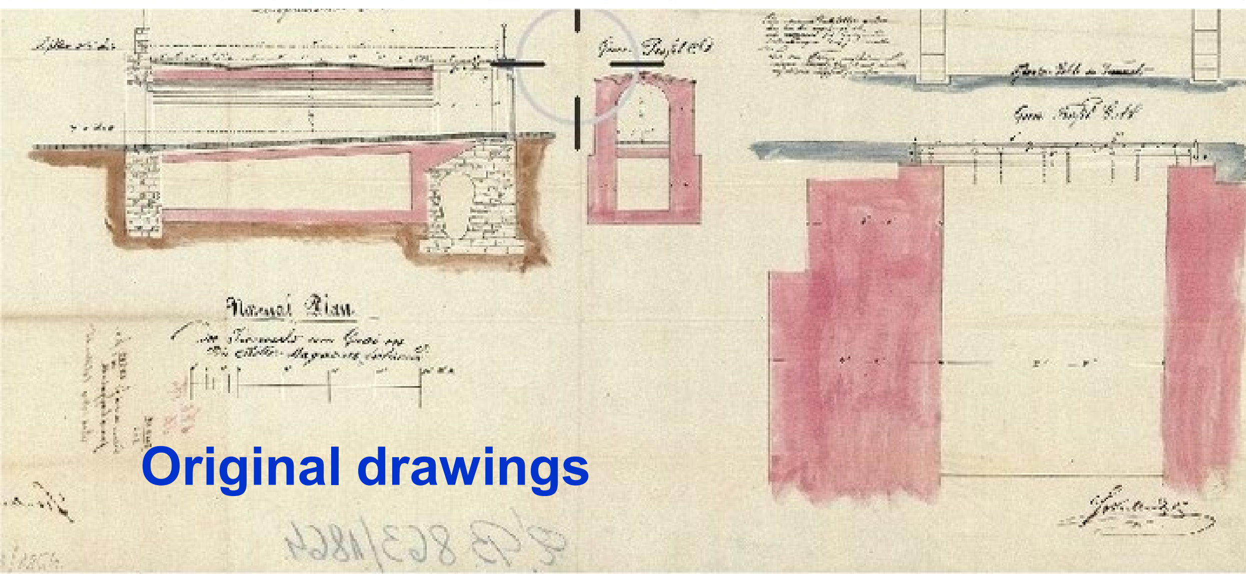


Georadar survey

CASE STUDY 2

/ Stone arches, Budapest /





Original drawings

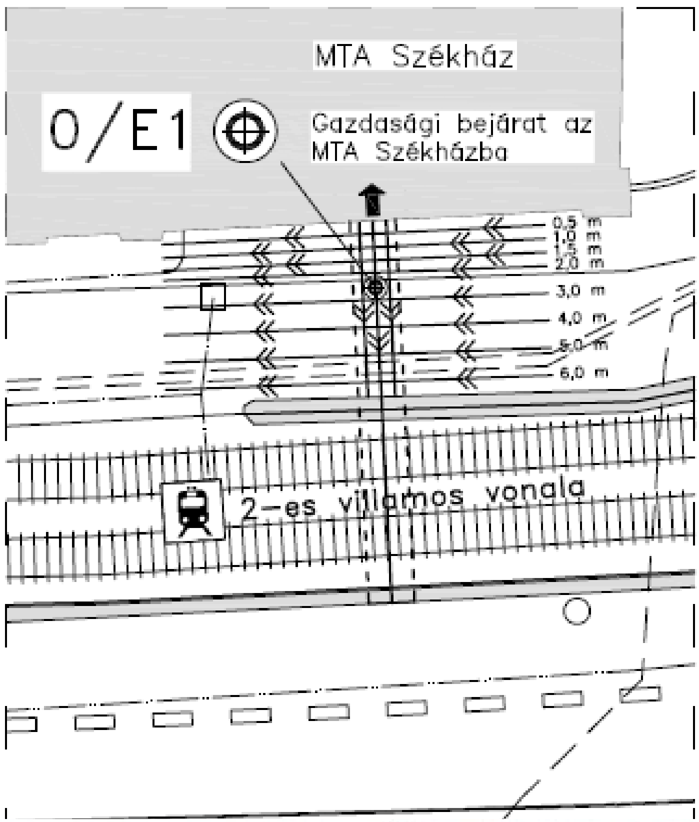

KIADO/FOR

In situ NDT tests

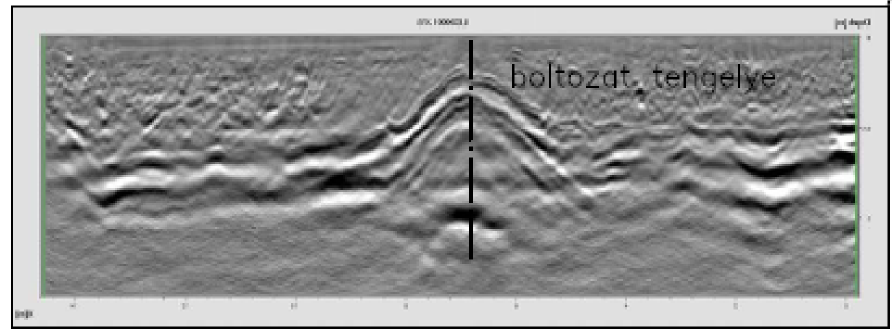
Radarszelvények boltozat tengelyére merőlegesen
M=1:125

. számú alagút diagnosztikai terve

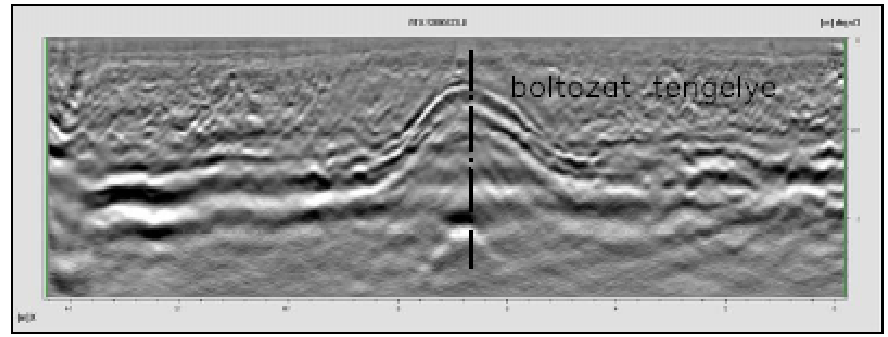
Helyszínrajzi részlet M=1:250



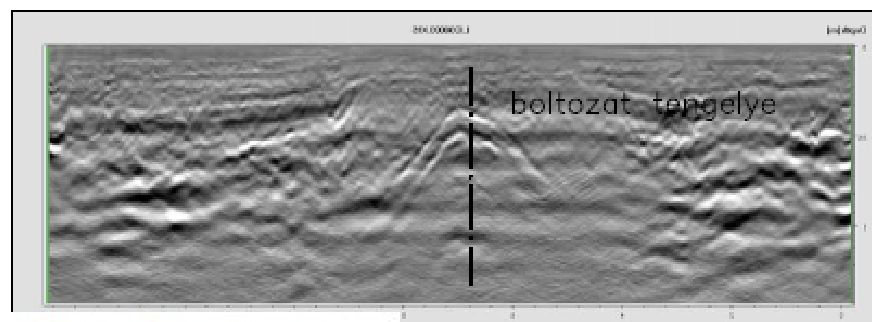
0,5 m

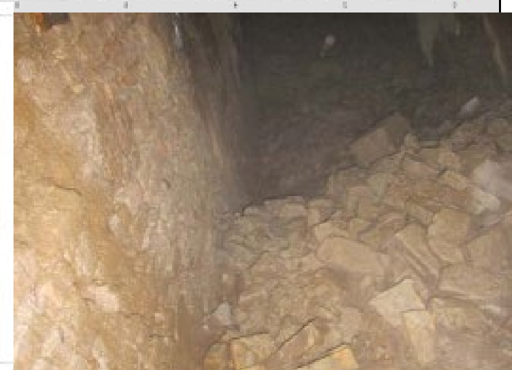


1,0 m

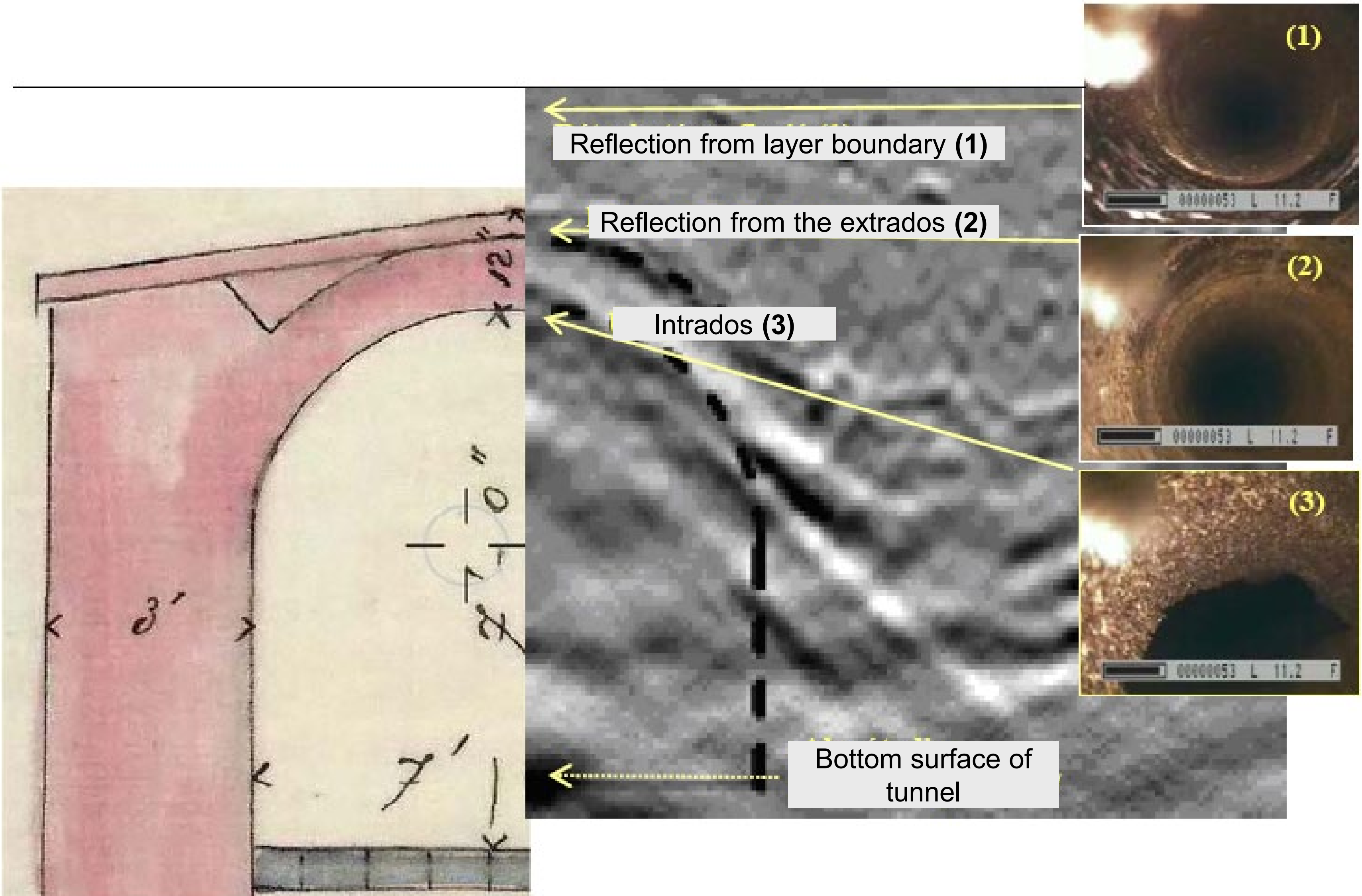


1,5 m

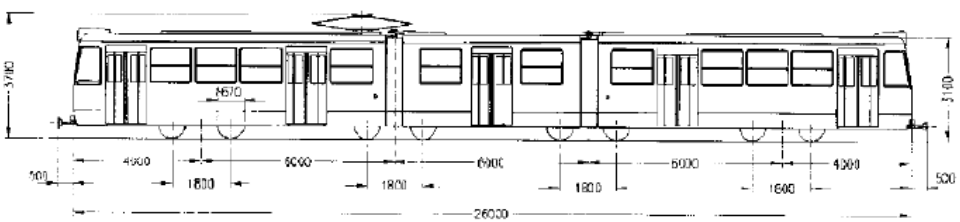


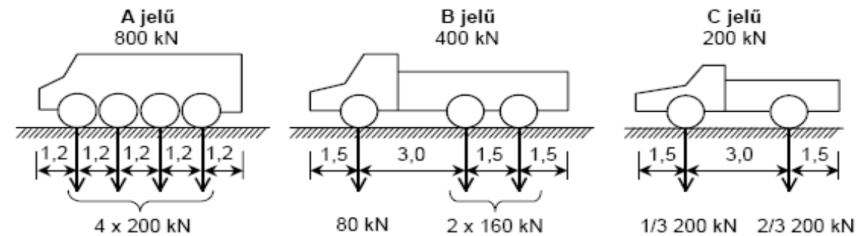


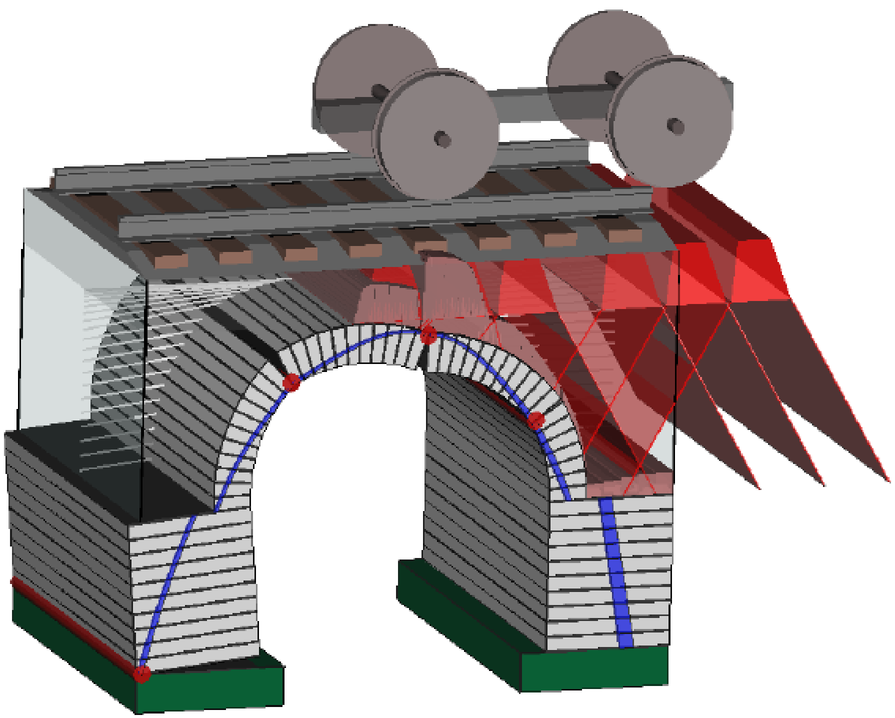
Comparison of test results with original drawings

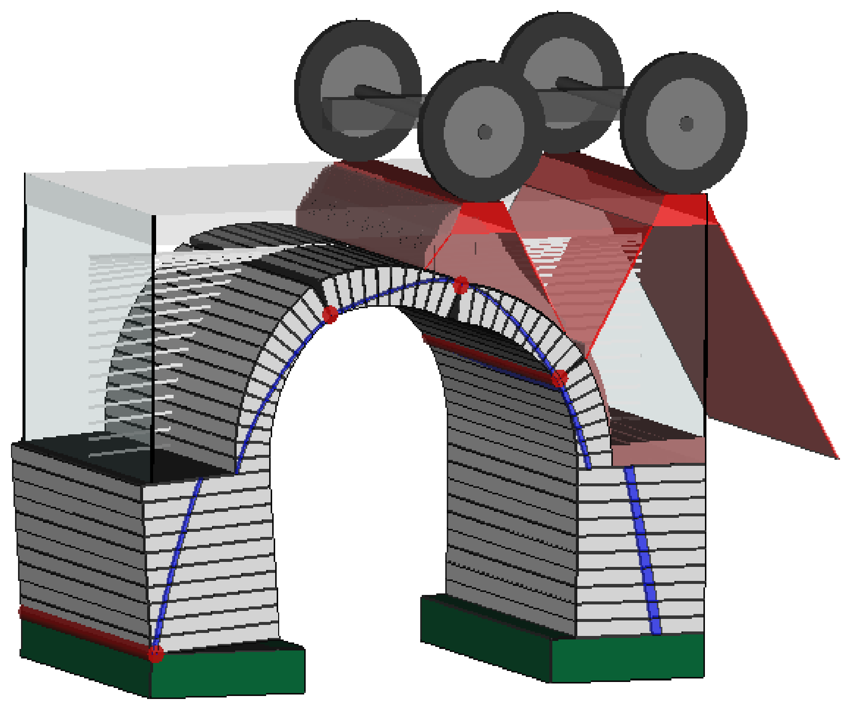


Structural analysis









DIAGNOSTICS OF STRUCTURES

LECTURE 13

Diagnostics and assessment of masonry arch bridges – Part1

Zoltán Orbán

University of Pécs
Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Background

Huge population of masonry arch railway bridges

Background

Huge population of masonry arch bridges

≈ 200 000 masonry arch railway bridges and culverts in Europe

≈ 50% of total railway bridge population!

Background

Concerns raised about existing arch bridges

Are they reliable enough?

Will they withstand future loads?

- Higher axle loads
- Increased train speeds & traffic

What is their remaining service life?

Replacement or Rehabilitation?

Construction History

The first arch bridges

Bridges in China and the Middle East /ca. 5000 BC/

Mycenaean Arcadido bridge /ca. 1300 BC, Greece/

Span: 1m
Length: 22 m
Width: 5.60
Height: 4 m

Roman arch bridges

Pont du Guard

/19 BC/

Length: 275 m
Height: 49 m

Segovia Aqueduct

/ca. 1st Century AD/

Ponte Saint-Martin

/ca. 25 BC/

Medieval bridges

Puente del Diablo

/1282, Spain/

span: 37,5 m

Ponte di Castelvecchio

/1356, Verona, Italy/

span: 48,7 m


Ponte Vecchio
/1345 and 1564, Firenze/

Renaissance bridges

Ponte Santa Trinita

/1569, Firenze/

The first elliptic arch in the world

Centre span: 32 m

Pont Neuf

/1607, Paris/

The first bridge accross river Seine


Stari Most
/1566, Mostar, Bosnia/


Fleischbrücke
/1598, Nürnberg, Germany/
Width: 15 m
Clear span: 27 m
Span to rise ratio: 6.4

18th century to present day

Pontypridd bridge

/1756, South Wales/

Span: 43 m


Petit Pont,
/1853, Paris/
Span: 32 m
Pont Saint Michel
/1624, Paris/
Center span: 17 m

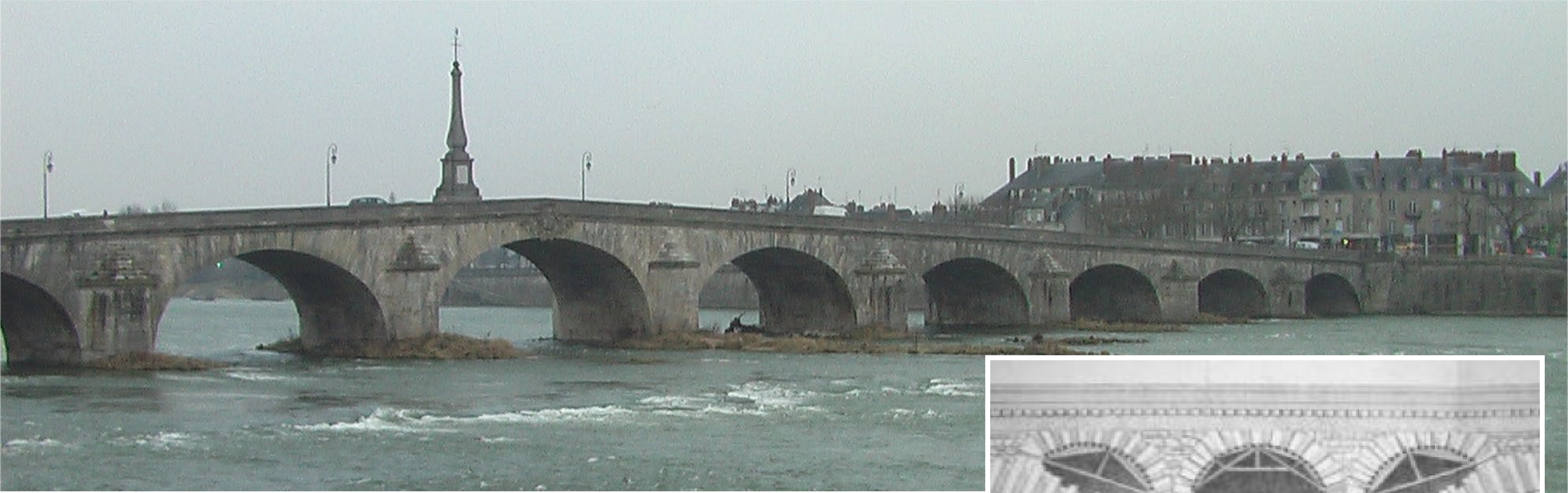
Jean-Rodolphe Perronet

/1708-1794/

Pont de la Concorde

/1756, Paris/

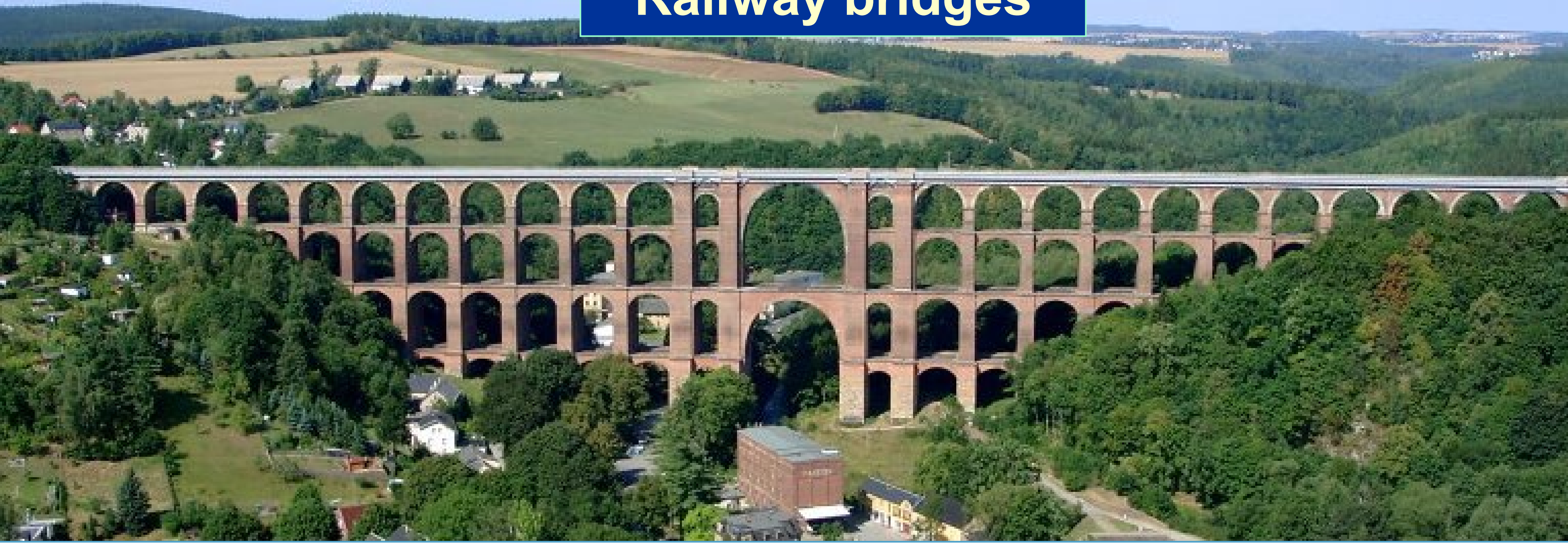
Span: 43 m



Bridge at Orleans

/1760/

Railway bridges



Göltzsch viadukt

/1845-1851, Germany/

The largest brickwork arch bridge

Height: 84 m

Length: 574 m

26 million bricks were used

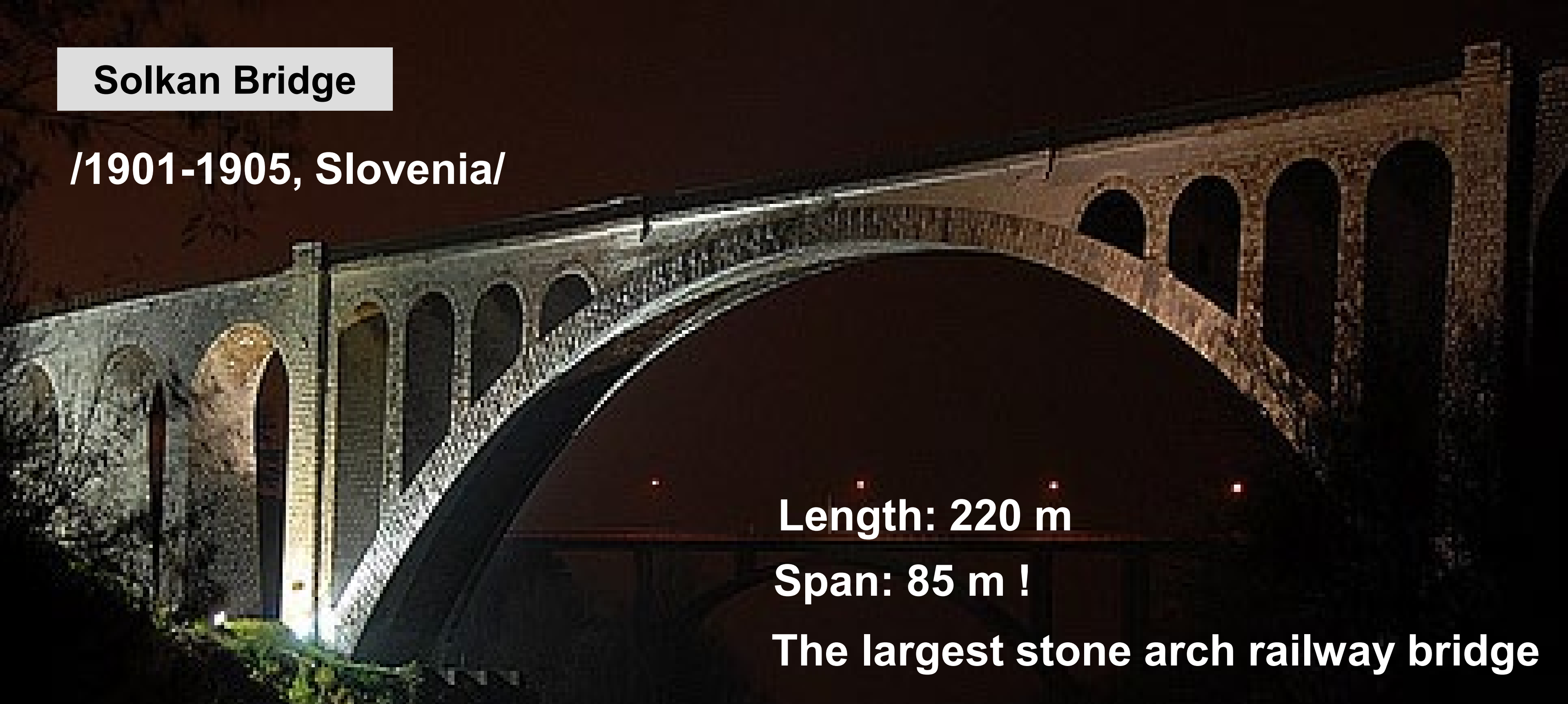
Solkan Bridge

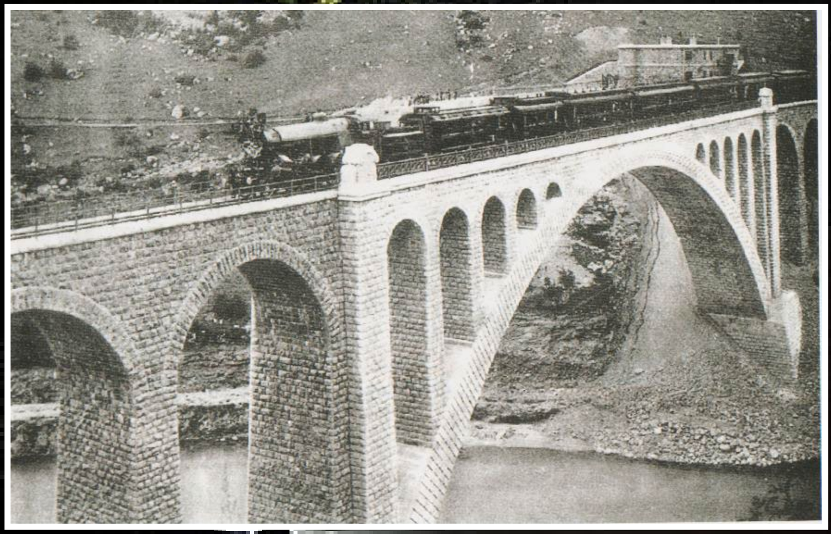
/1901-1905, Slovenia/

Length: 220 m

Span: 85 m !

The largest stone arch railway bridge






Viaduc Morlaix
SNCF, France


Viaduc Fontpedrouse
SNCF, France


Viaduc Saint-Chamas
SNCF, France

Stone railway bridge and viaduct

Network Rail, UK


GLACIER EXPRESS

Iranian bridges

Iranian bridges

Ancient arch, Iraq

Az adatok védelme érdekében a PowerPoint nem engedélyezte a kép automatikus letöltését.

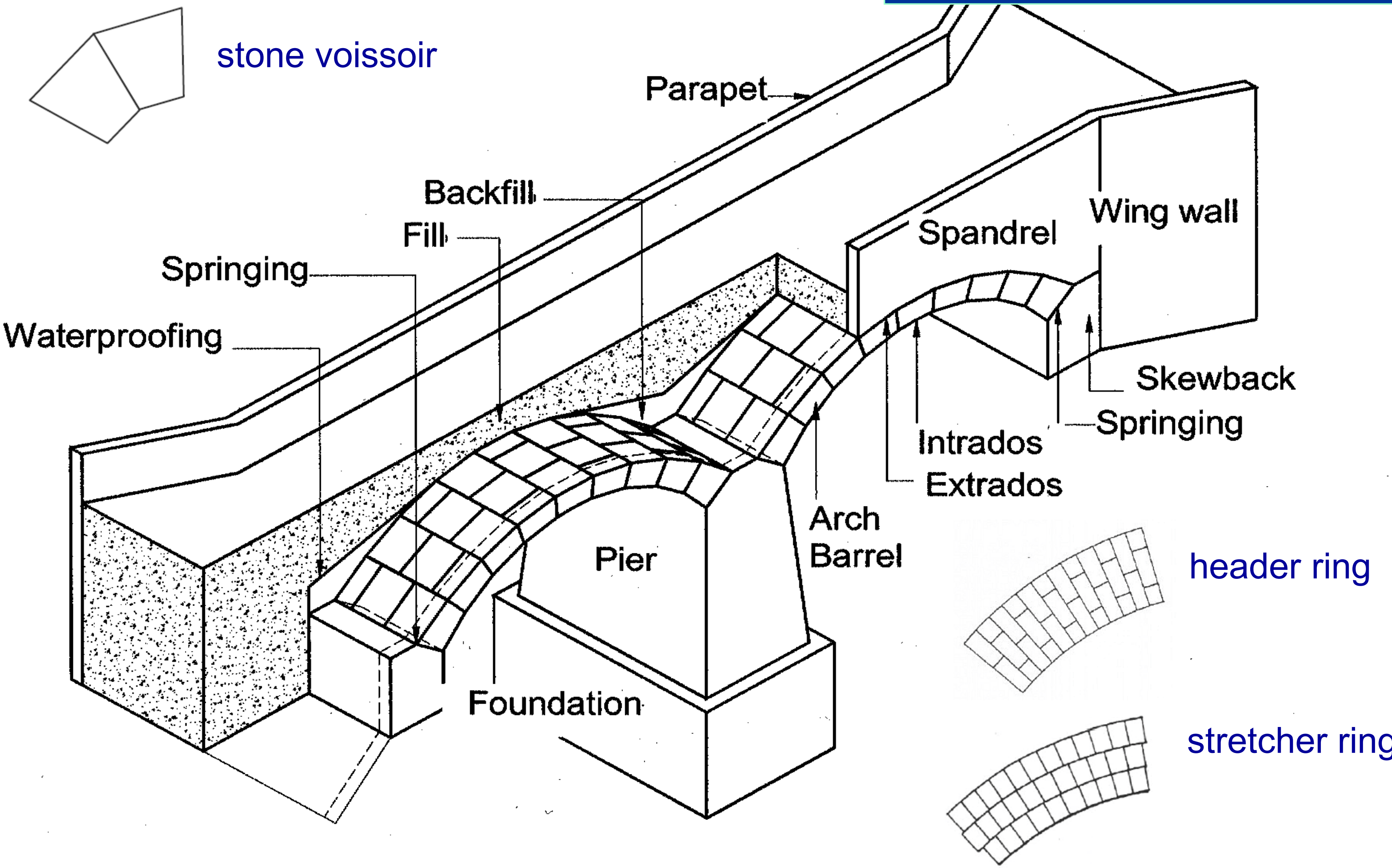
Afrin, Syria

Hama, Syria

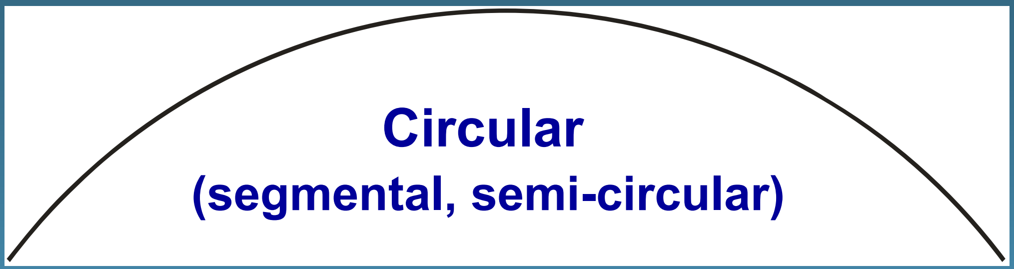
Ain Diwar Bridge, Syria

Construction details

Structural elements



Arch shapes

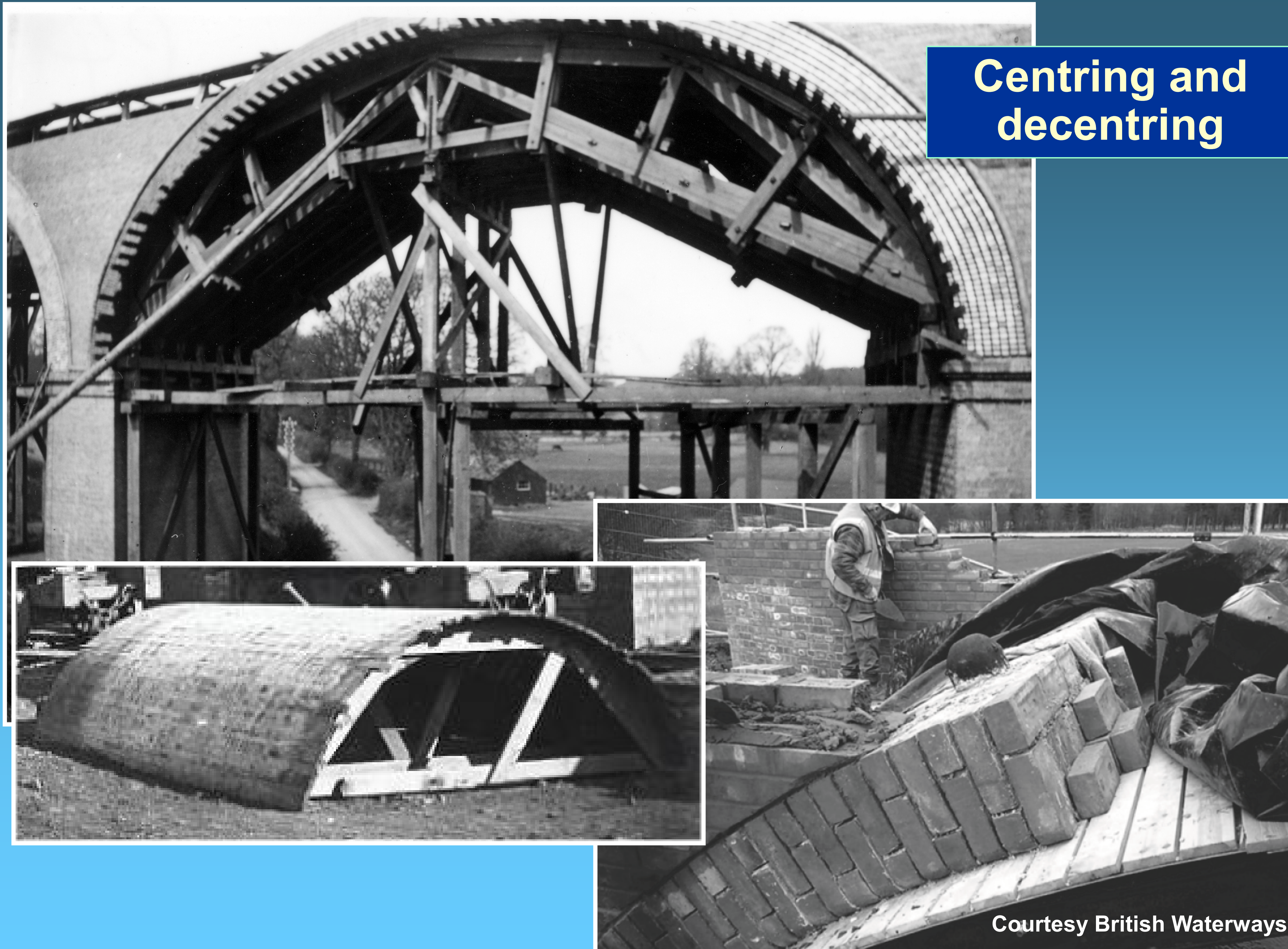

Circular
(segmental, semi-circular)


Three centred

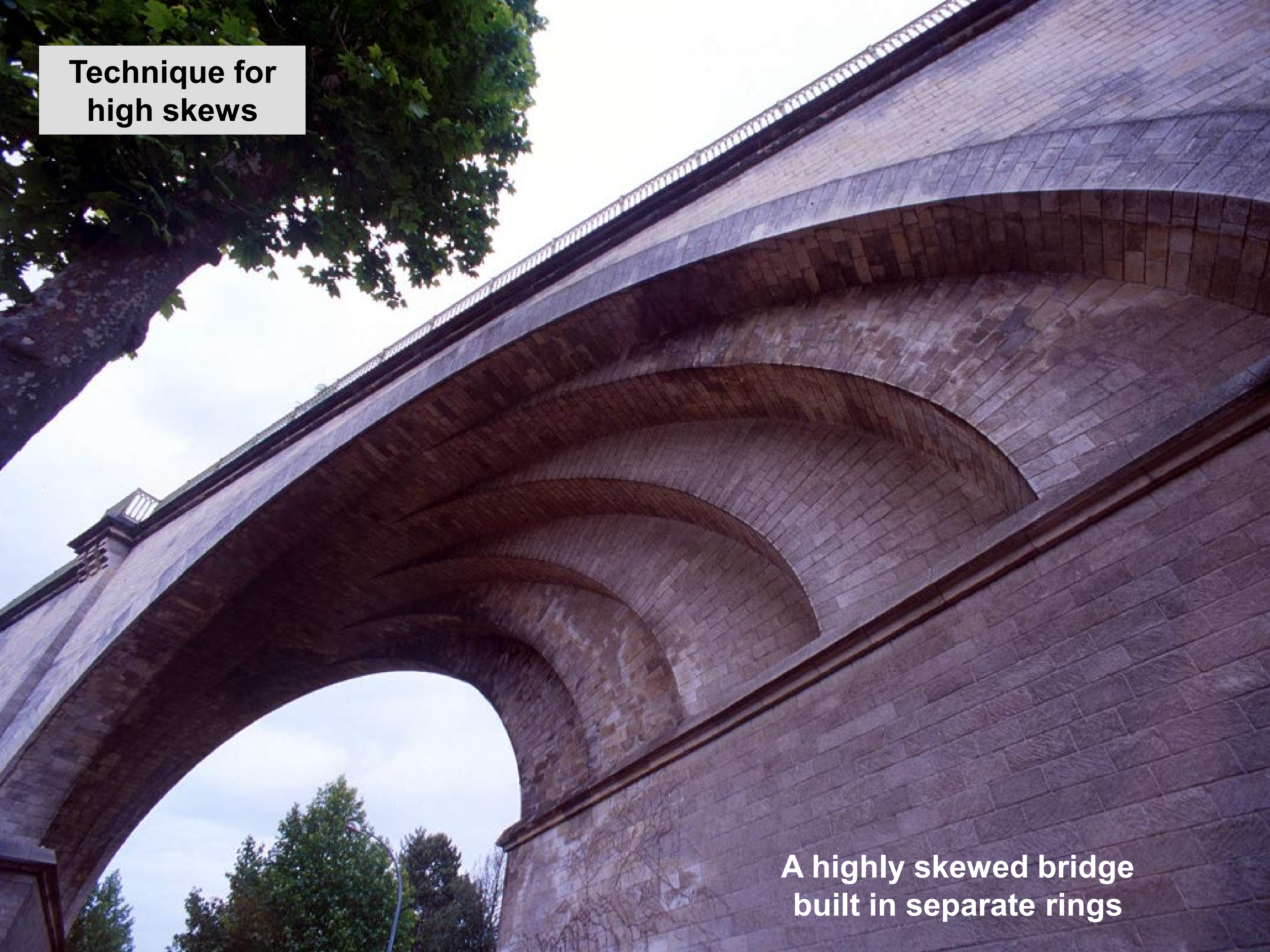

Semi Ellipse

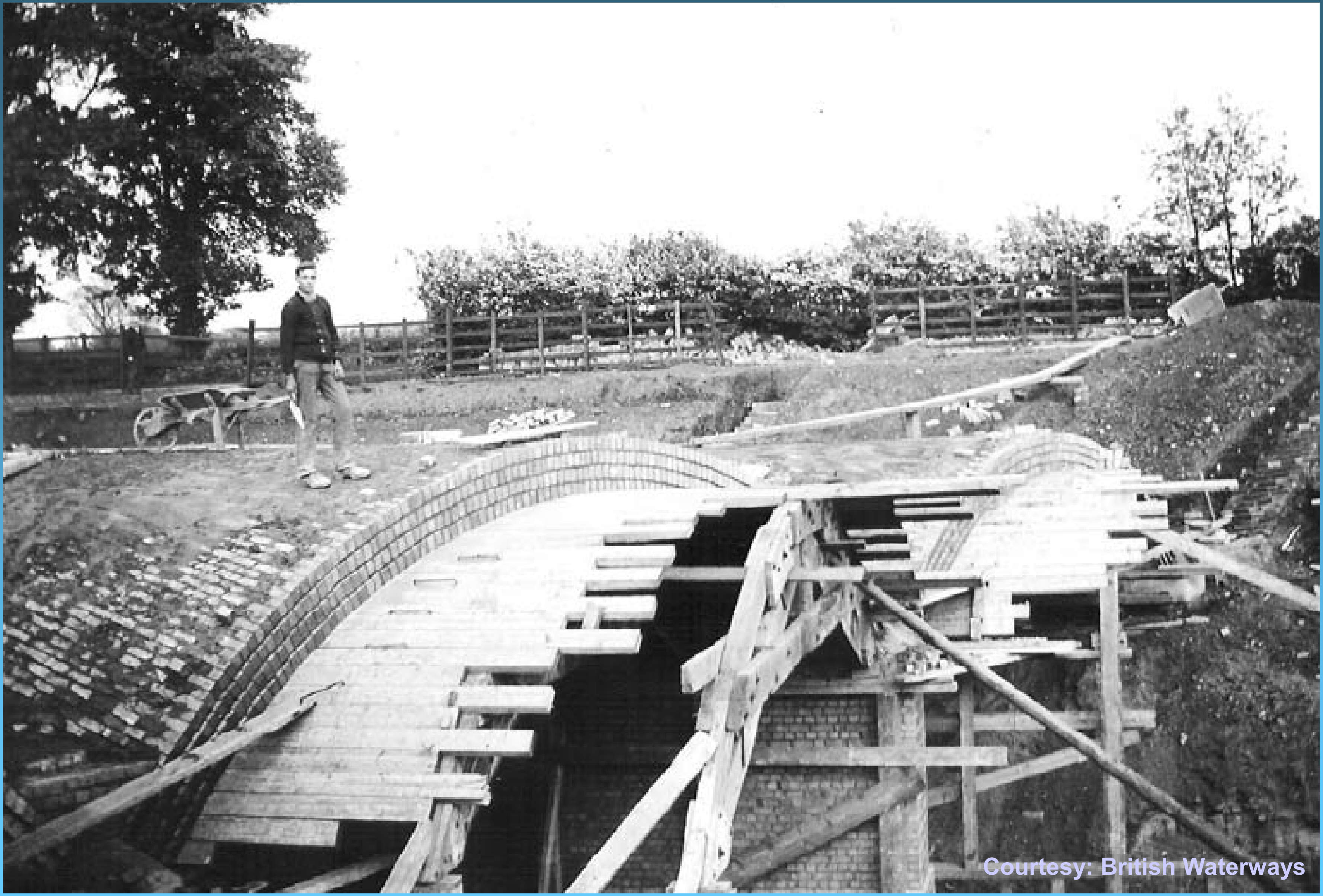

Parabolic

Centring and decentring

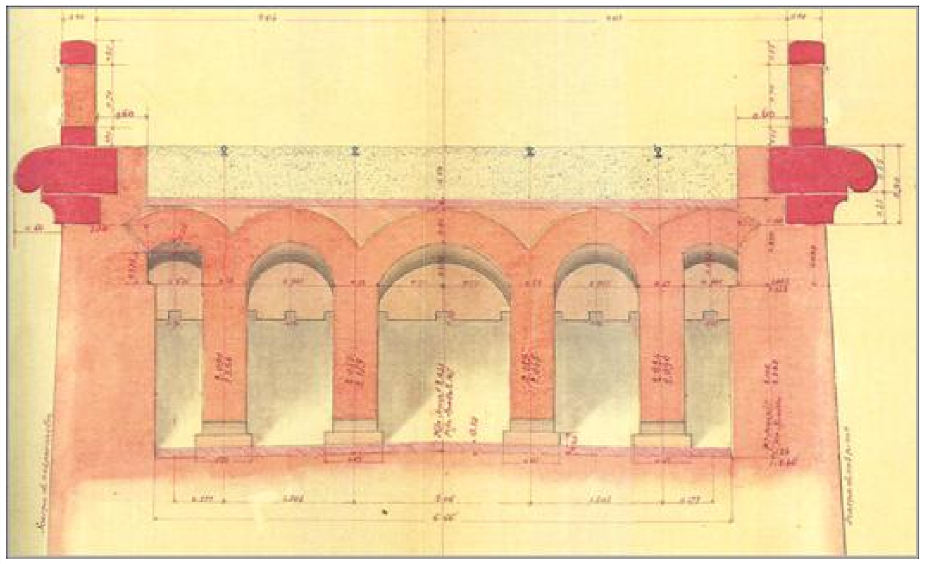


Courtesy British Waterways


Technique for high skews
A highly skewed bridge built in separate rings


Courtesy: British Waterways


Internal spandrels

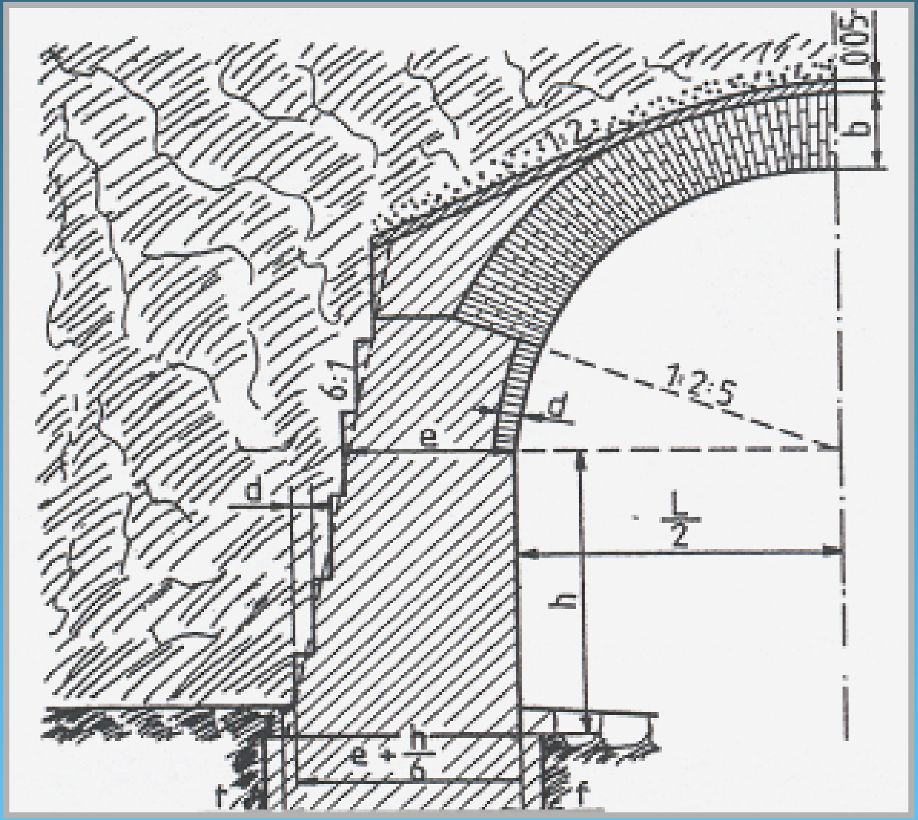


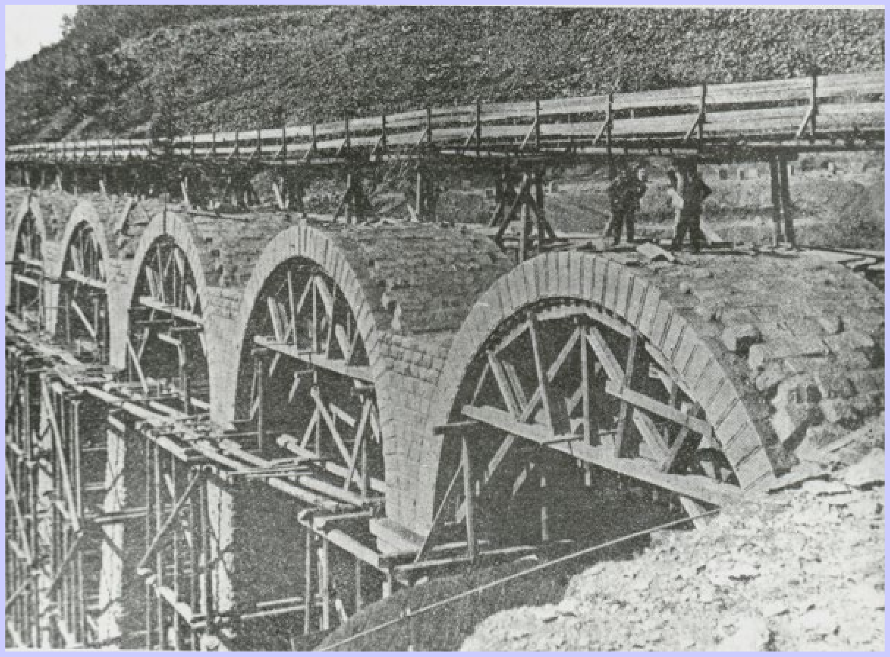
Open spandrels

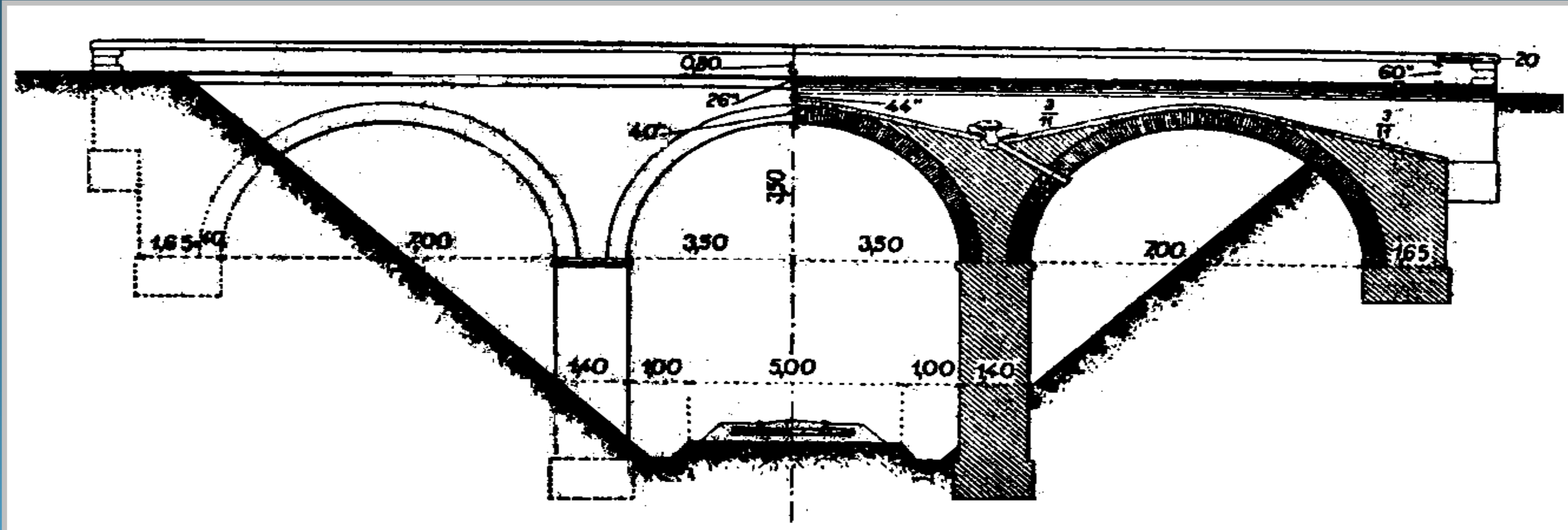
Voided structures

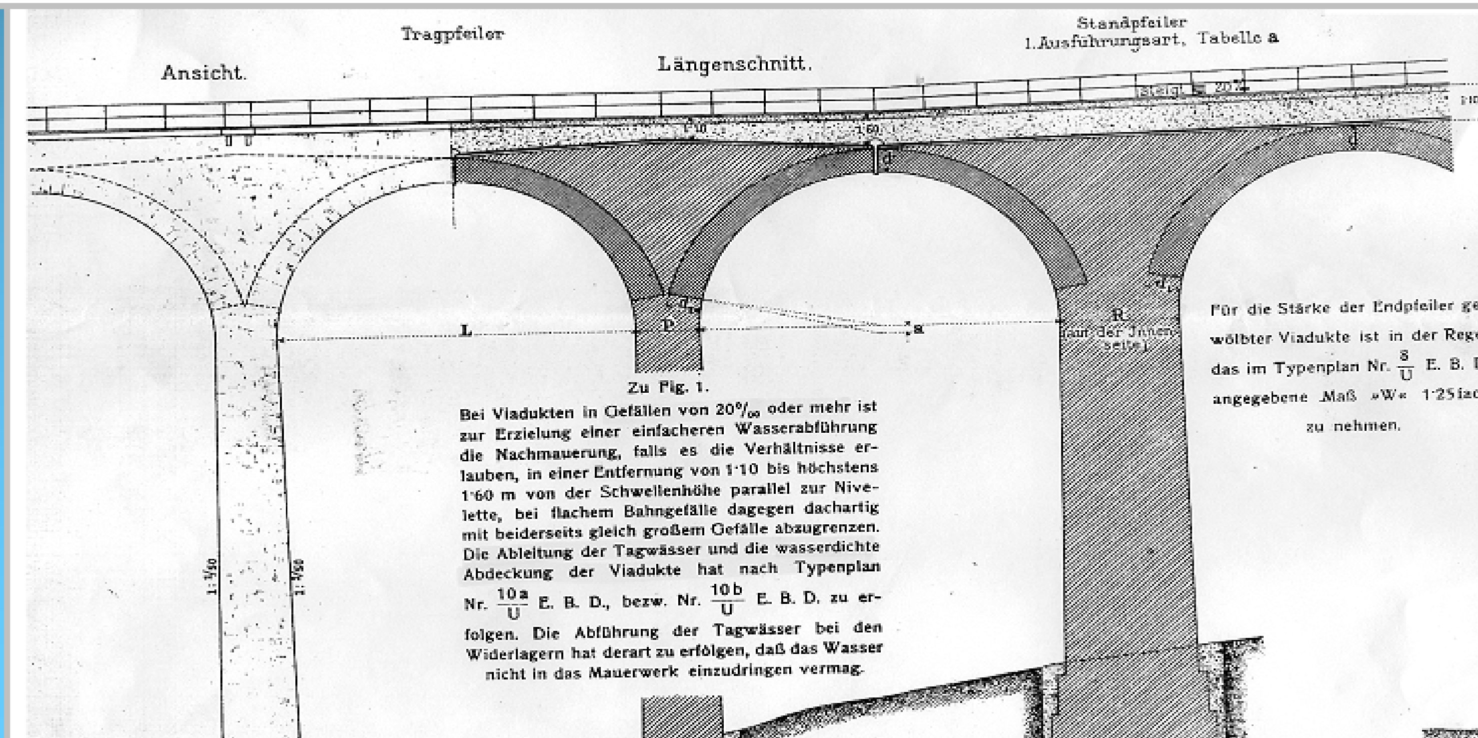
Courtesy: W. Harvey

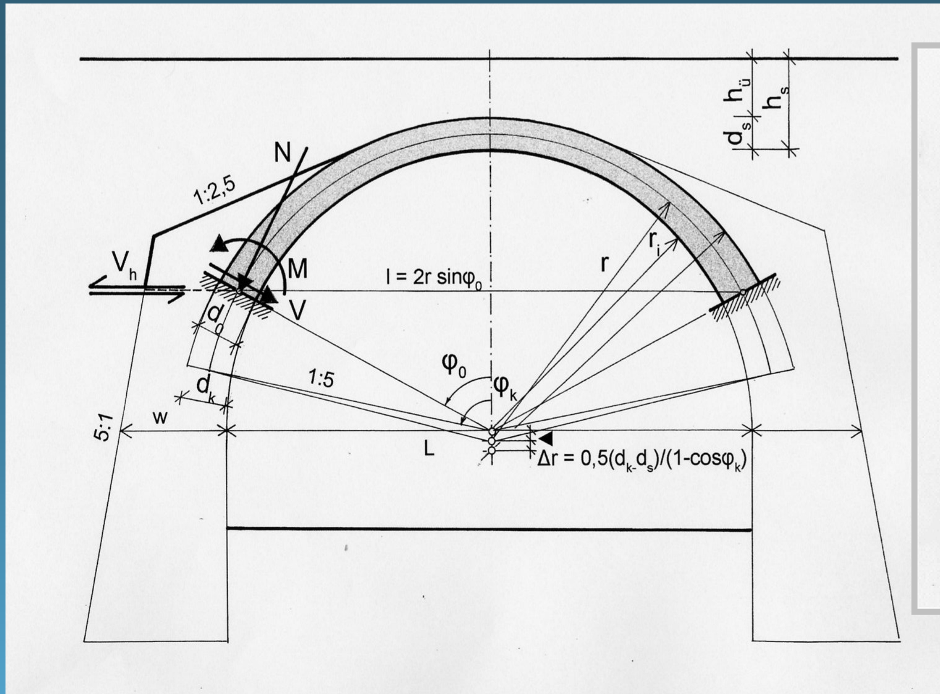
Backing and haunching



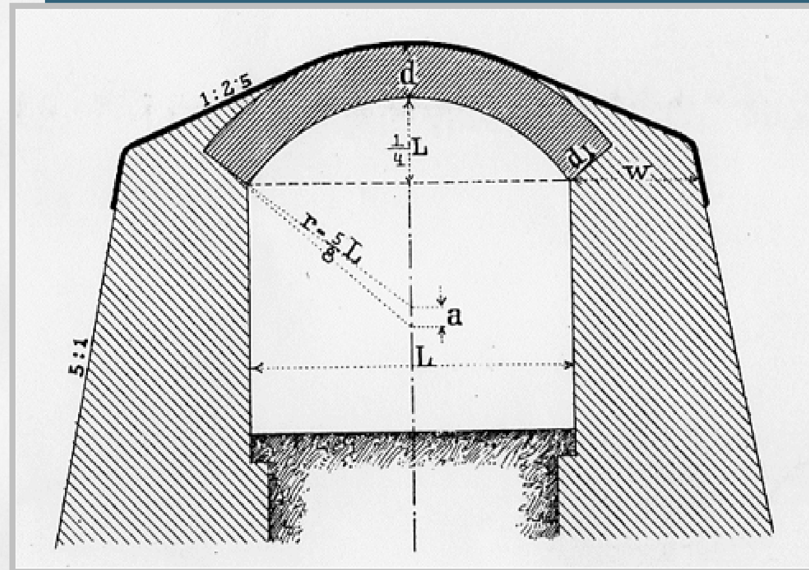



0,80
20
60"
26"
44"
40"
3/11
3/11
3,50
1,65
7,00
3,50
3,50
7,00
1,65
1,40
1,00
5,00
1,00
1,40

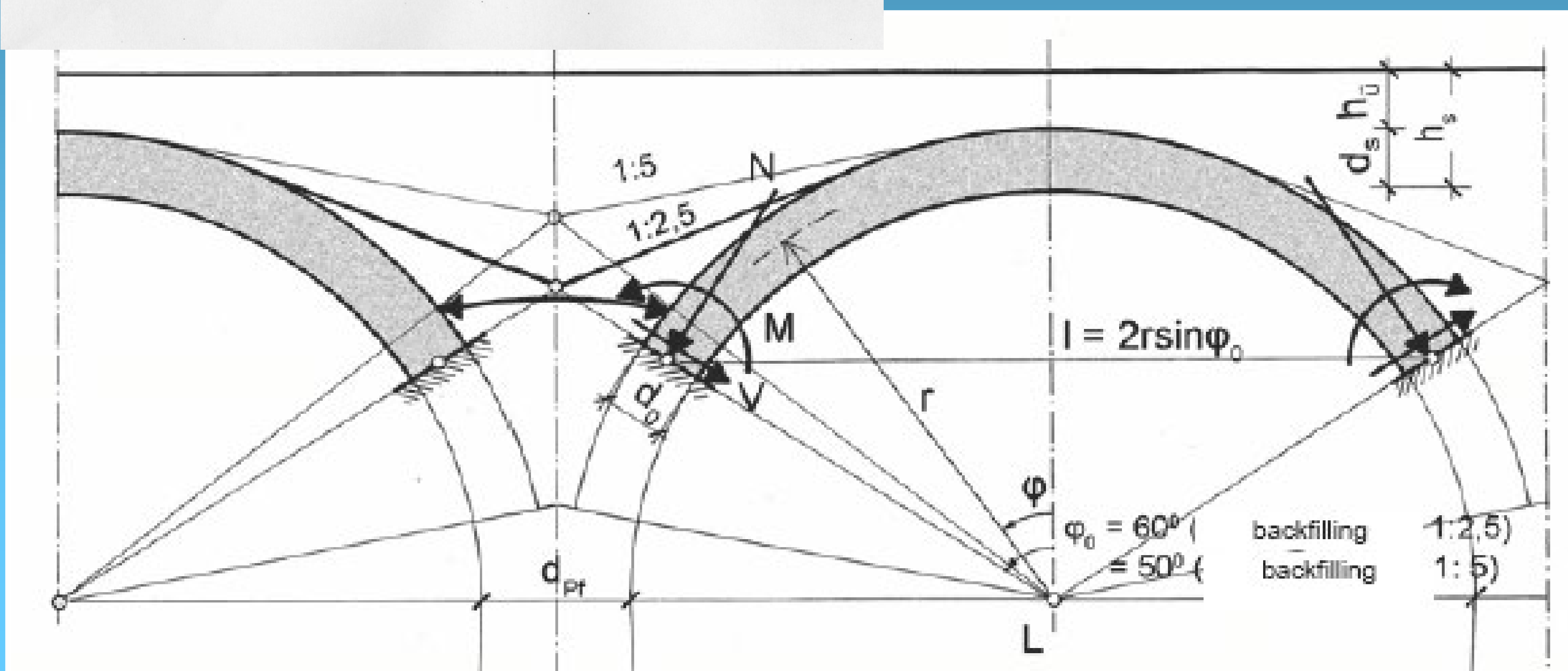

Tragpfeiler
Standpfeiler
1. Ausführungsart, Tabelle a
Ansicht.
Längenschnitt.
Steigt 20‰
1·10
1·60
L
D
d
s
R
(an der Innenseite)
1:1/50
1:1/50
Zu Fig. 1.
Bei Viadukten in Gefällen von 20‰ oder mehr ist zur Erzielung einer einfacheren Wasserabführung die Nachmauerung, falls es die Verhältnisse erlauben, in einer Entfernung von 1·10 bis höchstens 1·60 m von der Schwellenhöhe parallel zur Nivelette, bei flachem Bahngefälle dagegen dachartig mit beiderseits gleich großem Gefälle abzugrenzen. Die Ableitung der Tagwässer und die wasserdichte Abdeckung der Viadukte hat nach Typenplan Nr. 10 a/U E. B. D., bezw. Nr. 10 b/U E. B. D. zu erfolgen. Die Abführung der Tagwässer bei den Widerlagern hat derart zu erfolgen, daß das Wasser nicht in das Mauerwerk einzudringen vermag.
Für die Stärke der Endpfeiler gewölbter Viadukte ist in der Regel das im Typenplan Nr. 8/U E. B. D angegebene Maß »W« 1·25fach zu nehmen.



N
1:2,5
M
V
l = 2r sinφ0
r
ri
d0
1:5
φ0
φk
dk
w
5:1
L
Δr = 0,5(dk-ds)/(1-cosφk)
ds
hü
hs

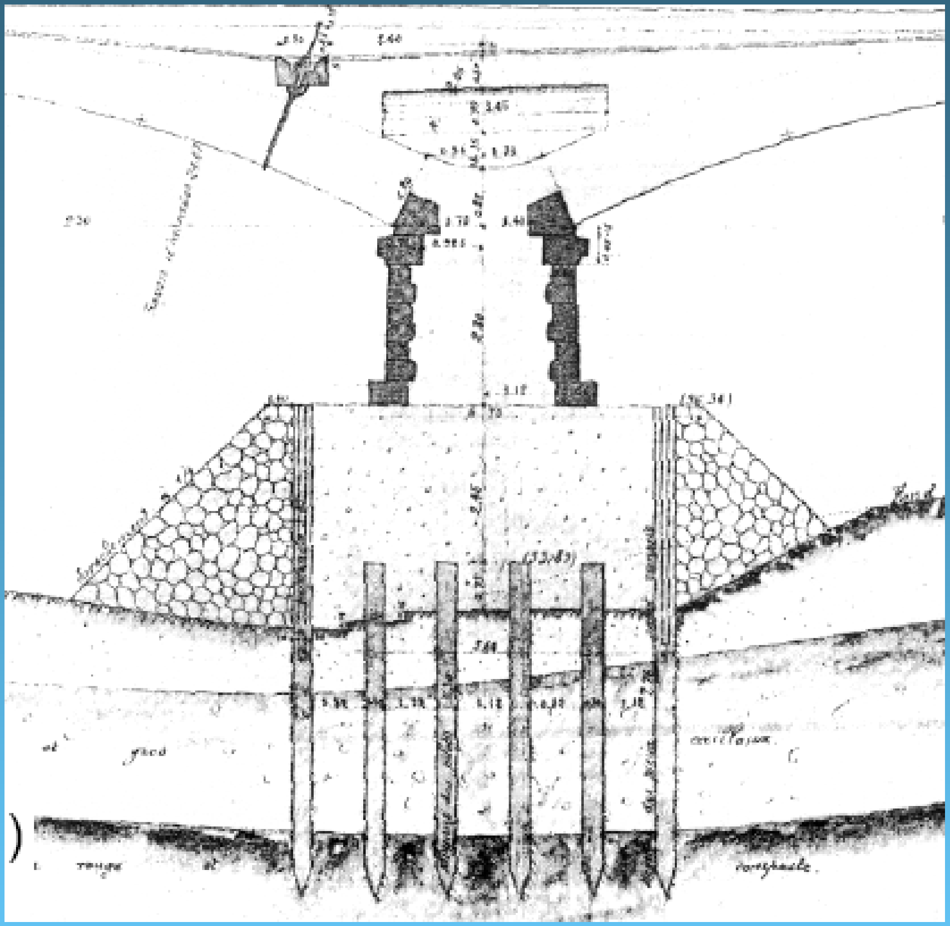


1:2·5
d
1/4 L
d1
w
r = 5/8 L
a
L
5:1



1:5
N
1:2,5
M
V
l = 2rsinφ0
r
d0
φ
φ0 = 60° (backfilling 1:2,5)
= 50° (backfilling 1: 5)
dPf
L
hü
ds
hs

Piers and foundations



DIAGNOSTICS OF STRUCTURES

LECTURE 14

Diagnostics and assessment of masonry arch bridges – Part2

Zoltán Orbán

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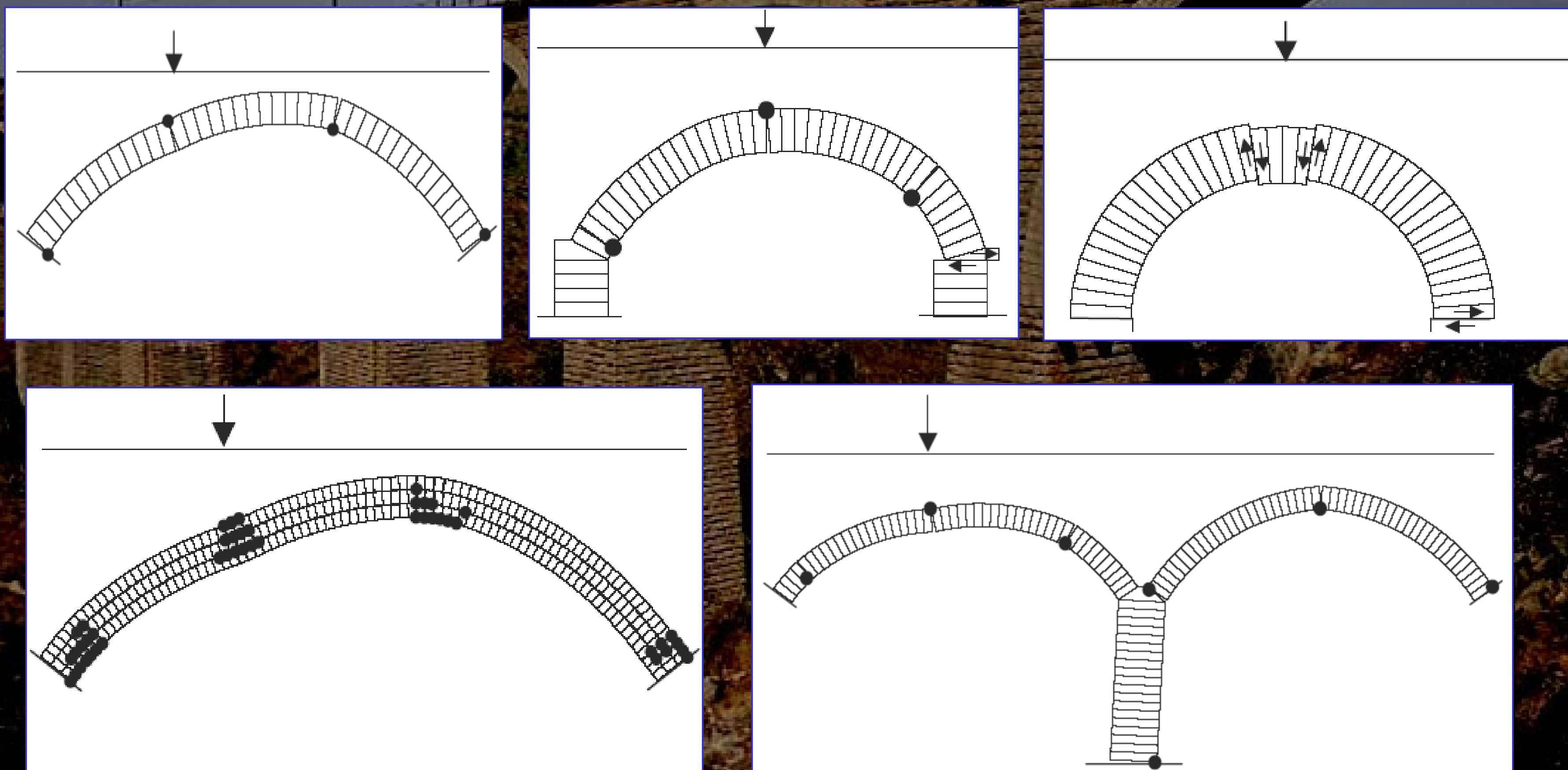
Faculty of Engineering and Information Technology
Department of Civil Engineering

STRUCTURAL
DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Structural behaviour

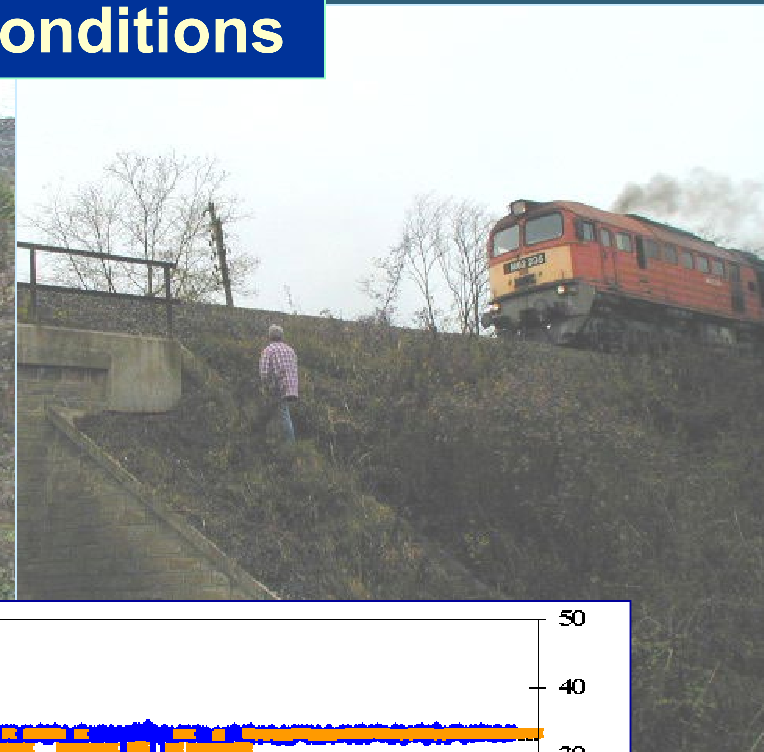
Basic forms of failure mechanisms

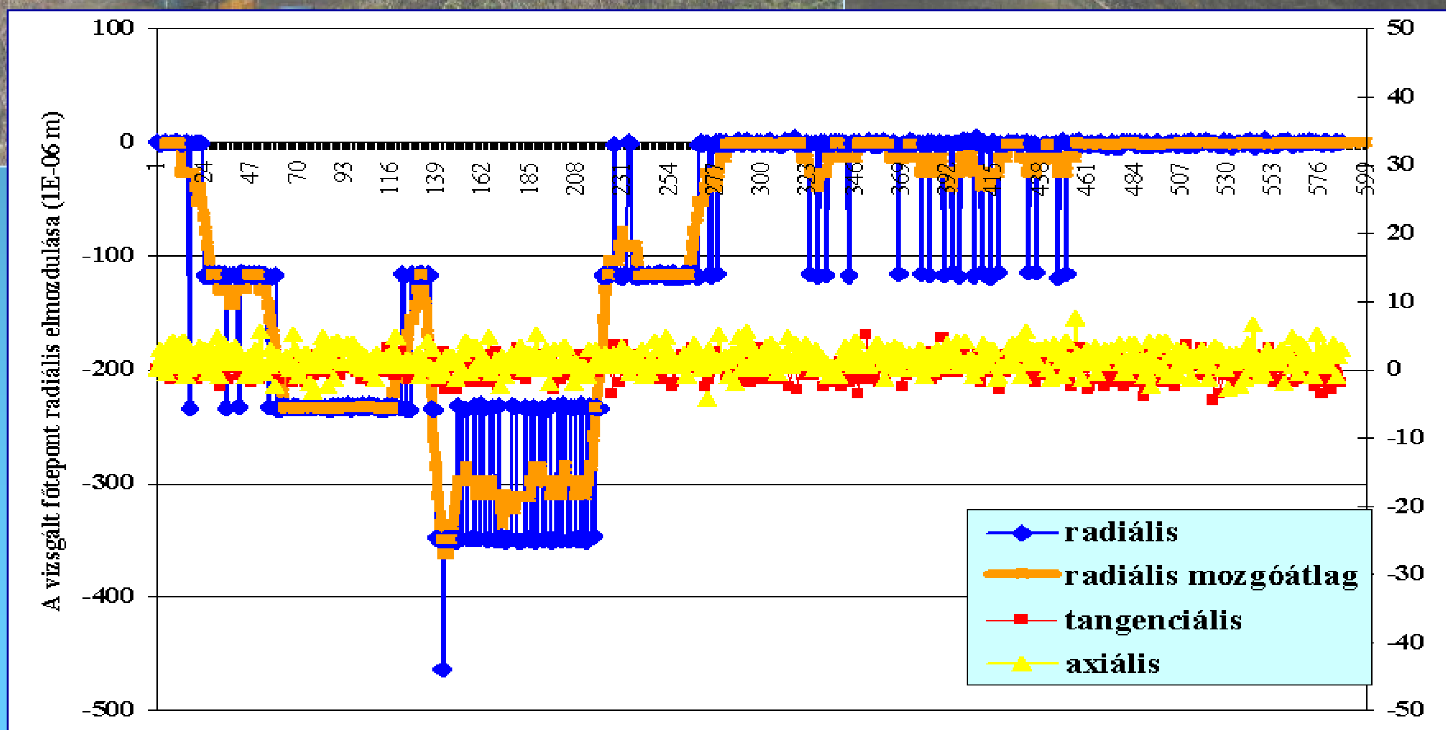


Hinge formation on a viaduct

Courtesy: A Brencich

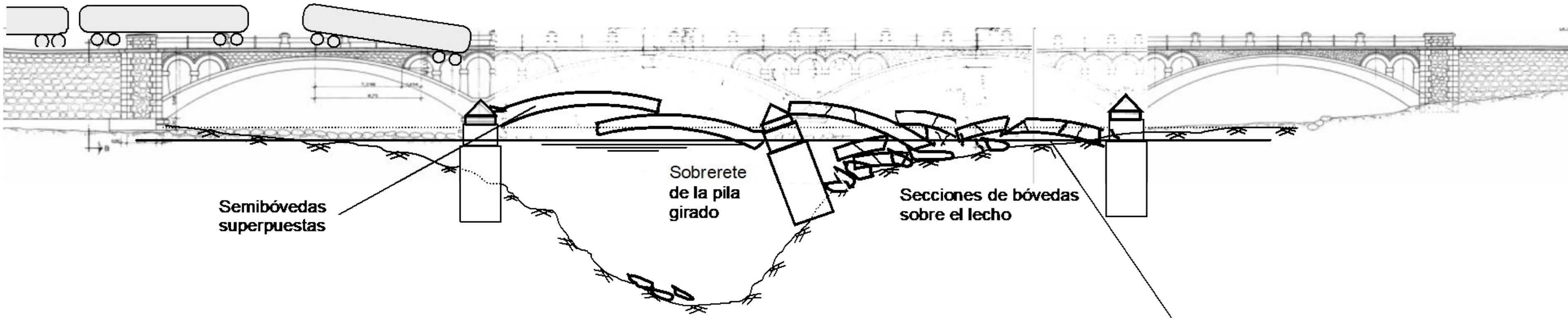
Behaviour under service loading conditions





Masonry arch bridges have extra resources in load carrying capacity to mobilise…

… but can be susceptible to progressive collapse…



Vequellina de Órbigo, March 2001 - Reference by RENFE, Spain

…and may deteriorate rapidly when the loading regime changes…

…or climate changes…

Effects of structural damages

What are the main sources and seriousness of damages?

What influences they have on structural behaviour and load carrying capacity?


1st group of damages
Do not endanger structural safety directly
Relatively frequent


Waterproofing damage - saturation

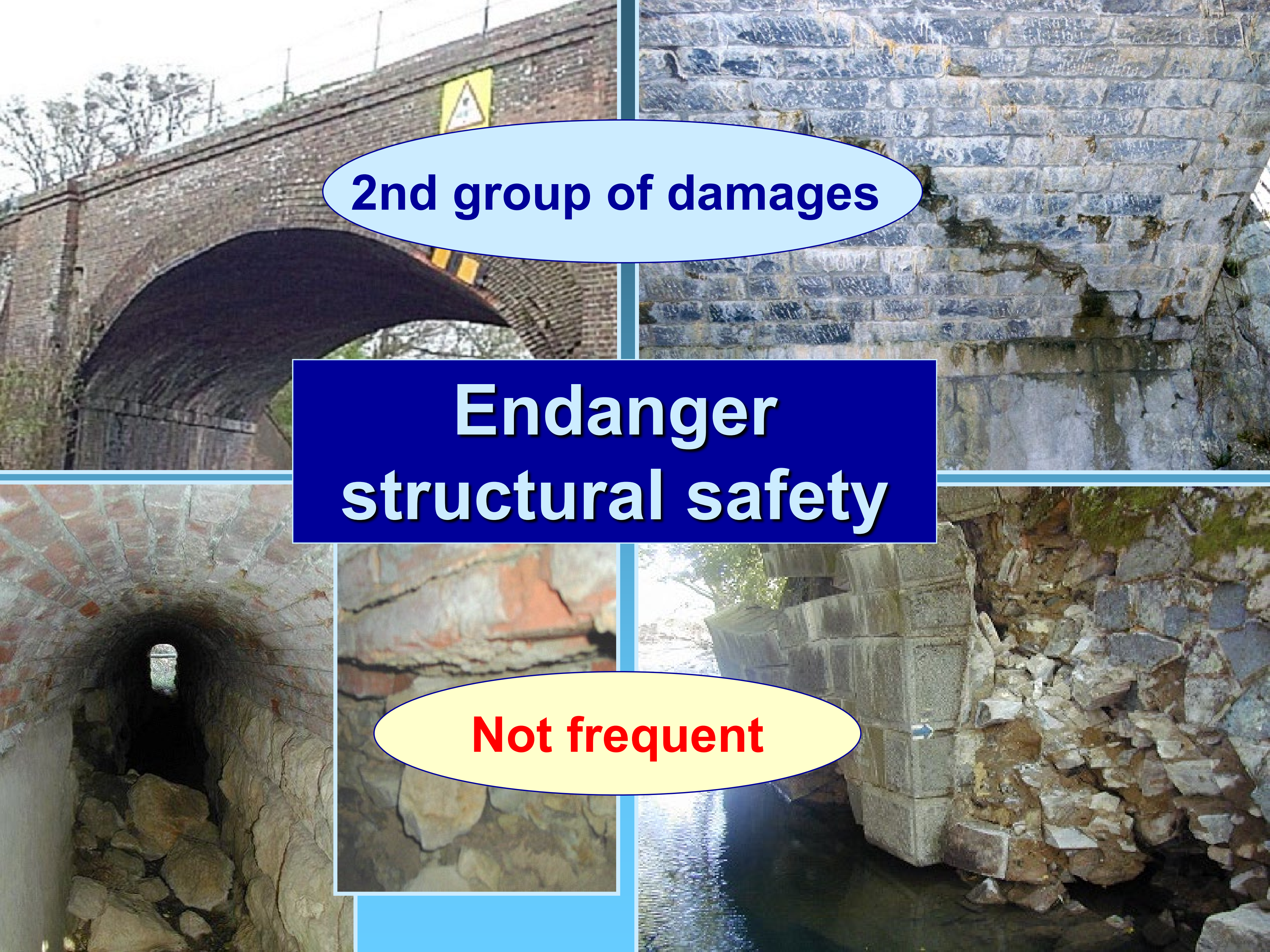

Weathering of stones


Loss of bricks


Loss of fill material


Vegetation


Cracks under spandrel walls


2nd group of damages
Endanger structural safety
Not frequent


Diagonal cracks
30 N
25


Flood, scour


Assessment

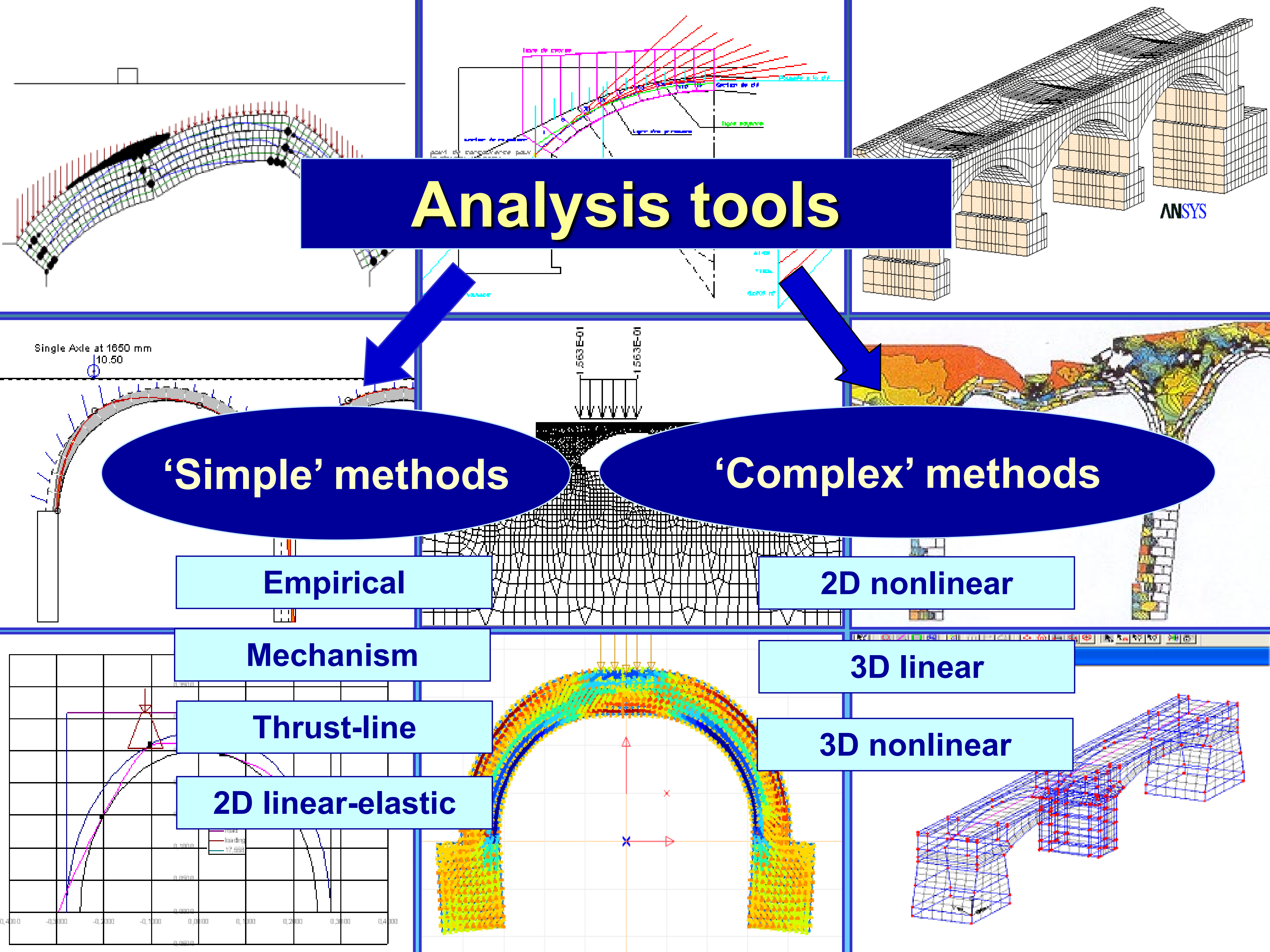
Principles of assessment

Objective

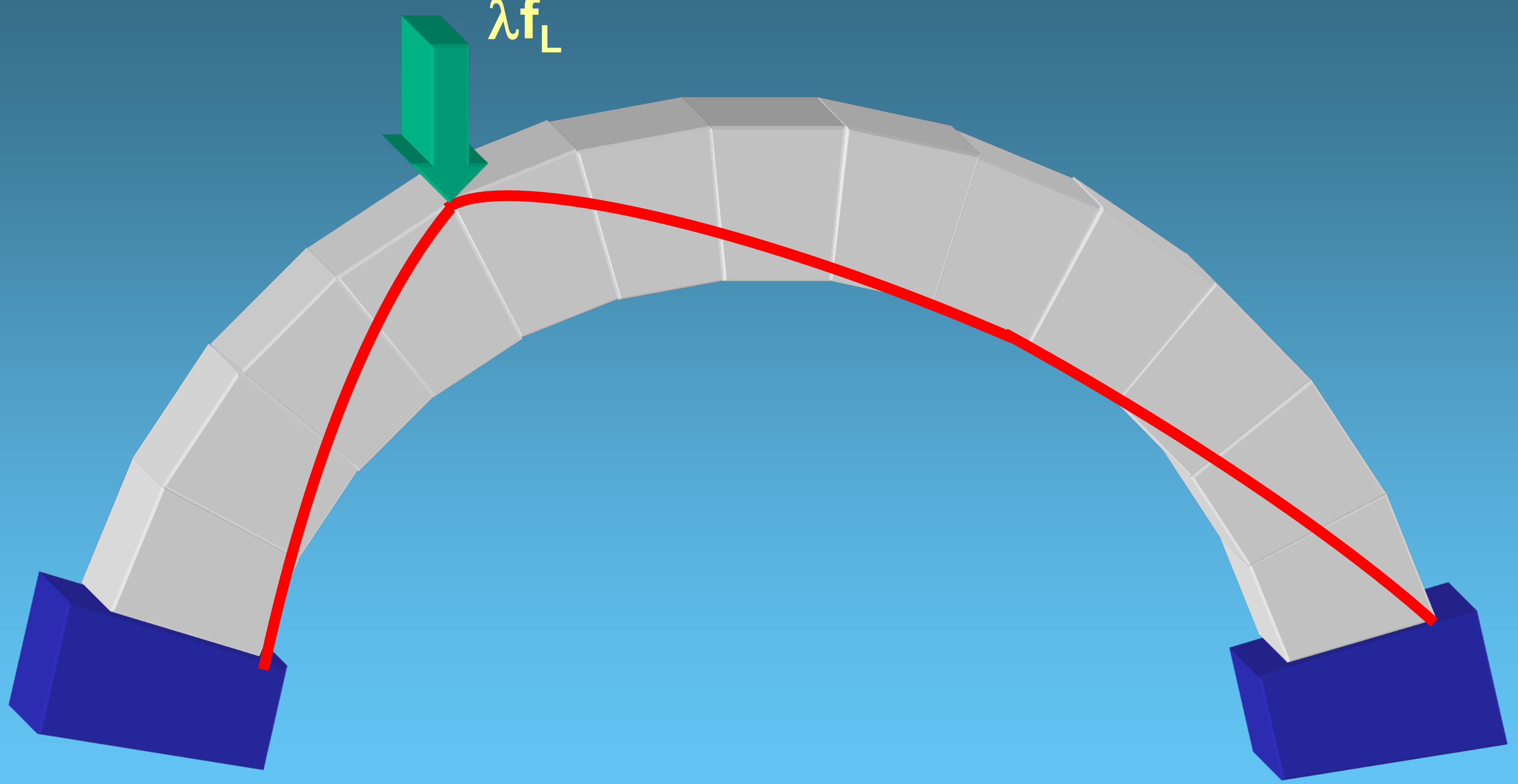
- To confirm that the load capacity of the bridge is sufficient for the current and foreseeable loads without accelerated deterioration

Steps

- Desk study $\Rightarrow$ Collation of available information
- Inspection for assessment $\Rightarrow$ Provide input data
- Analysis $\Rightarrow$ Determination of the load capacity
- Report $\Rightarrow$ Documentation, conclusions

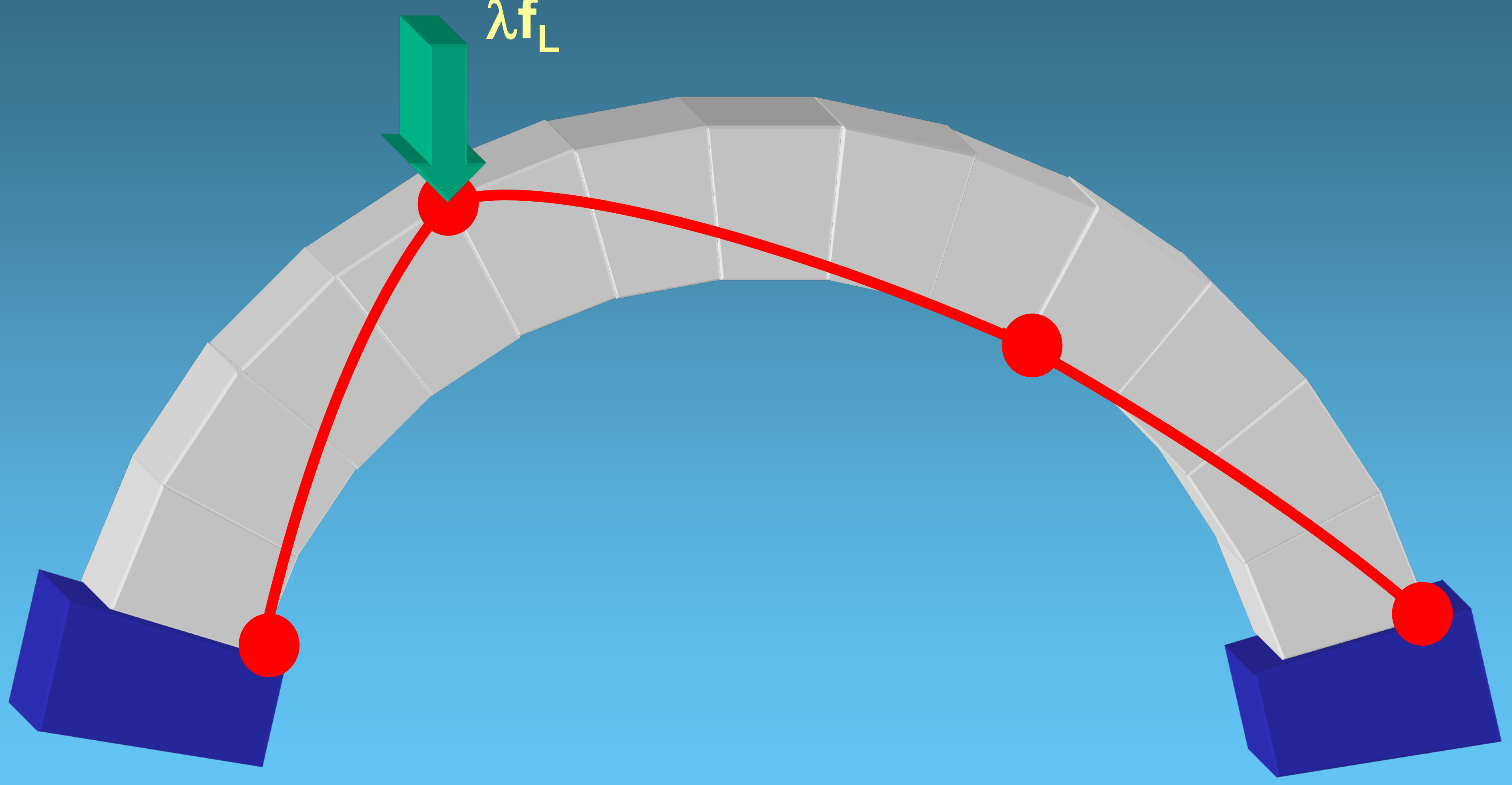

Analysis tools
‘Simple’ methods
‘Complex’ methods
Empirical
Mechanism
Thrust-line
2D linear-elastic
2D nonlinear
3D linear
3D nonlinear
ANSYS
Single Axle at 1650 mm
10.50
1.563E-01
1.563E-01

Mechanism method



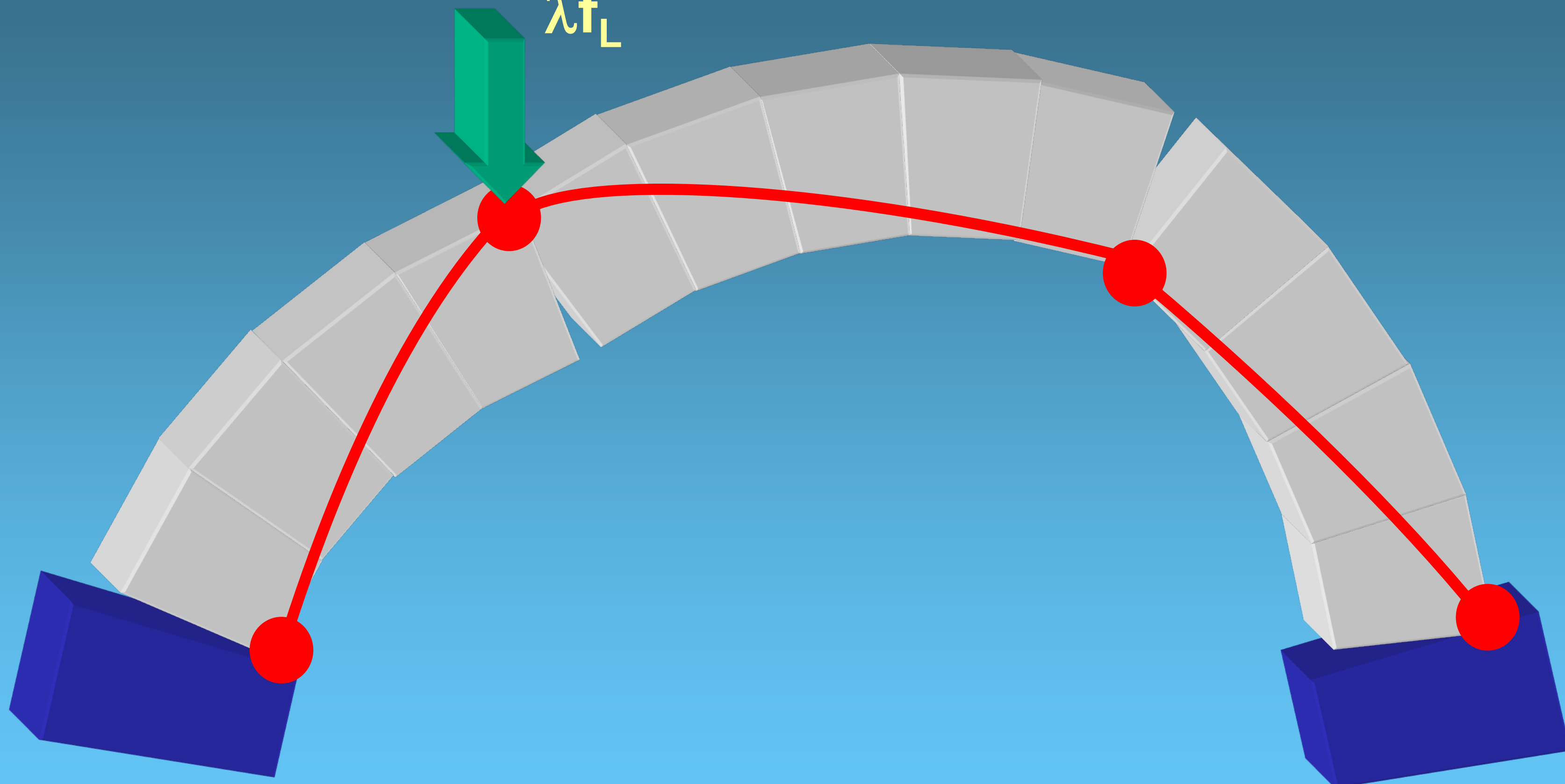
Courtesy M Gilbert

Mechanism method

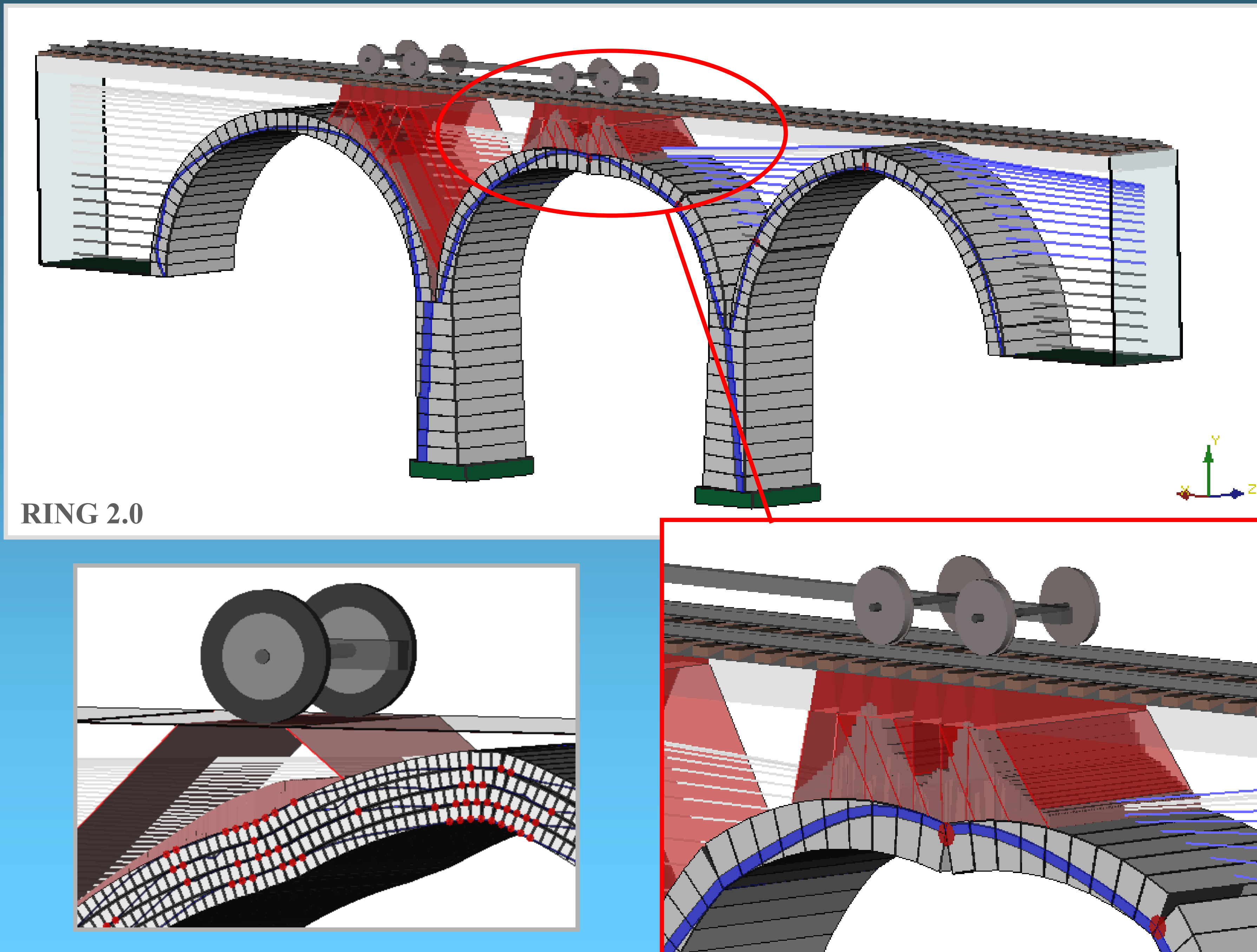


Courtesy M Gilbert

Mechanism method

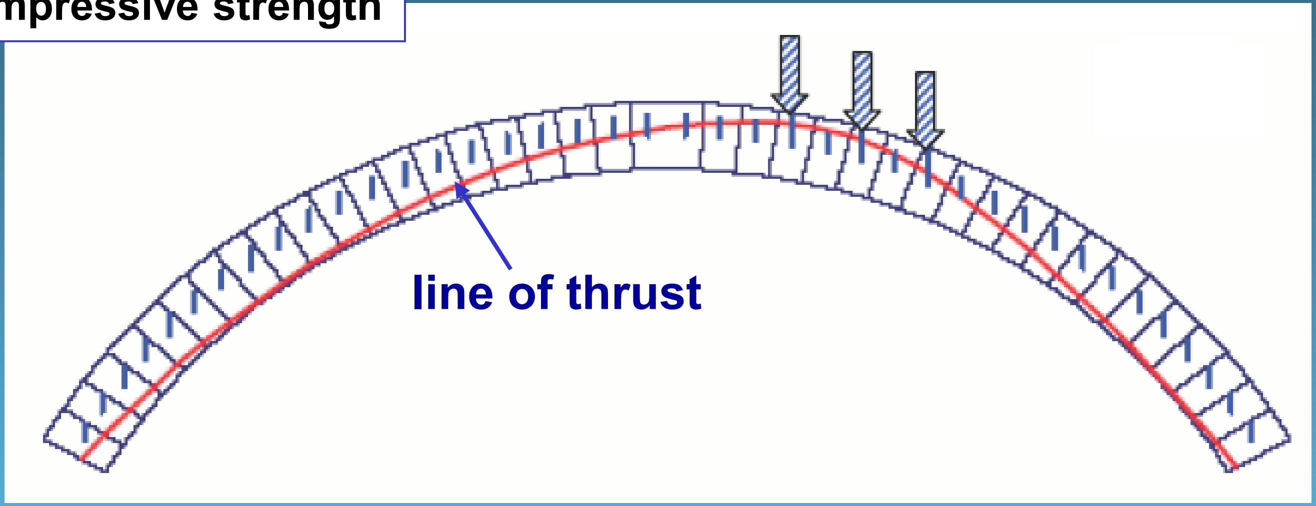


Courtesy M Gilbert

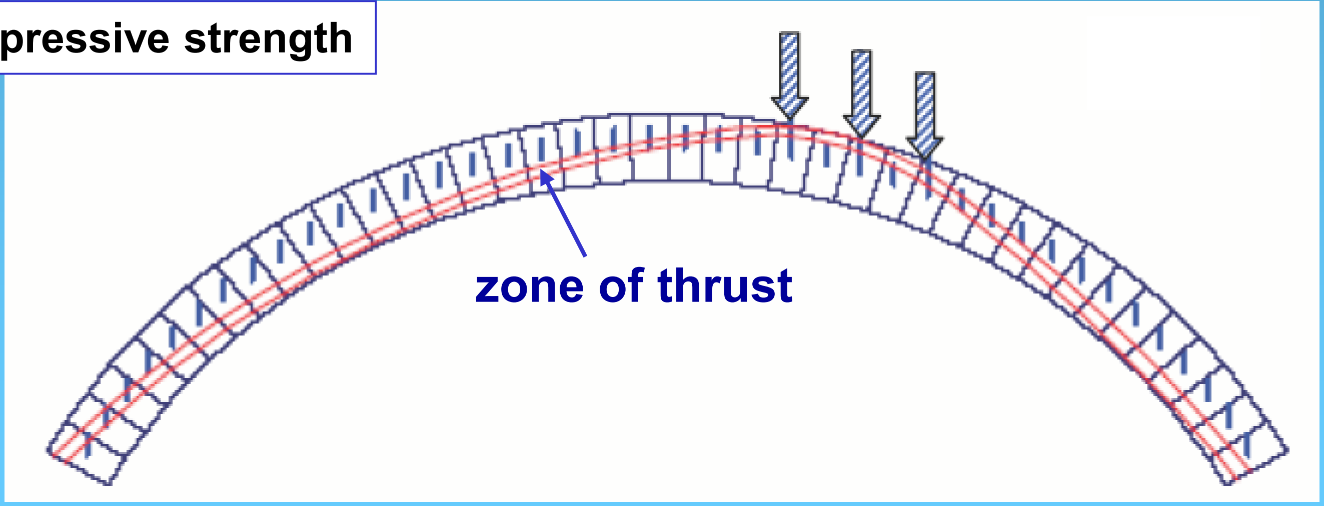

RING 2.0

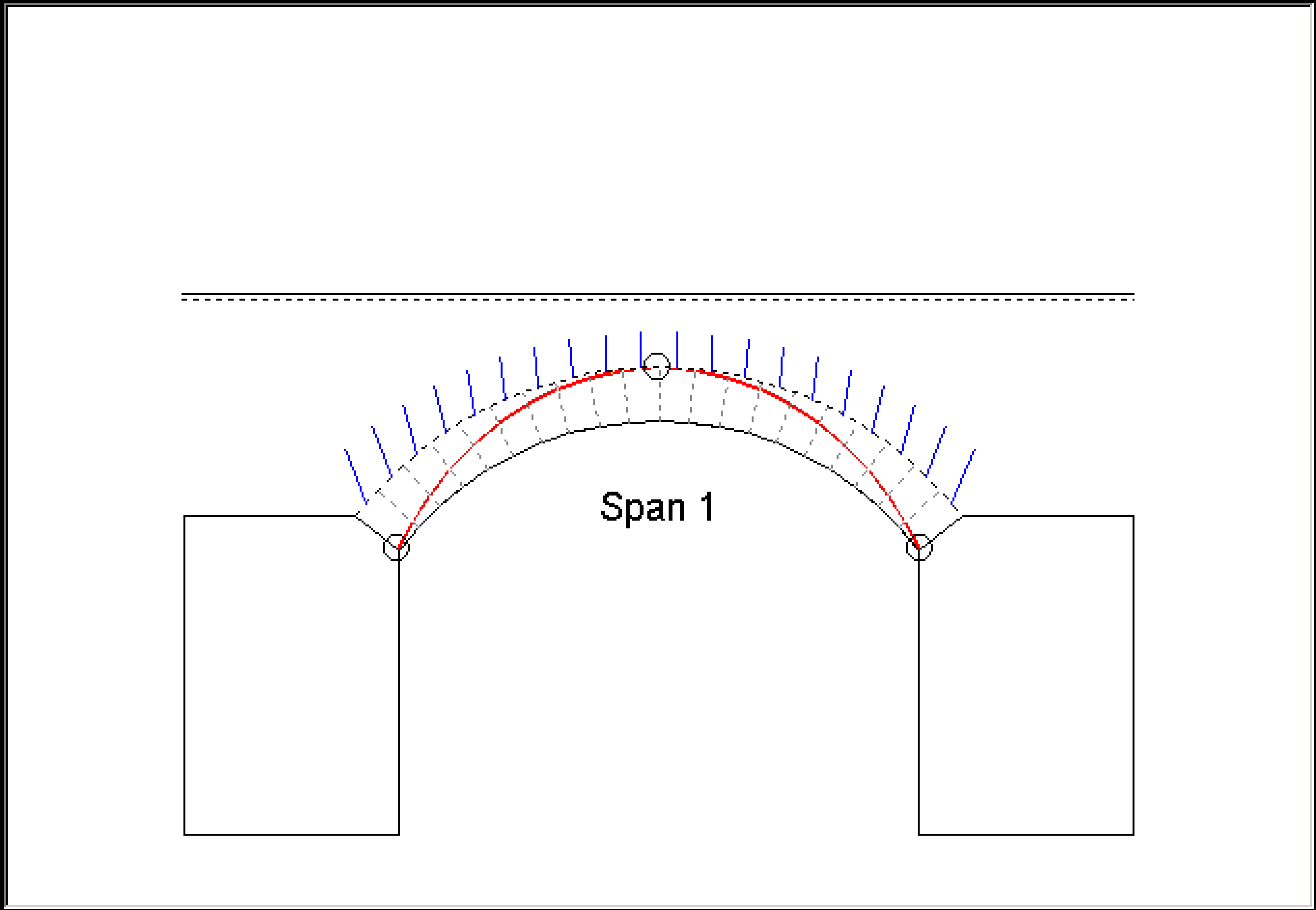
Thrust-line method

Infinite compressive strength



Finite compressive strength

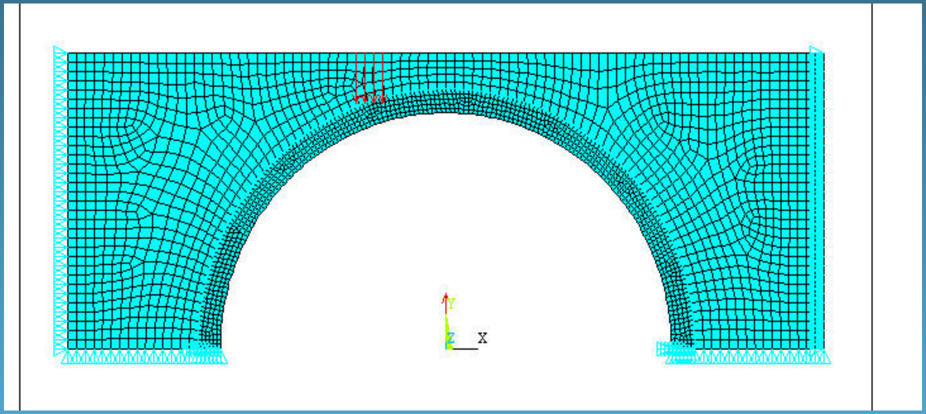


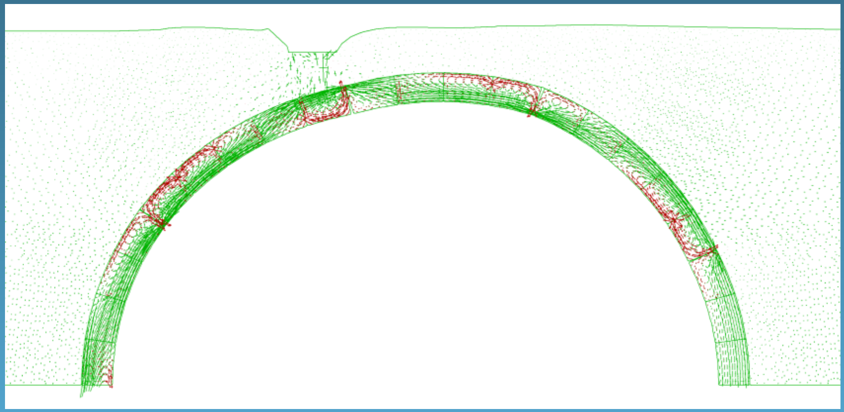
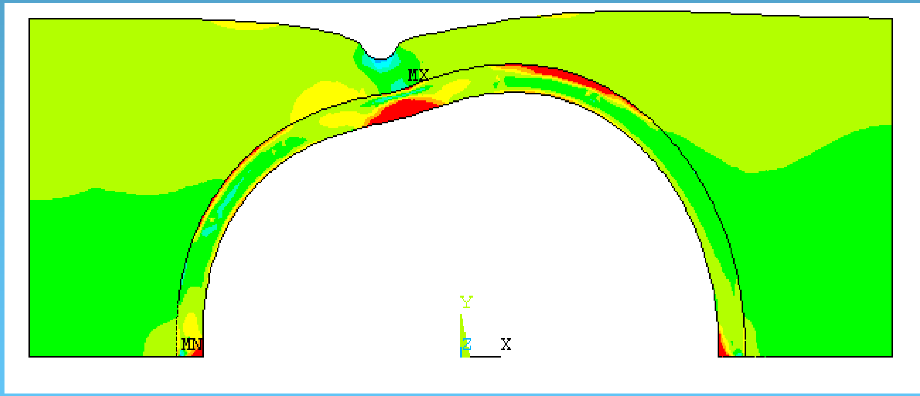


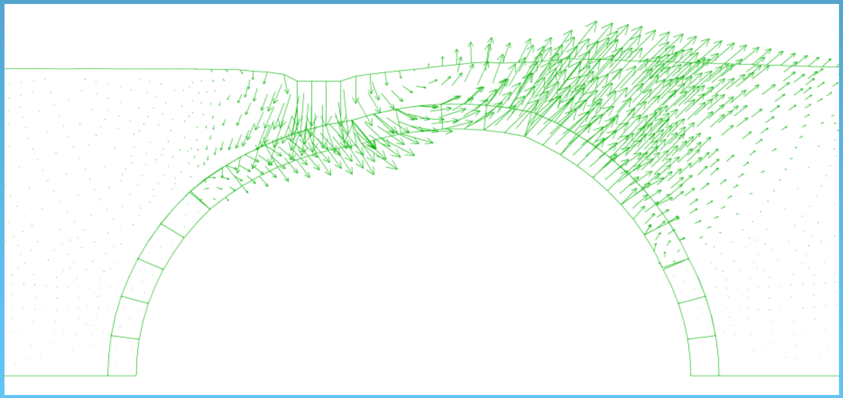
Courtesy W Harvey

Finite Element and Discrete Element Methods

‘Nonlinear analysis’

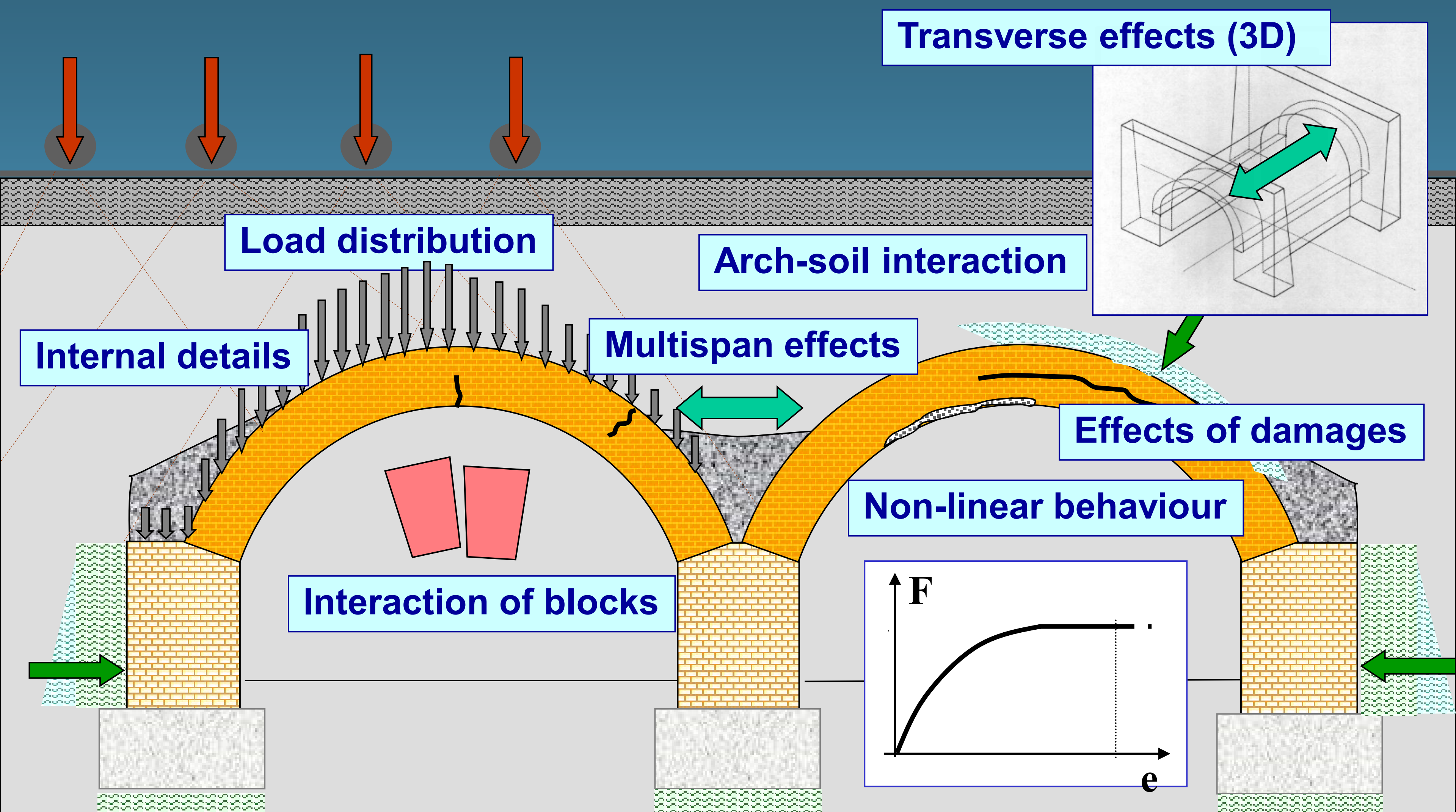


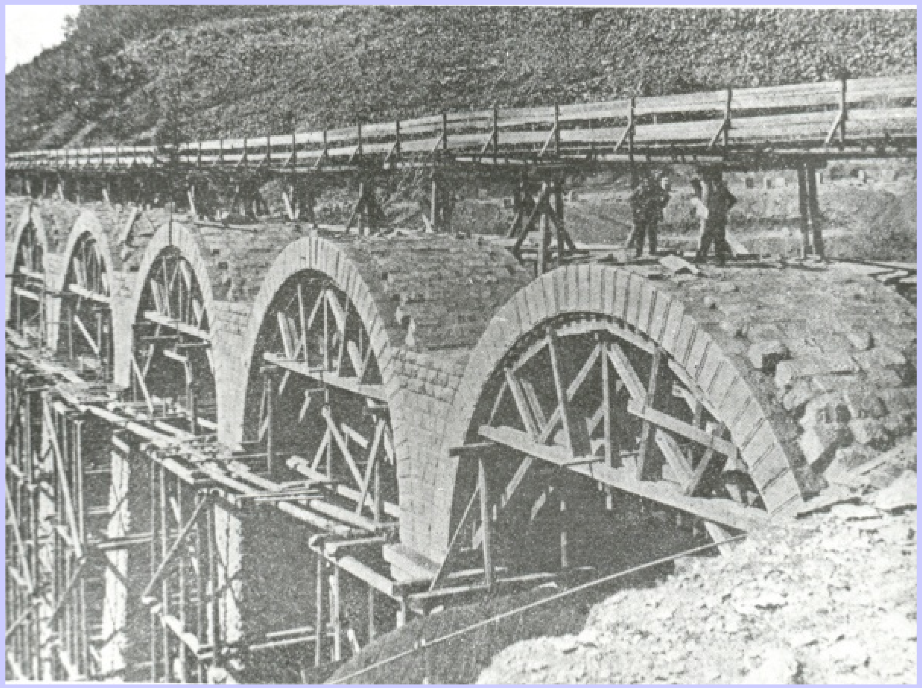


- **Arch:** Elastic, No-Tensile Resistant (NTR)
- **Fill:** Mohr-Coulomb
- **Contact:** Frictional

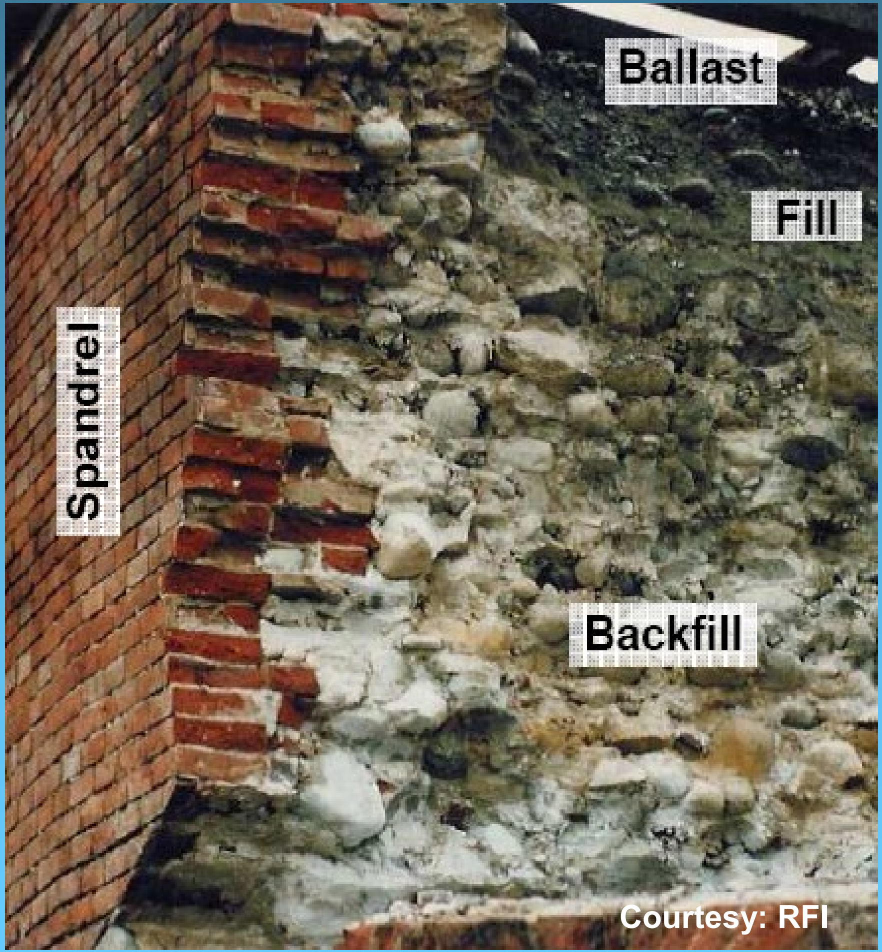
Difficulties in arch analysis and assessment



LARGE UNCERTAINTY IN INPUT PARAMETERS!



Unknown construction, hidden structural details and material properties



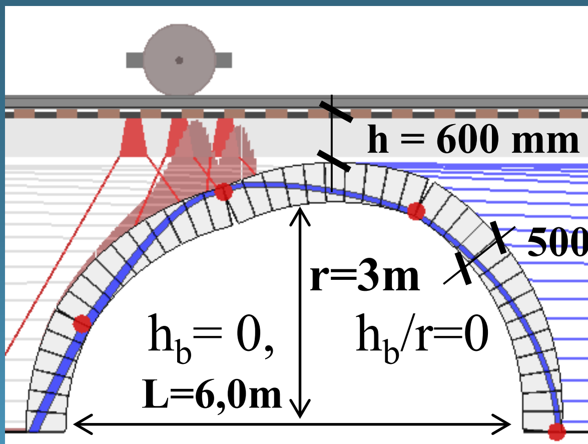
Courtesy: RFI

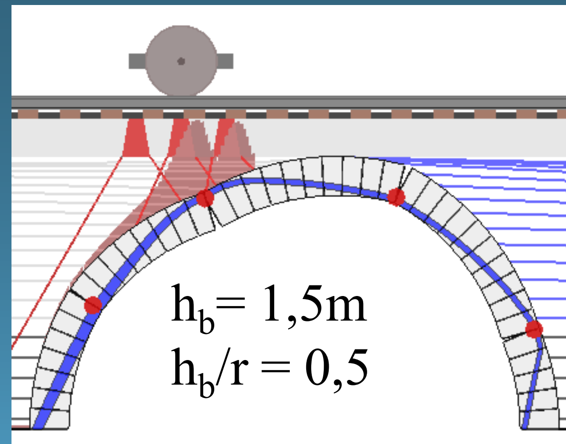
Courtesy: W Harvey

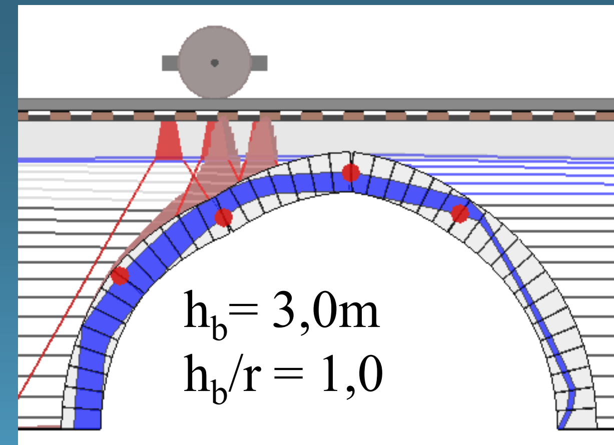

Courtesy: SNCF

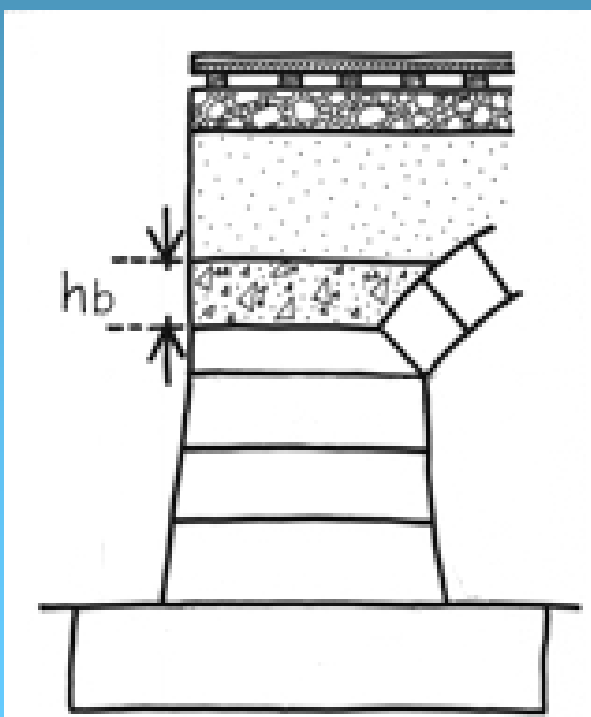

Courtesy: SNCF

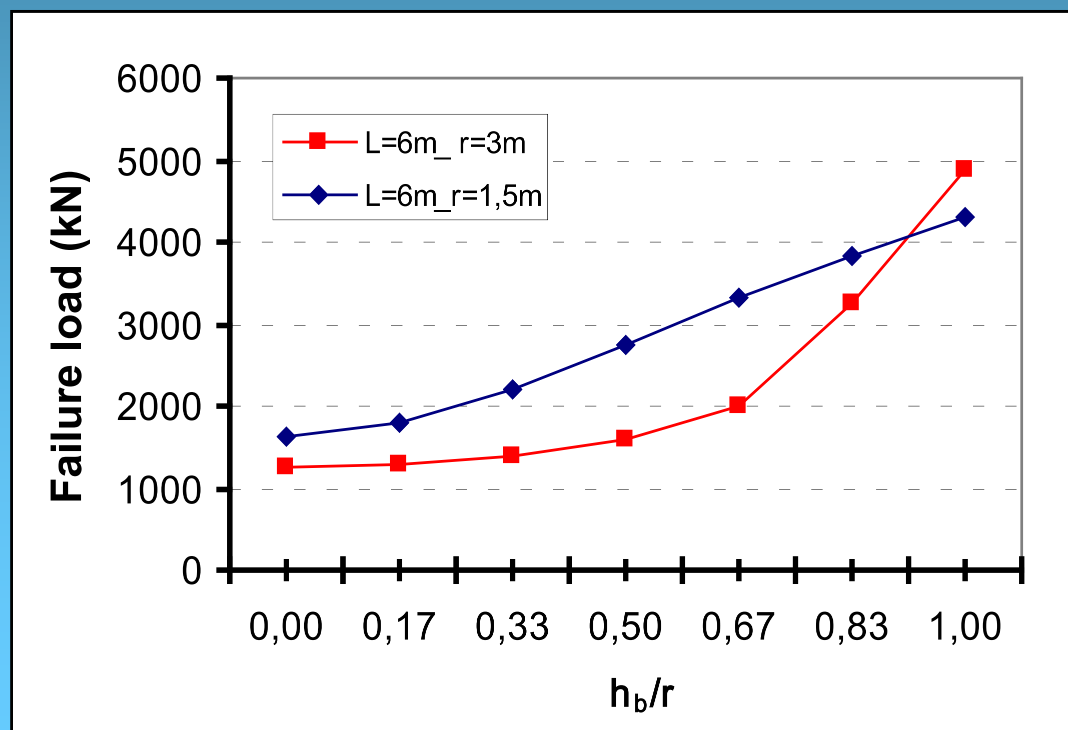
Effect of backing on load carrying capacity











Multi-level assessment procedure

	Analysis tool	Inspection to gain data
1st level	**Simple methods** (empirical)	**Mainly visual inspection**
2nd level	**2D Elastic and Limit analysis methods** (mechanism, thrust line)	**Simple measurements and tests**
3rd level	**High-level assessment** (2D/3D FEM, DEM)	**DT, NDT methods**

DIAGNOSTICS OF STRUCTURES

LECTURE 15

Diagnostics and assessment of masonry arch bridges – Part3

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DIAGNOSTICS & ANALYSIS RESEARCH GROUP

Overview on test methods

Destructive Testing methods	Non-Destructive Testing methods	Monitoring methods

Destructive Testing methods

Tests on prisms or cored samples

Semi-Destructive Testing methods

Boroscopy, endoscopy,

Flat-jack tests,

Surface measurements

Drilling resistance

Non-Destructive Testing methods

Georadar,

Infrared thermography,

Sonic methods,

Conductivity measurement,

Acoustic emission

Monitoring methods

Hammer tapping,

Crack monitoring,

Laser profiling, 3D scanning,

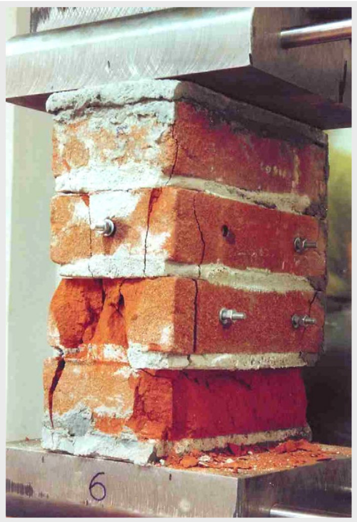
Photogrammetry,

Deformation monitoring,

Dynamic test,

Load test

Destructive tests vs. NDT methods

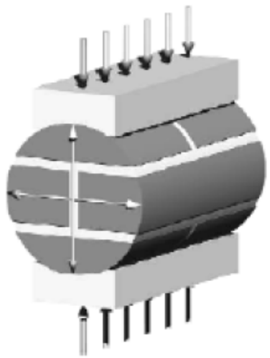


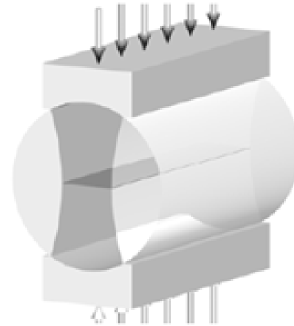

- Quantitative results
- Direct information local to the position of samples taken
- The number of samples should be minimized

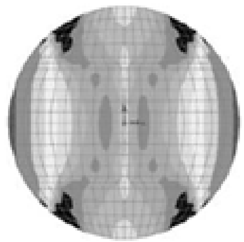
- Qualitative results
- Global information on the condition of the structure
- No limit in the number of samples or test areas

Destructive tests

Test on large diameter cored samples







$$f_c^{M} = q\frac{F_{ult}}{\phi\, l}$$

where

q = correction factor $\in$ (1,8 or 2,2)
ϕ = the cylinder diameter
l = the specimen length (typically 100 - 240 mm)

The strength of masonry

The characteristic value of strength parameters

$$f_k = f_m - k\,s_f = (1 - k\,\mu) f_m = K\,f_m$$

where

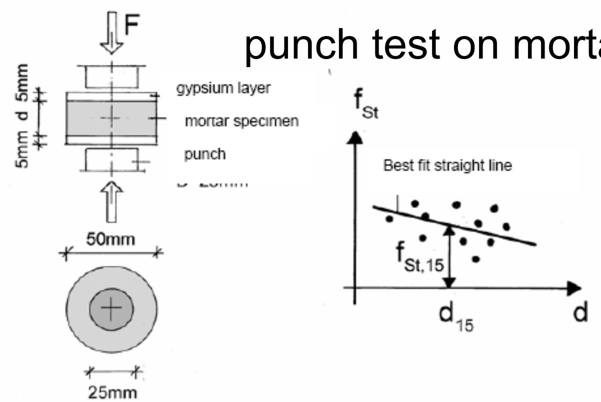
f_k	- characteristic value
f_m	- mean value of the measured data
s_f	- standard deviation of the measured data
$\mu = s_f / f_m$	- coefficient of variation (CoV)
k and $K = (1 - k\mu)$	- parameters taking into account the number of test data
N	- number of test data

N	3	6	8	10	12	16	20	25	≥ 30
k	2.33	2.19	2.14	2.10	2.07	2.03	2.00	1.97	1.94
K	0.30	0.34	0.36	0.37	0.38	0.39	0.40	0.41	0.42

Destructive tests

Test on small diameter cored samples

punch test on mortar



$$f_k = K f_b^{0.7} f_m^{0.3}$$

f_b is the normalized compressive strength of the masonry units in N/mm^2,

f_m is the specified compressive strength of the general purpose mortar in N/mm^2

K constant ($K \approx 0{,}5$)

Destructive tests

Required number of samples

Should take account of:

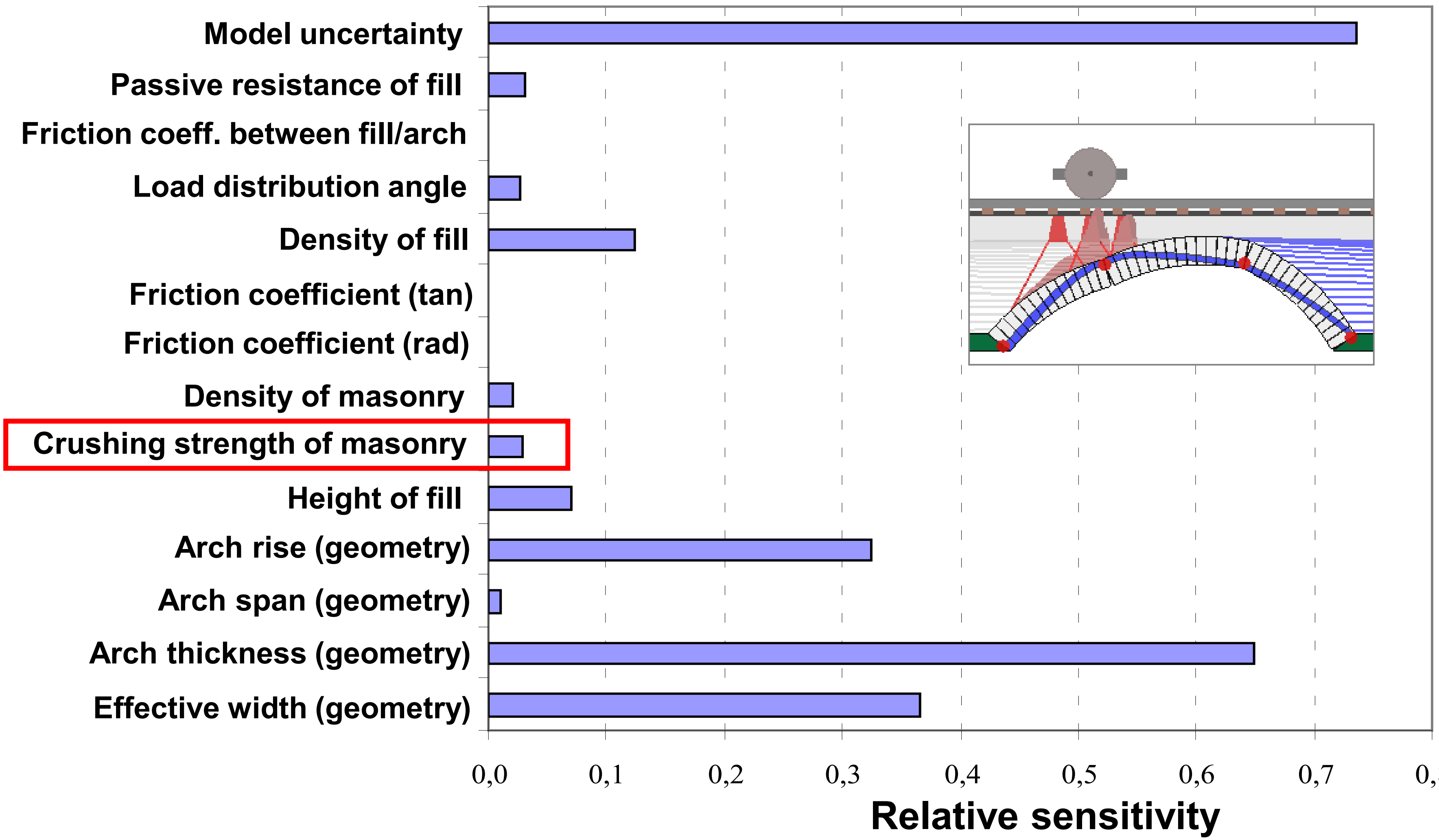
- **the required accuracy of the strength parameters**
- **the importance of the data and the reliability of other parameters used in the assessment**

<u>The suggested optimal number of test specimens:</u>

» 3 - 6 for strength properties for level 2 assessments
» 10-15 for level 3 assessments or when more accurate value is required

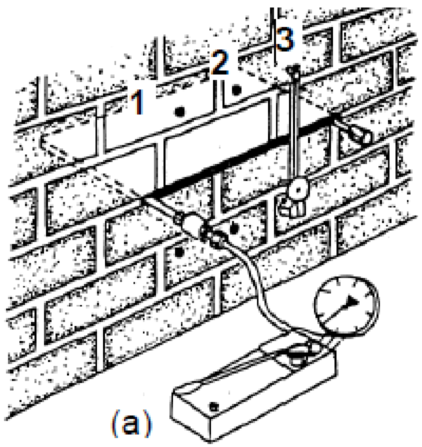
Effect of parameter uncertainties on CoV of failure load

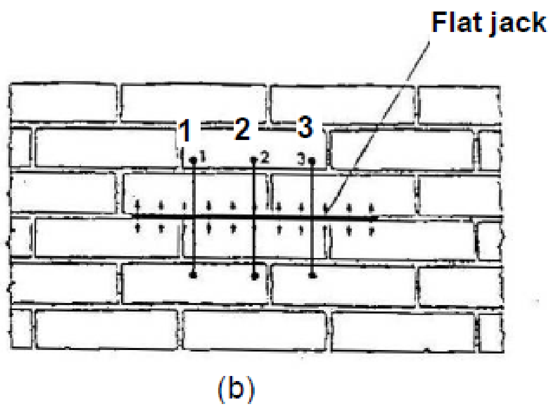
(example based on stochastic sensitivity analysis using RING 2.0)



Semi-Destructive Tests

Flat jack test





» **stress state in masonry** (single and double jacks)

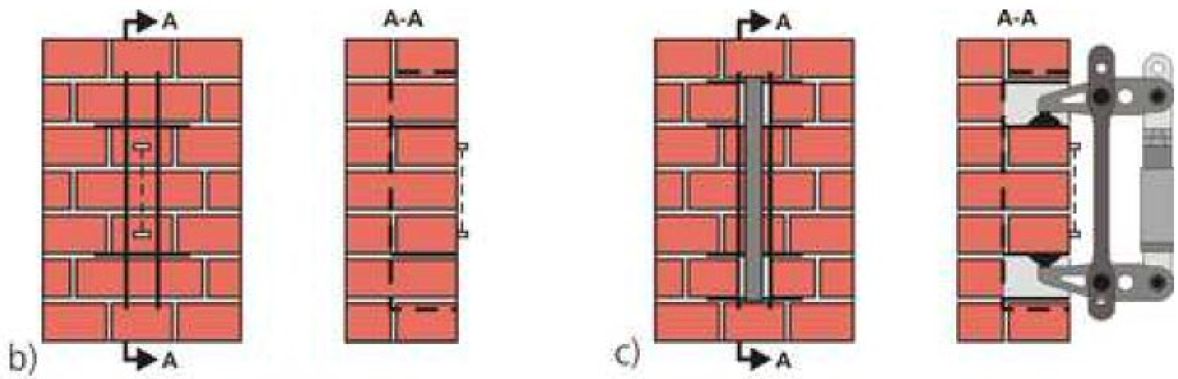
$$\sigma_c = K_m \cdot K_a \cdot p$$

» **compressive strength** (double jacks)

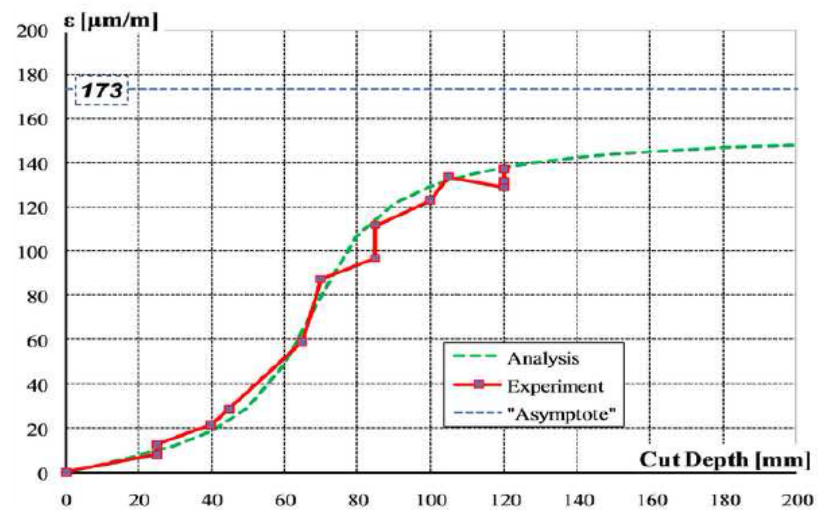
» **elastic modulus** (double jacks)

Semi-Destructive Tests

Modified flat-jack test

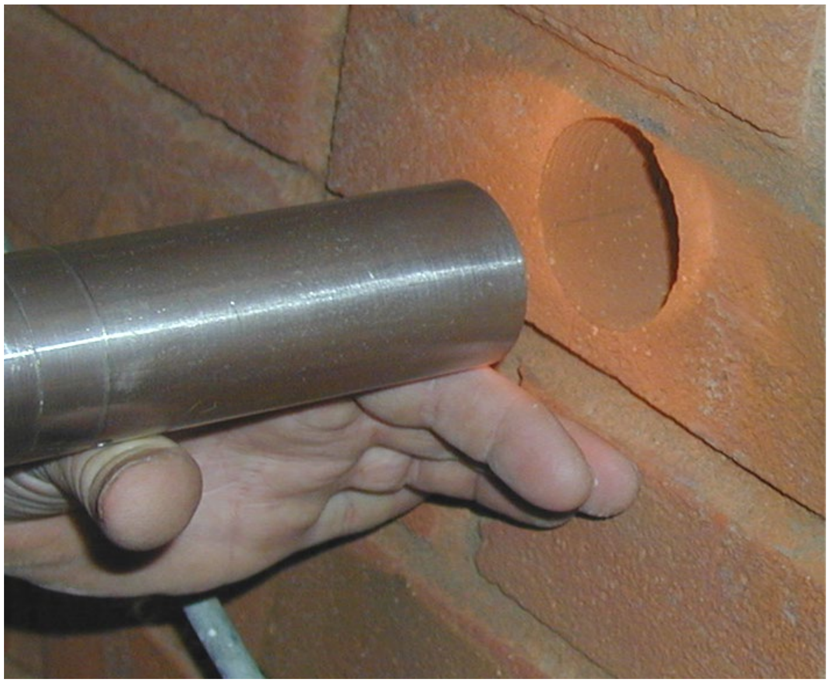


Orban, Z., Gutermann, M. (2009), *Engineering Structures*

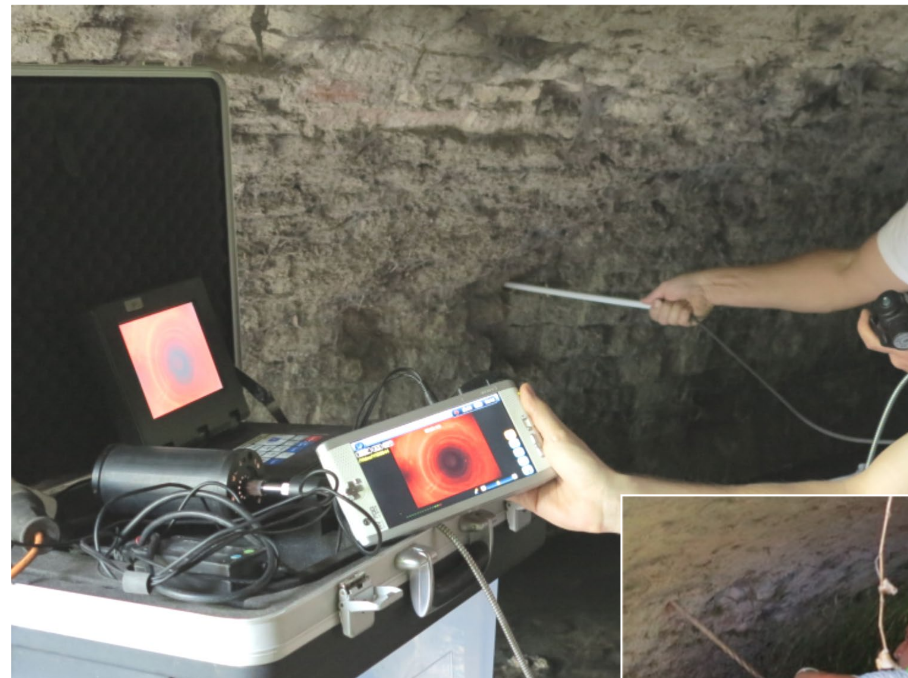


Semi-Destructive Tests

Boroscopy

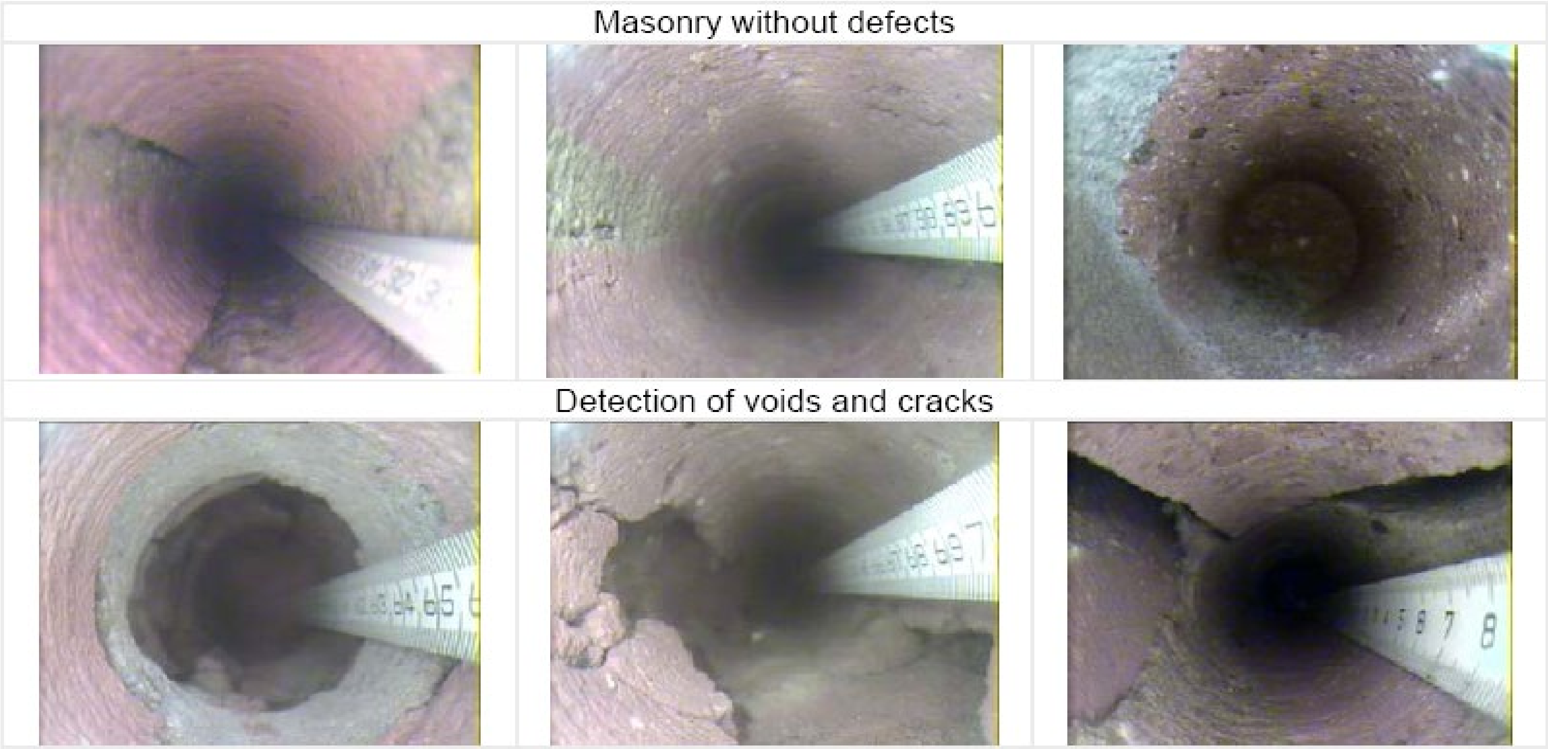


Endoscopy



A small camera is inserted into boreholes drilled in the structure allowing a detailed study of its surface.

Semi-Destructive Tests



Information obtained are used for:

- Detection of large cavities, cracks
- Qualitative test of material condition
- Calibration of other test techniques

Limits:

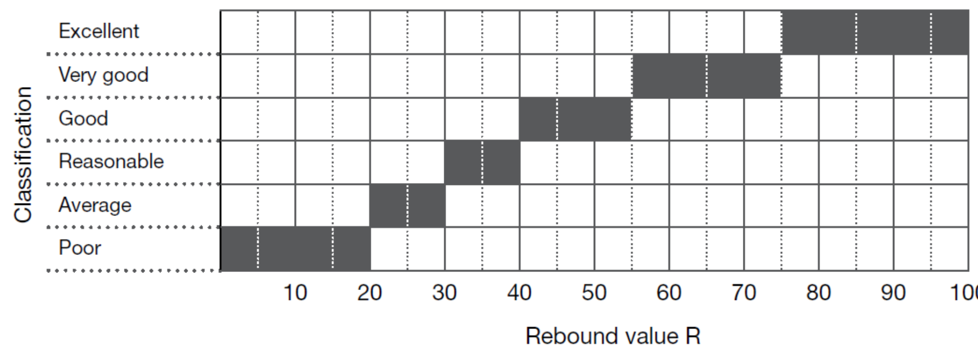
- Only local information
- Slightly destructive

Non-Destructive Tests (NDT)

Pendulum Hammer (e.g. Schmidt type PT and PM)

PT

PM



Type PT: used for masonry units

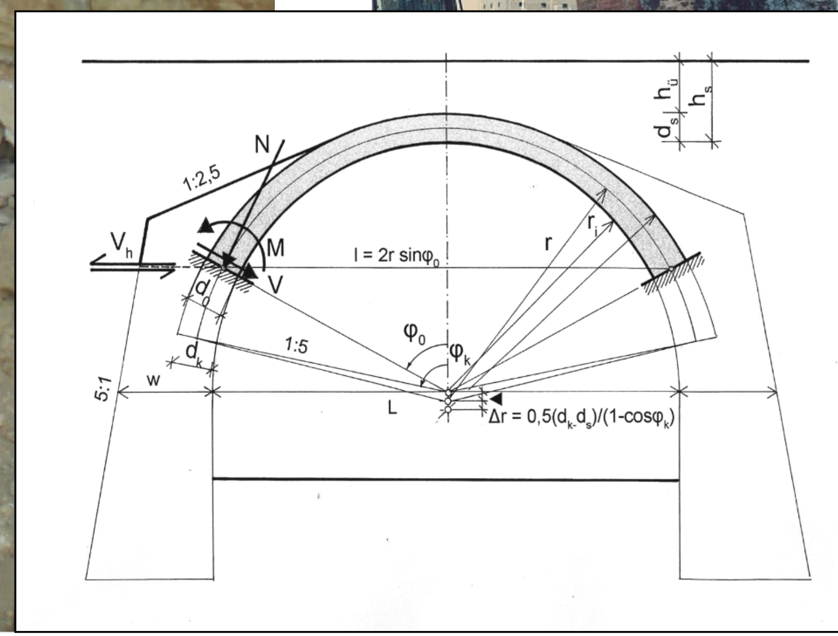
Type PM: used for masonry mortar joint

Qualitative test on low strength masonry

Non-Destructive Tests (NDT)

Other reasons for using NDT methods

- To determine hidden dimensions



Non-Destructive Tests (NDT)

Other reasons for using NDT methods

- To determine hidden dimensions
- To investigate variations in type of materials

Non-Destructive Tests (NDT)

Other reasons for using NDT methods

- To determine hidden dimensions
- To investigate variations in type of materials
- To identify damages



Non-Destructive Tests (NDT)

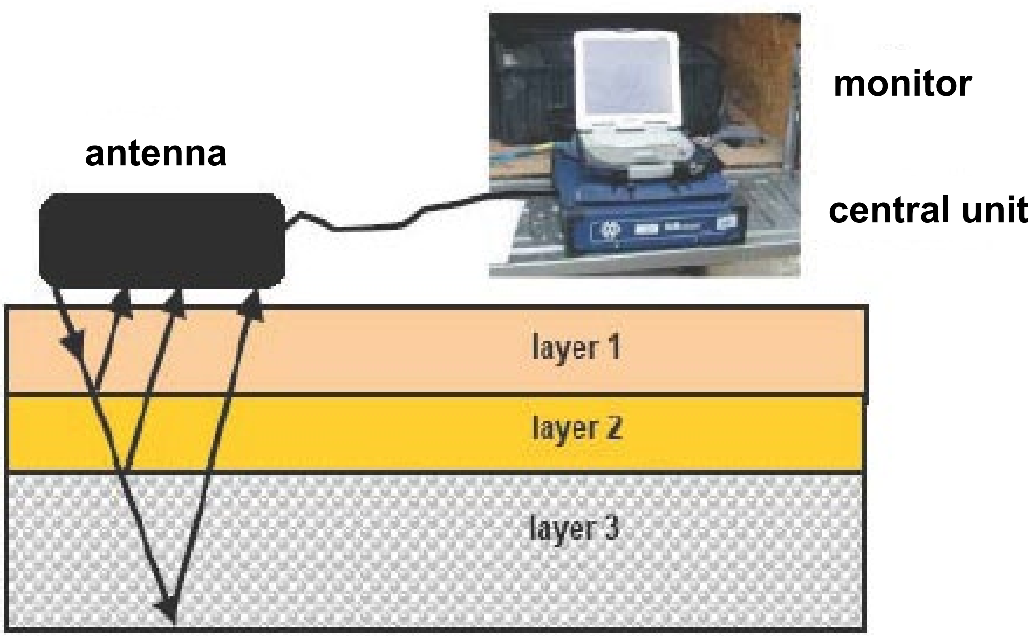
Other reasons for using NDT methods

- To determine hidden dimensions
- To investigate variations in type of materials
- To identify damages
- To identify previous intervention

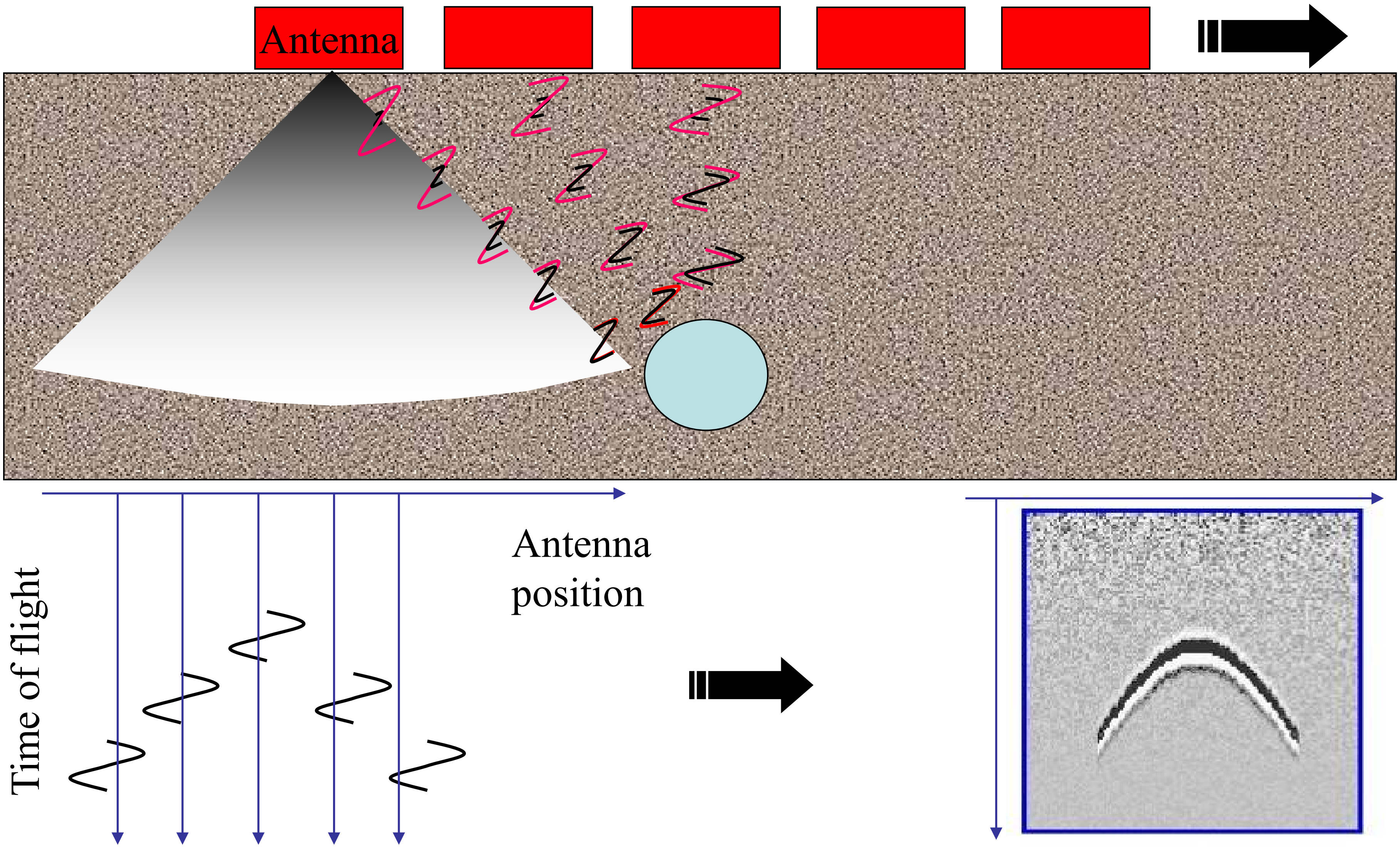
Non-Destructive Tests (NDT)

Ground Penetrating Radar (GPR)

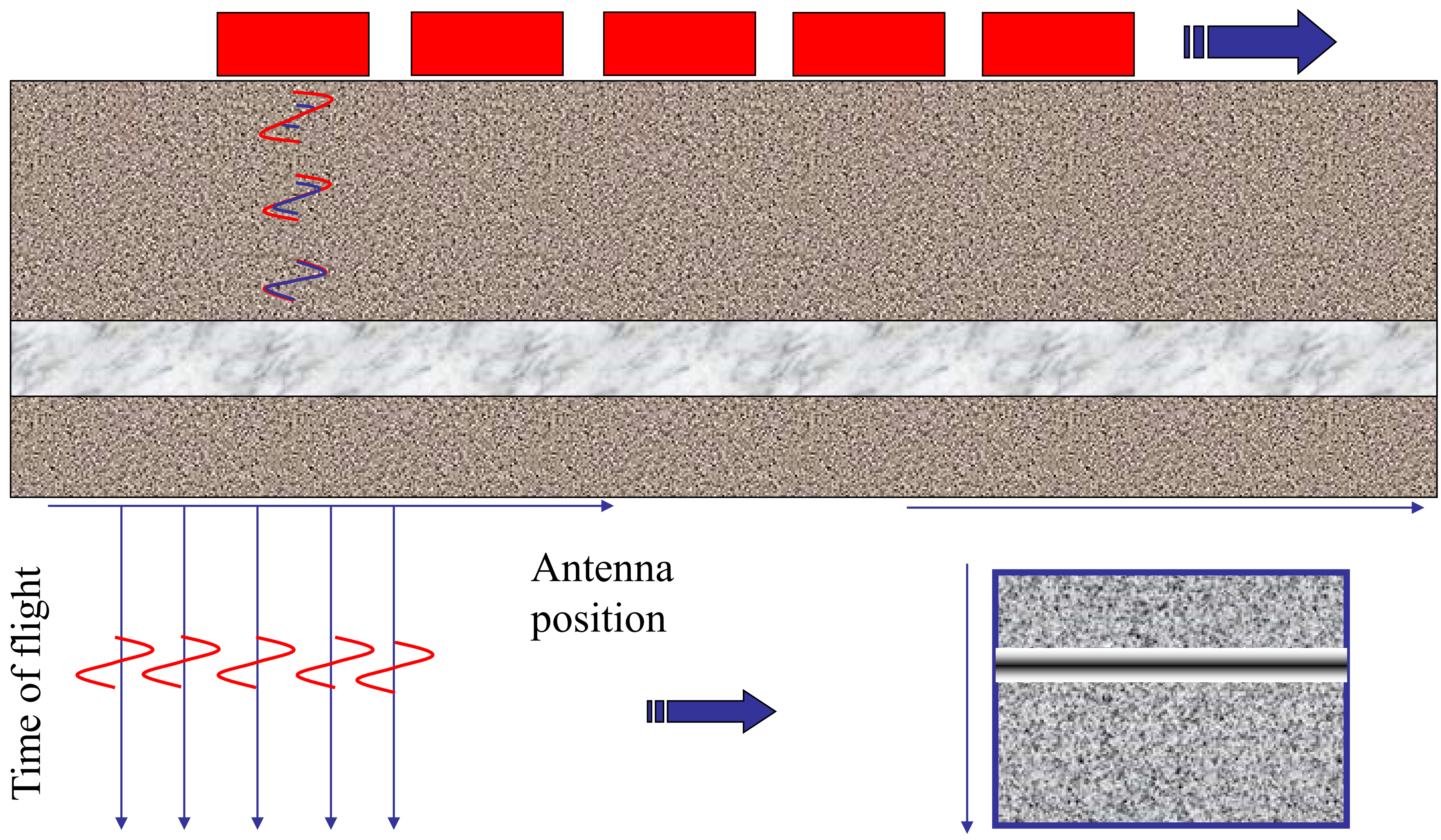
Electromagnetic impulses are transmitted into the material and recorded by a receiver.



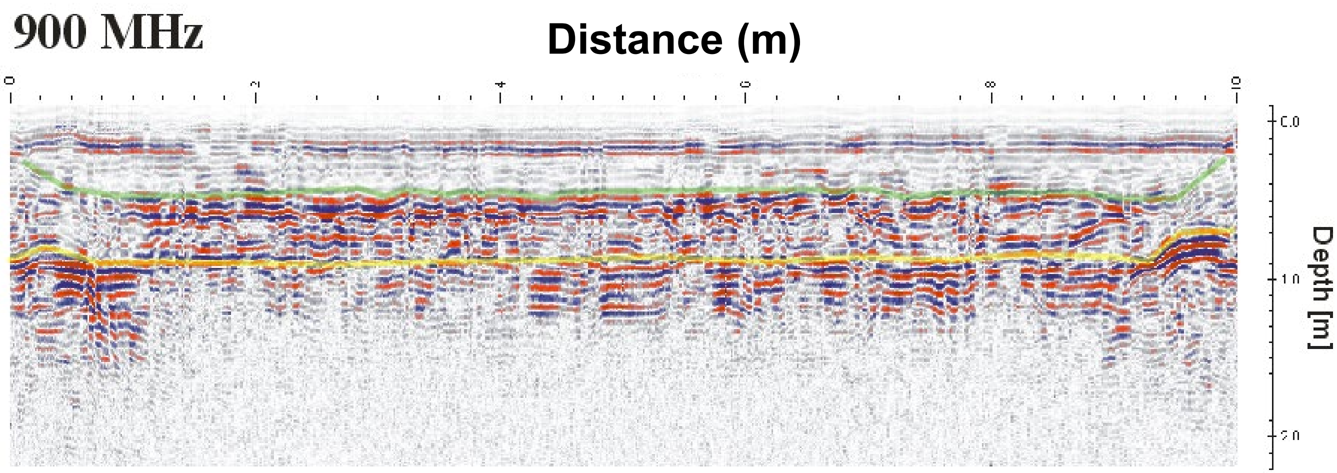
Detecting "point target" with GPR



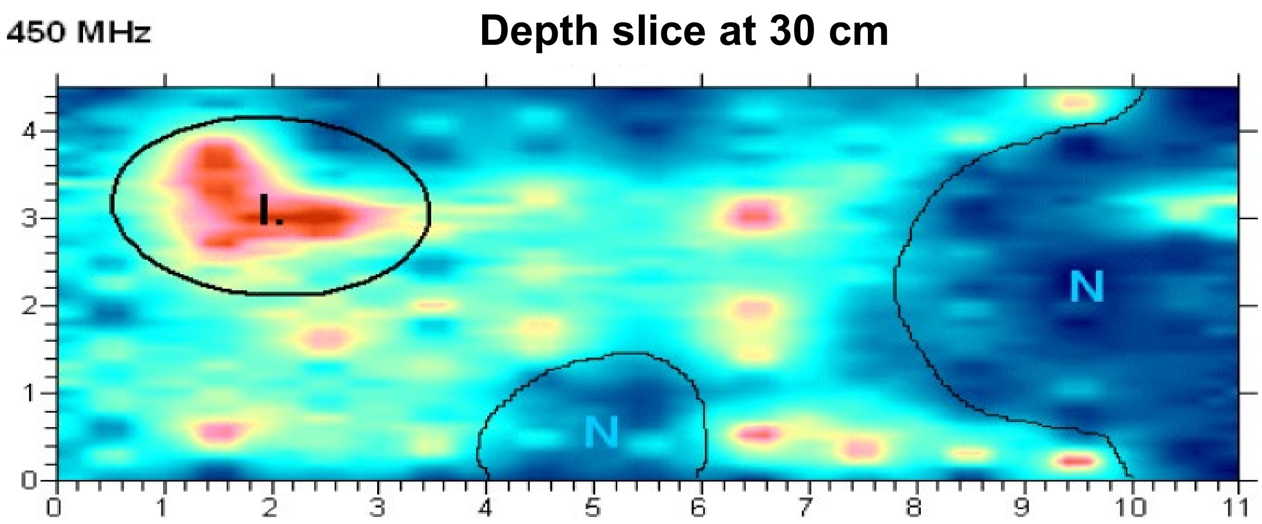
Detecting ″linear target″ with GPR



Representation of measured GPR data (examples)

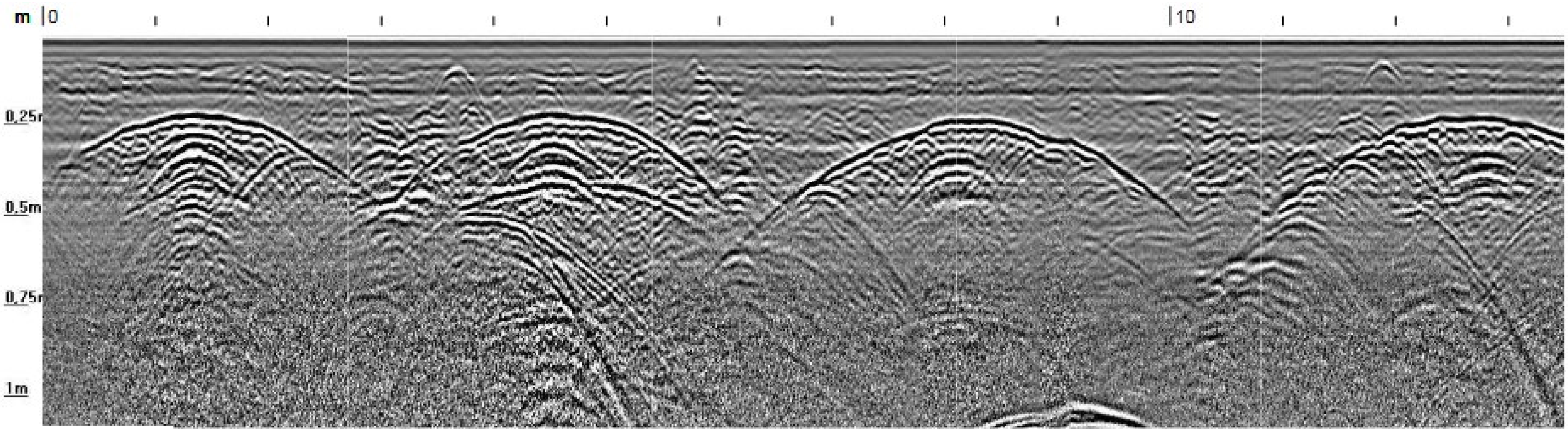


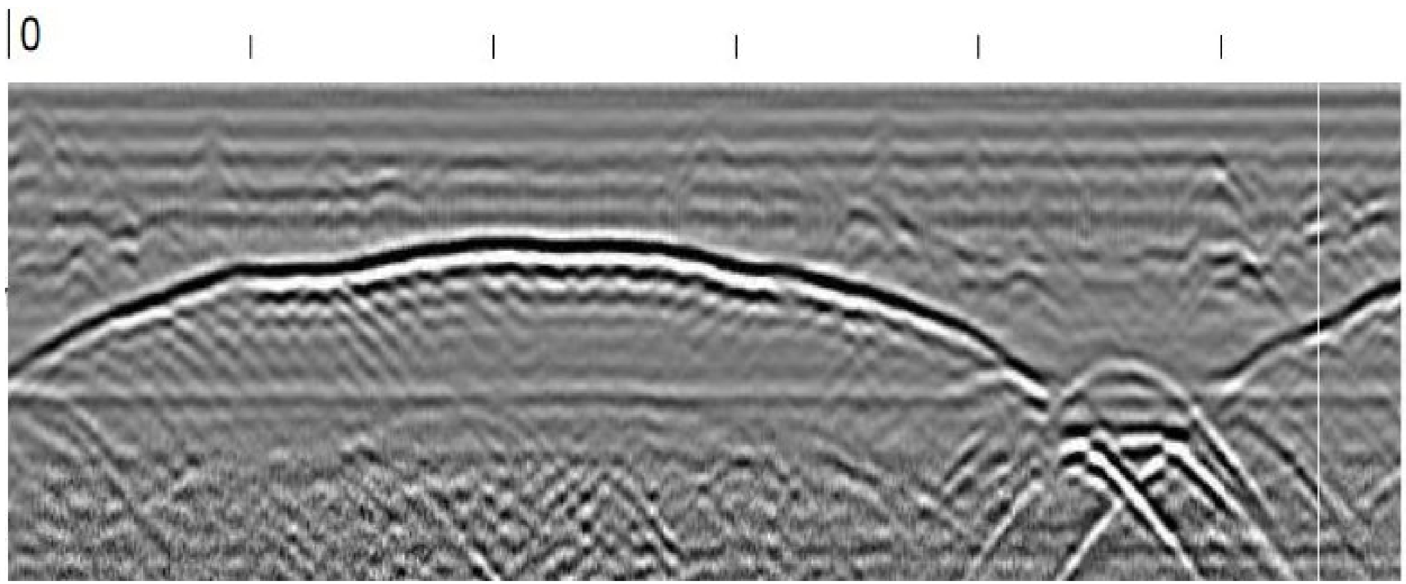
Radargram



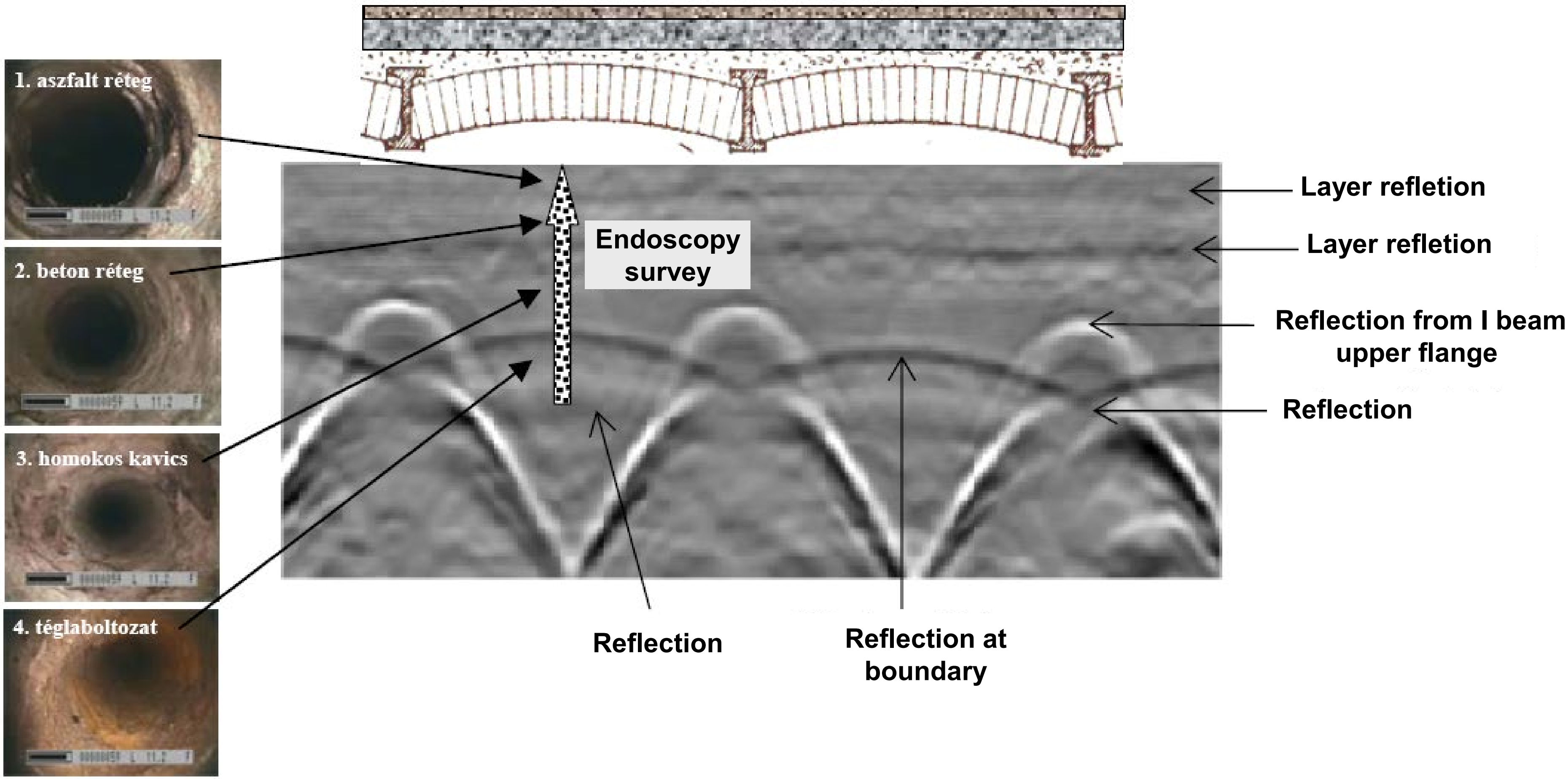
Anomaly map (depth slices)

Tests on arches from upper surface





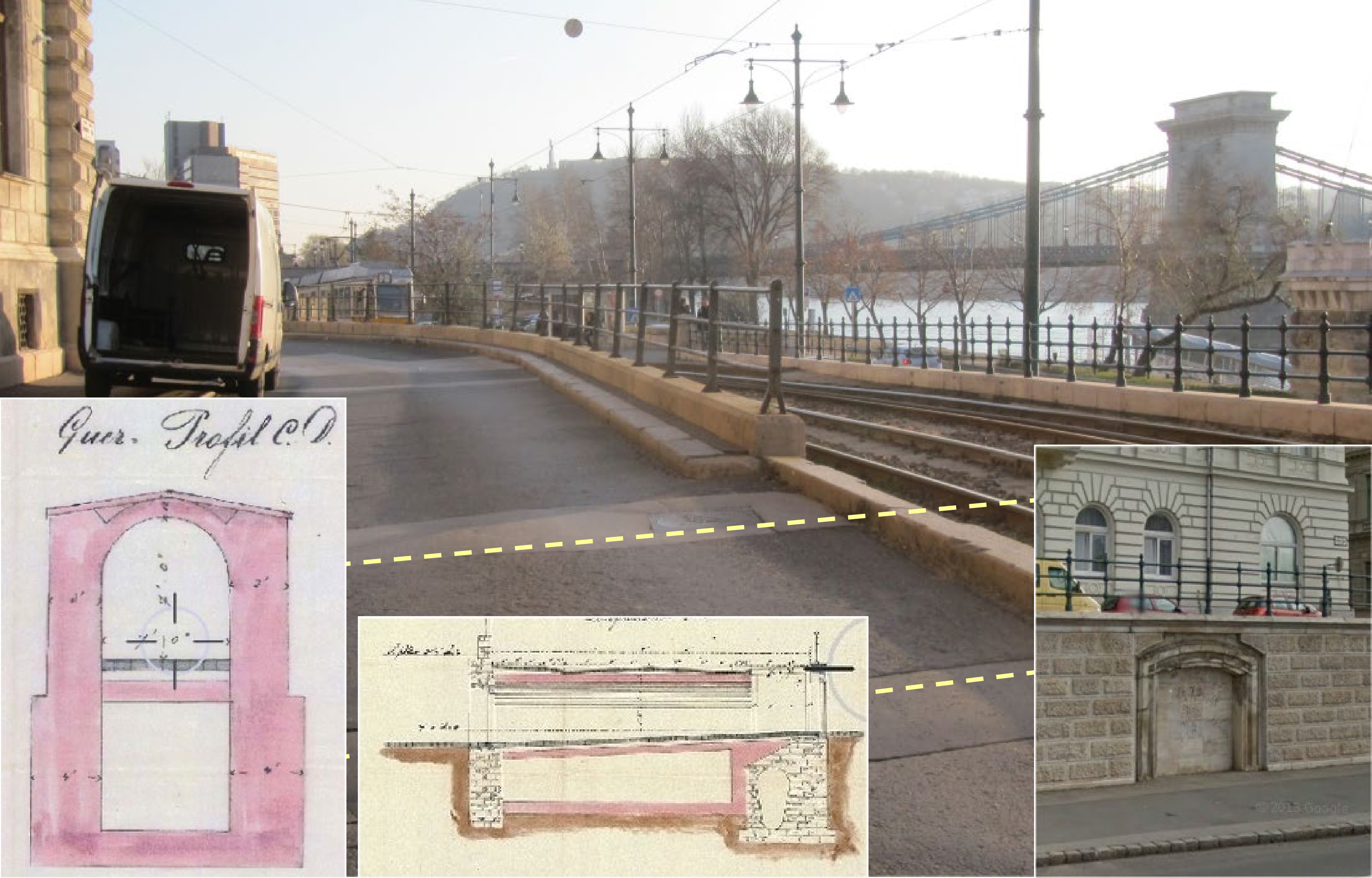
Tests on Jack-arch structure (Case Study)



EF/F2 endoszkópos vizsgálat

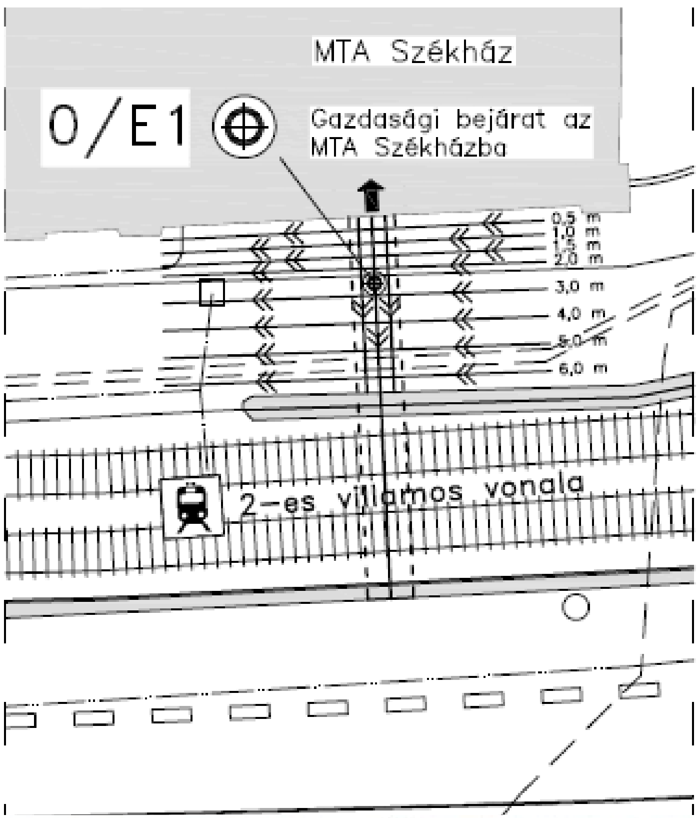
Combination of GPR with endoscopy

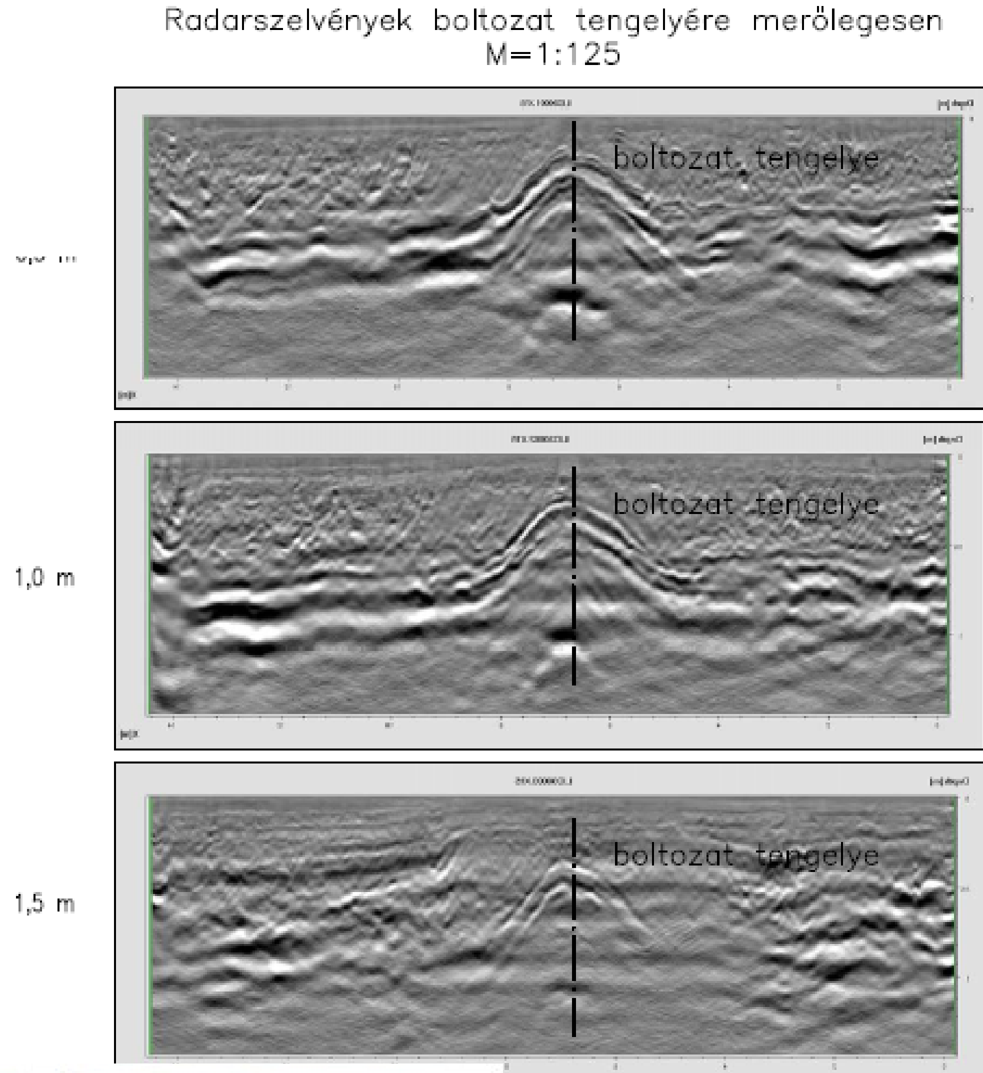
Stone arches with no access (Case Study)
(Budapest)

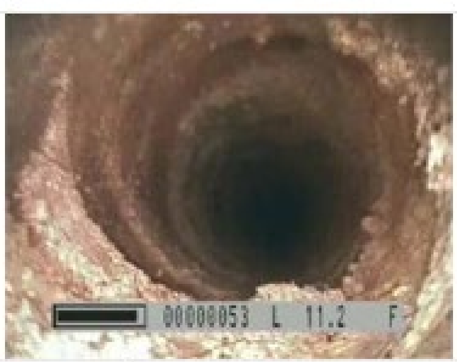


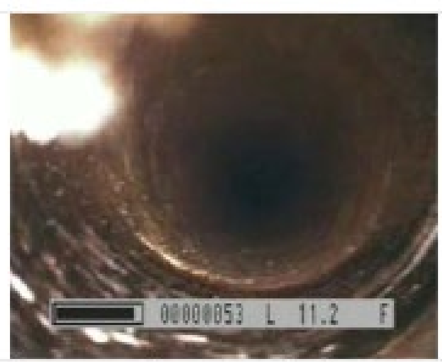
In situ NDT tests

Combination of radar and endoscopy survey

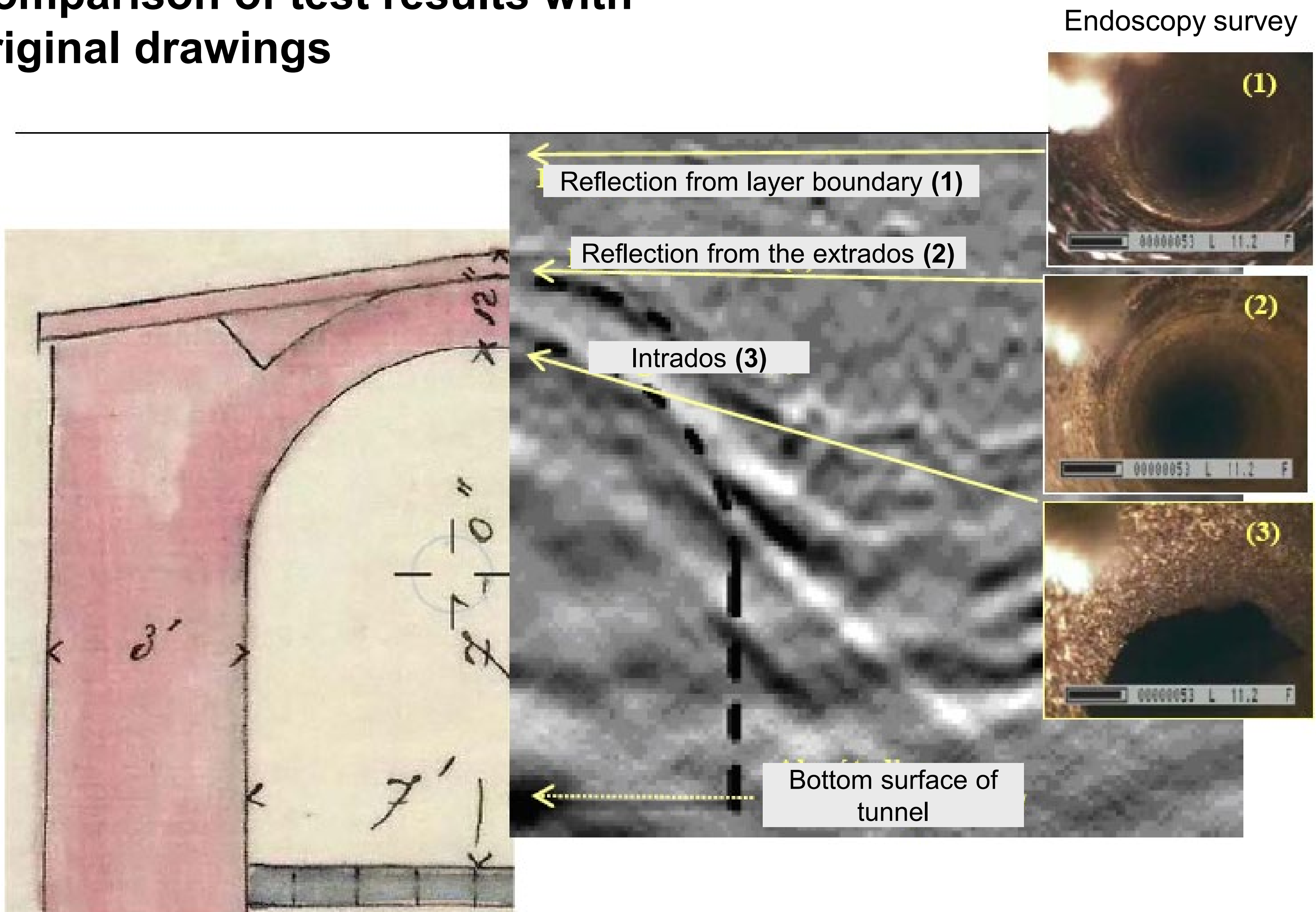








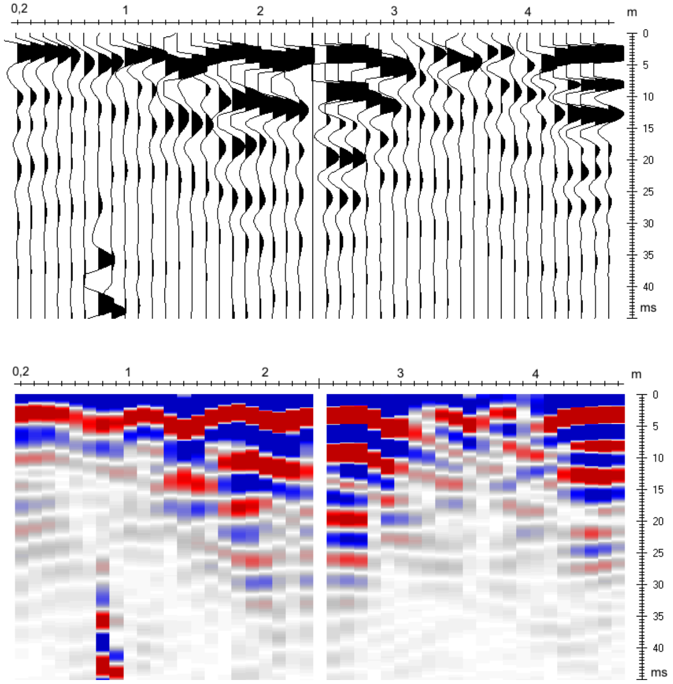
Comparison of test results with original drawings



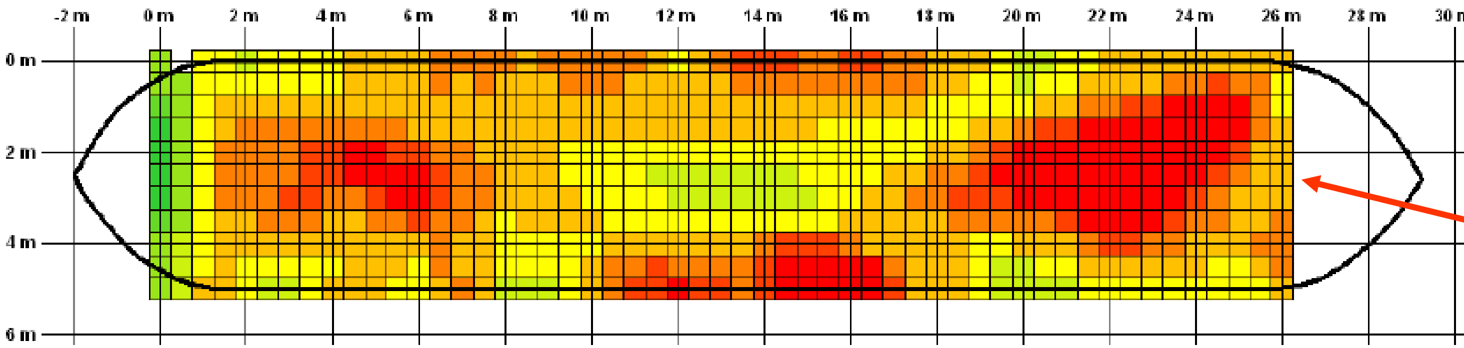
Non-Destructive Tests (NDT)

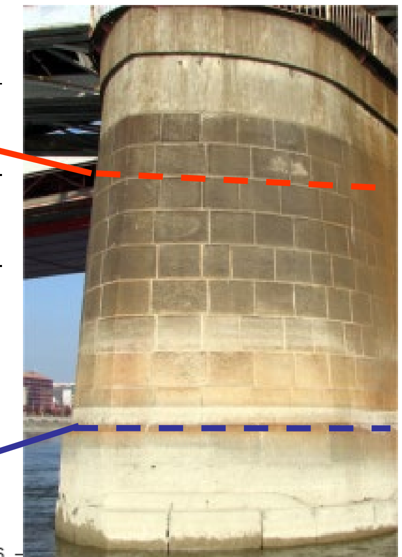
Sonic methods

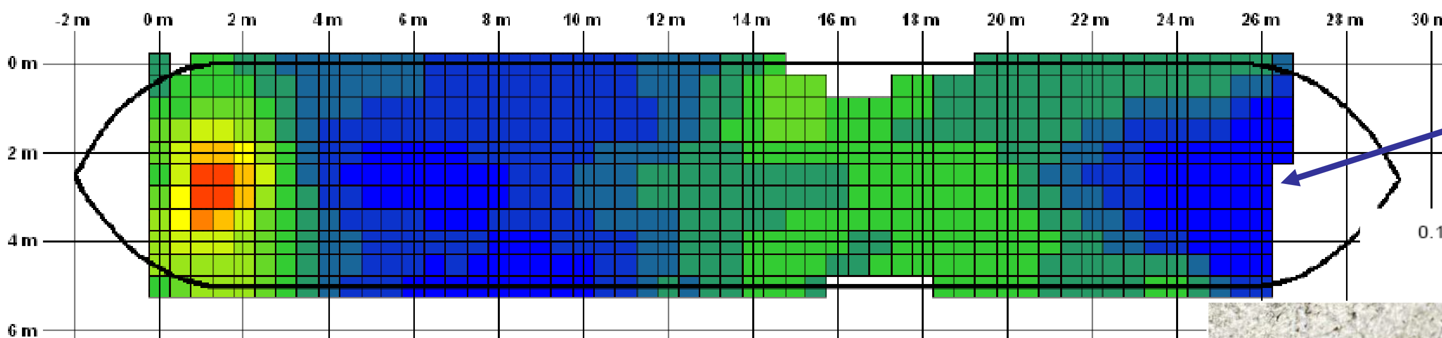
Sonic waves are transmitted through the structure. The velocity of the waves is proportional to the properties of the material.



Sonic methods (seismic tomography of a bridge pier – Case Study)







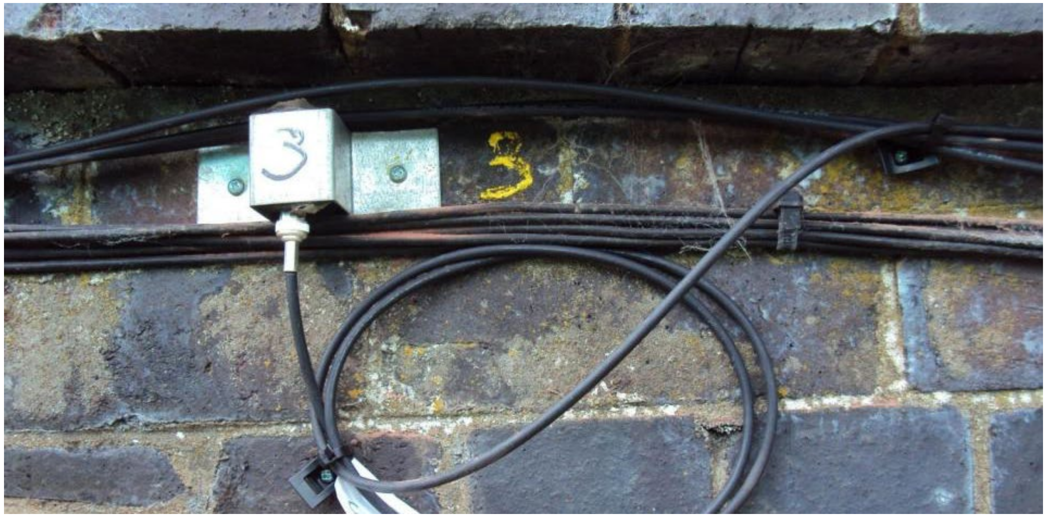
key to velocity distribution

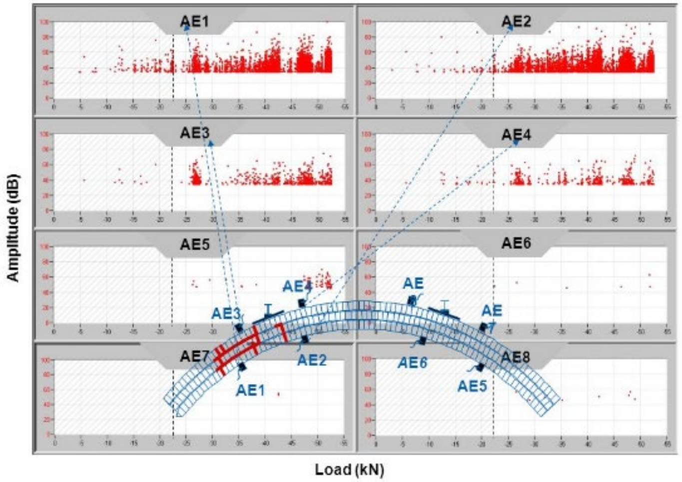
Non-Destructive Tests (NDT)

Acoustic Emission (AE)

AE is a stress wave emission technique used to monitor defect formation and failures in structural materials.

The detection system waits for the occurrence and capture of stress wave emissions associated with cracking.



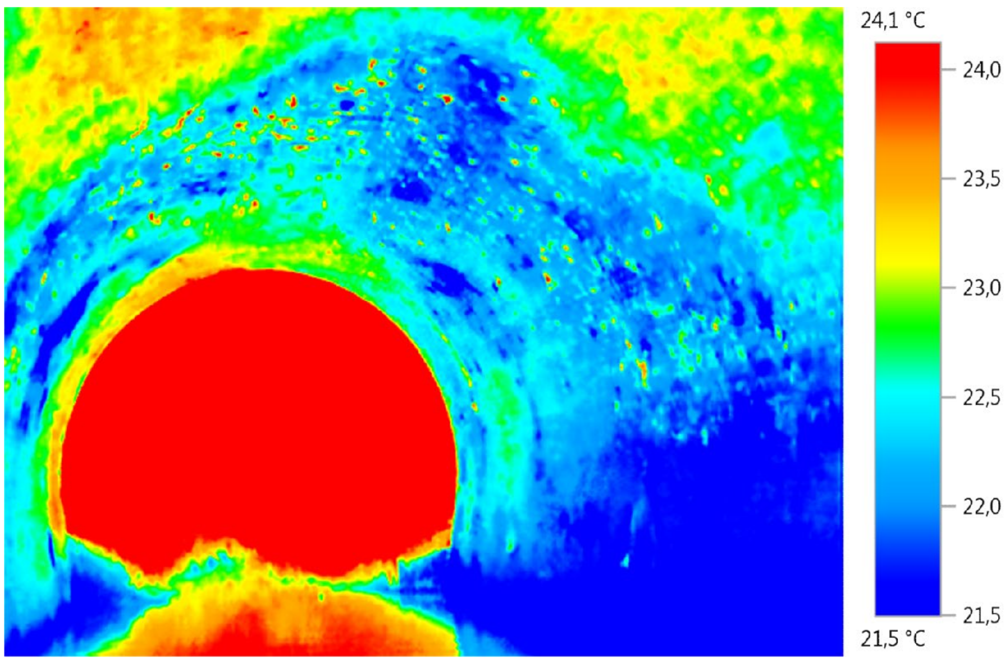


(Courtesy A Tomor)

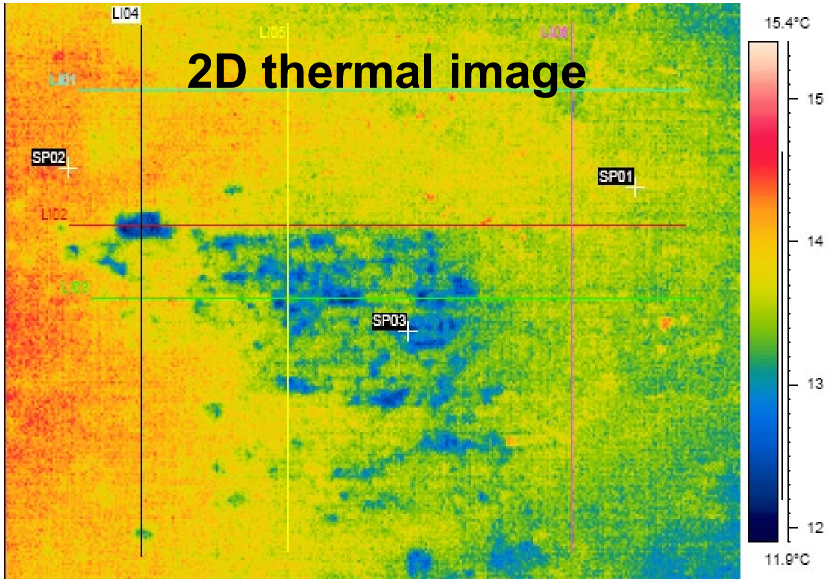
Non-Destructive Tests (NDT)

Infrared Thermography (IRT)

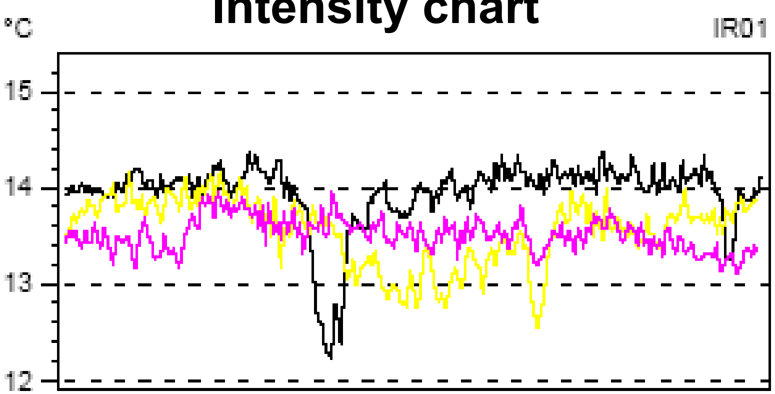
The thermal radiation from the surface is collected by an infrared camera.
The thermal radiation pattern is converted into a visual image.
Used to detect subsurface defects, material anomalies, cracks, moisture, etc.



Representation of measured data

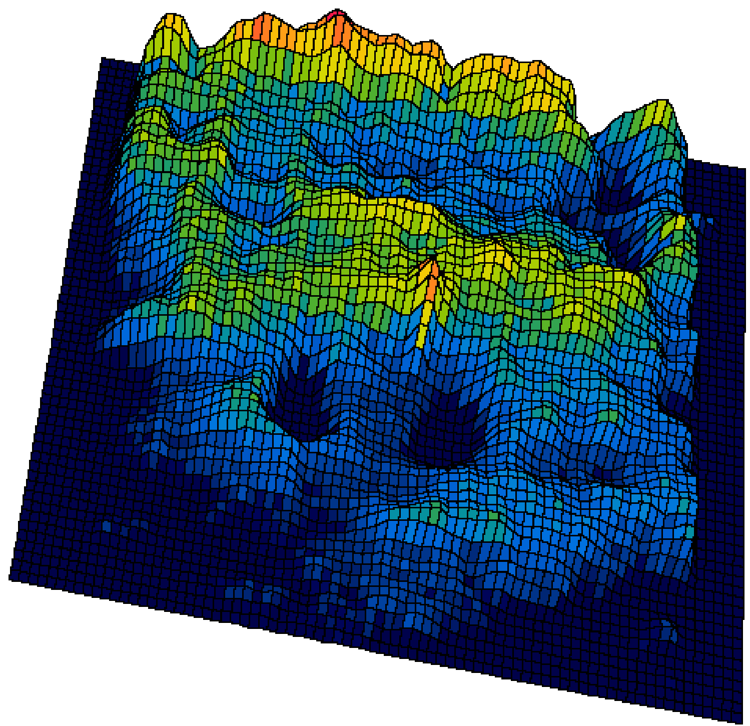


Intensity chart

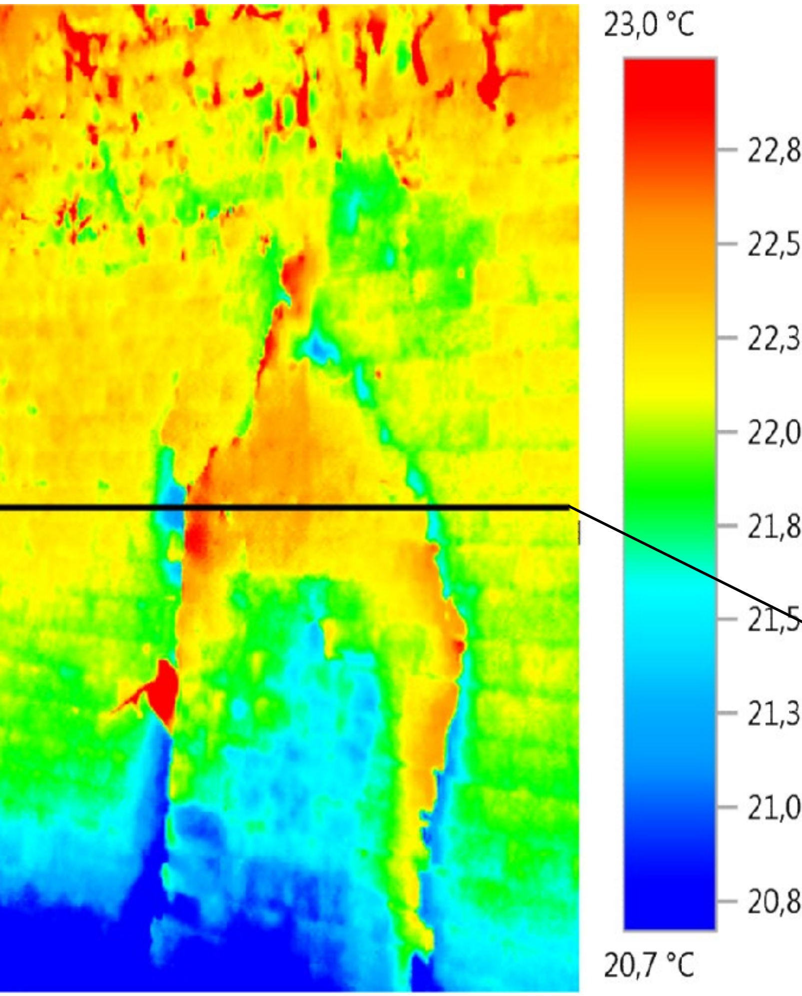


Line	Min	Max	Cursor
li04	12.2°C	14.4°C	-
li05	12.5°C	14.2°C	-
li06	13.1°C	14.0°C	-

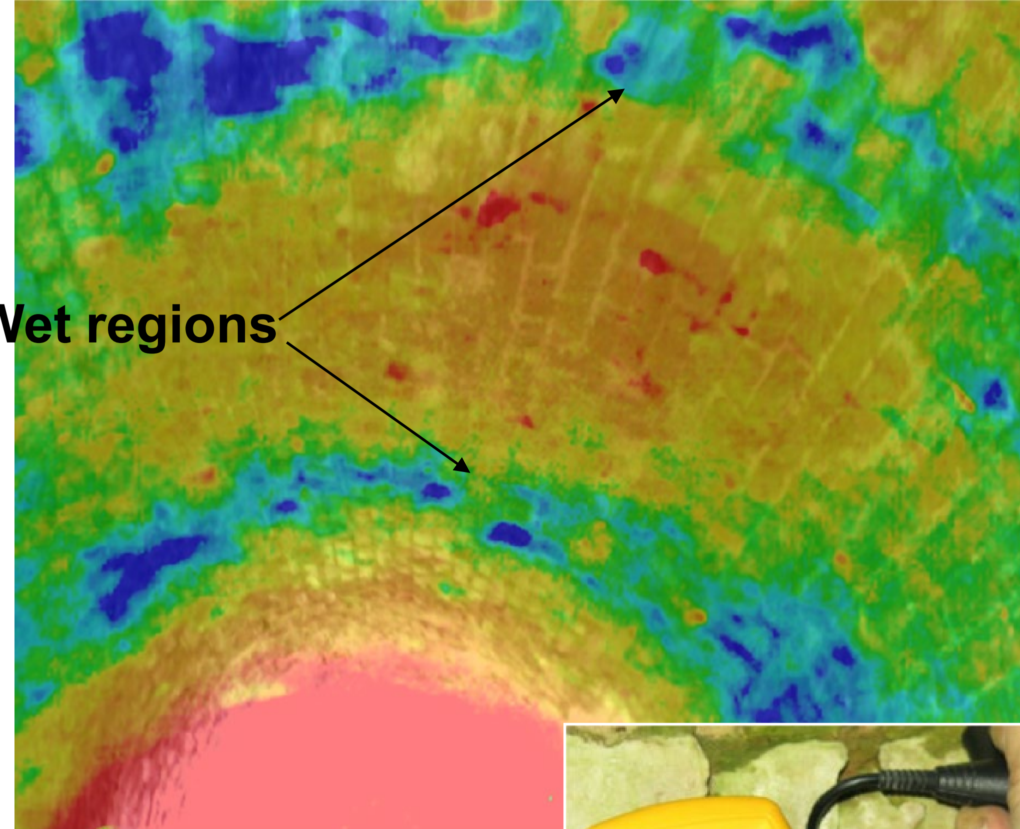
3D thermal image



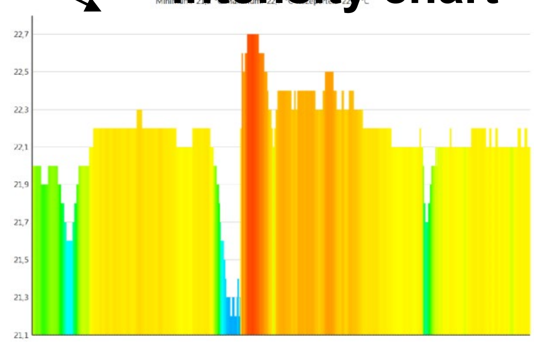
Delaminated surface



Wet regions

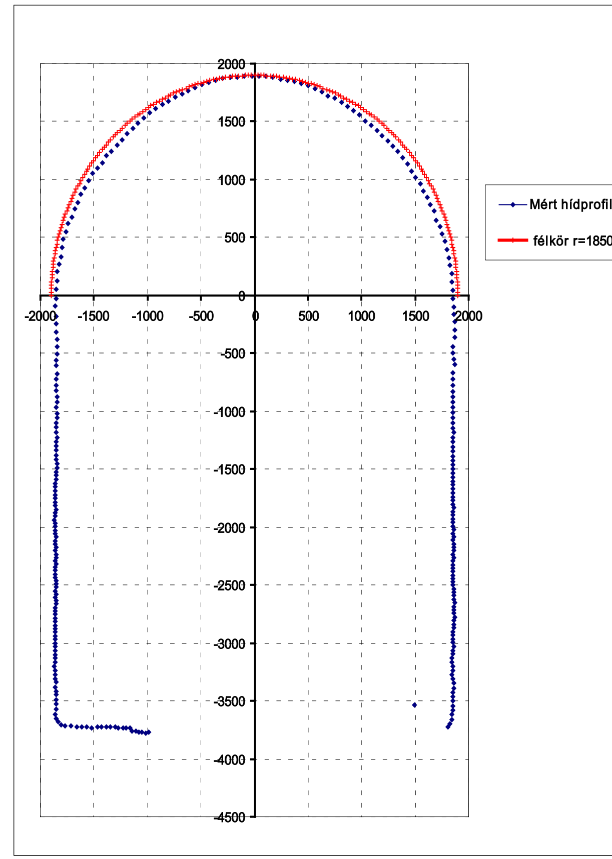


intensity chart

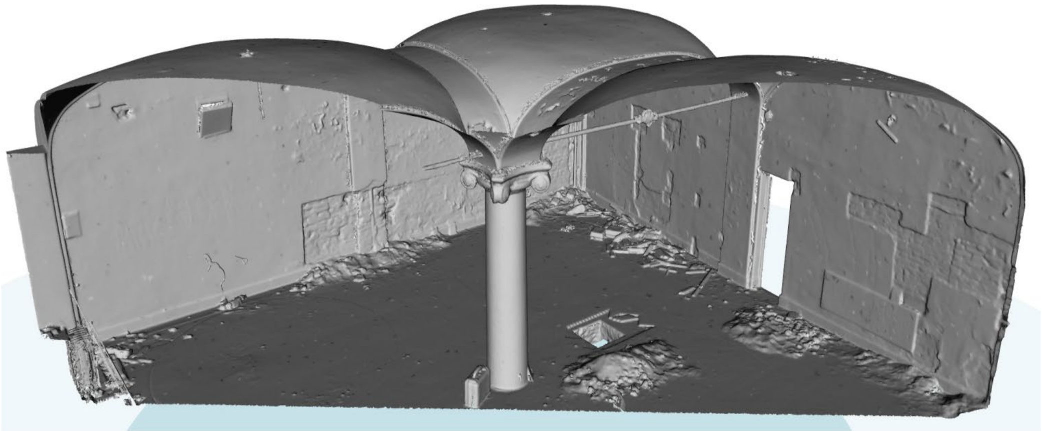


Non-Destructive Tests (NDT)

Laser profiling & 3D scanning



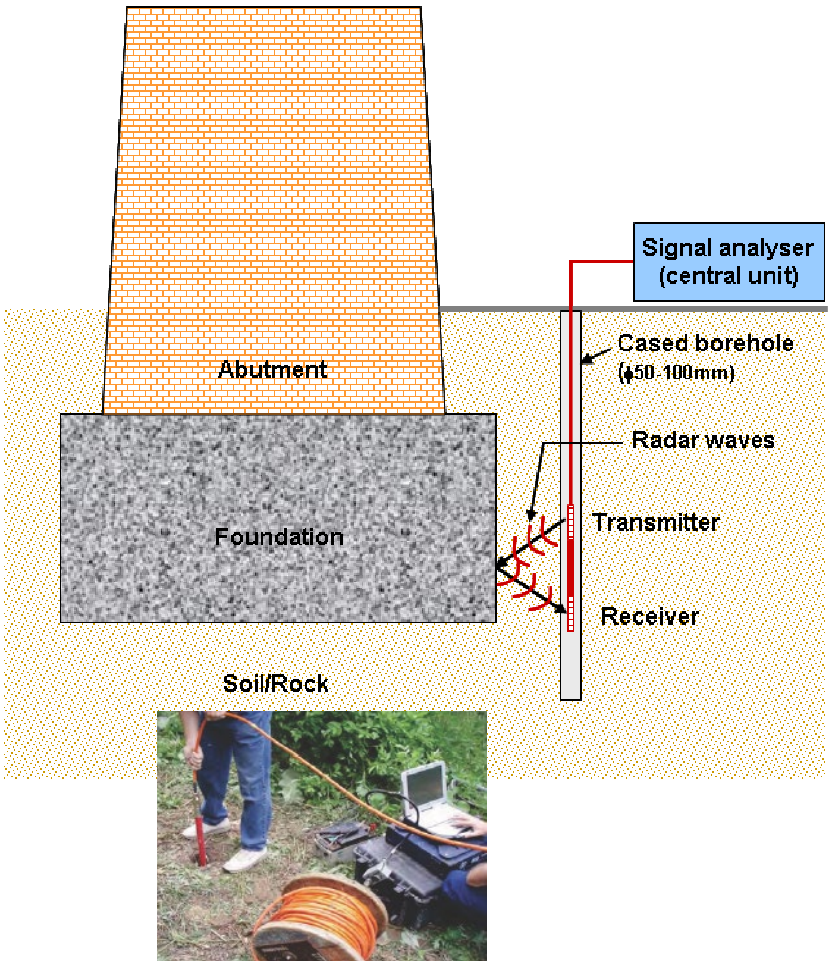
Laser profiling & 3D scanning



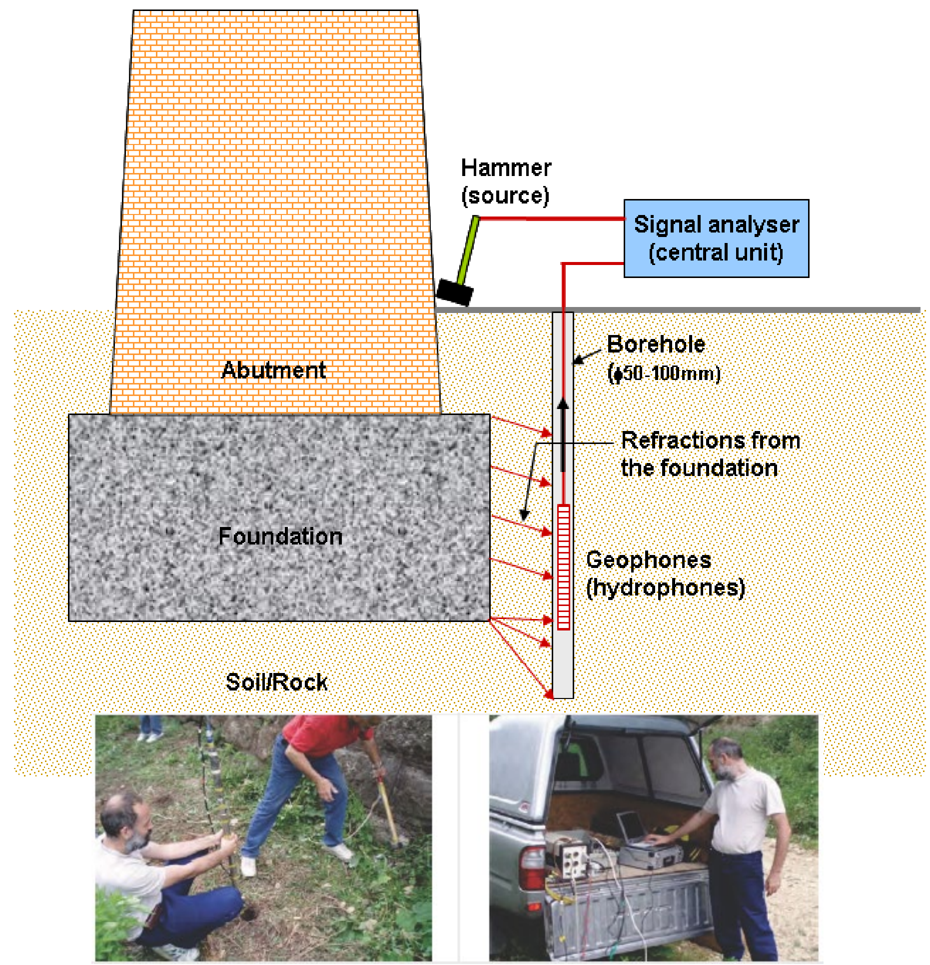
Laser profiling & 3D scanning

Mapping Foundations with NDT

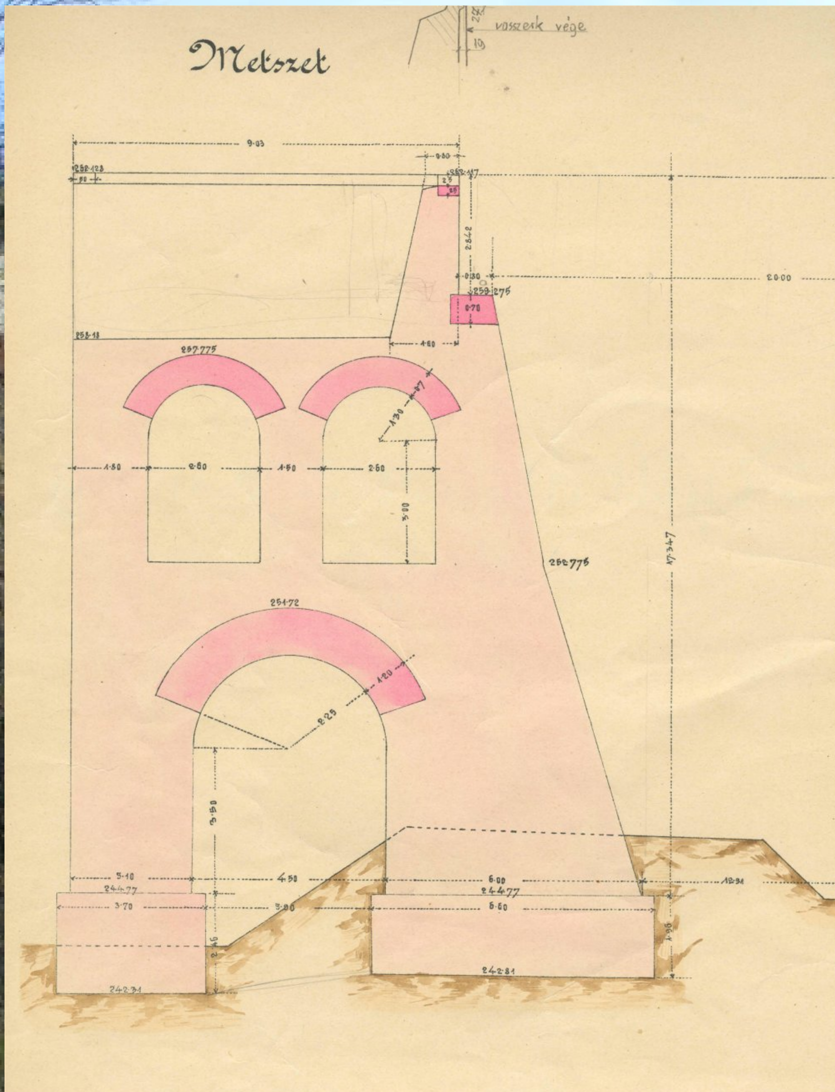
Borehole radar method



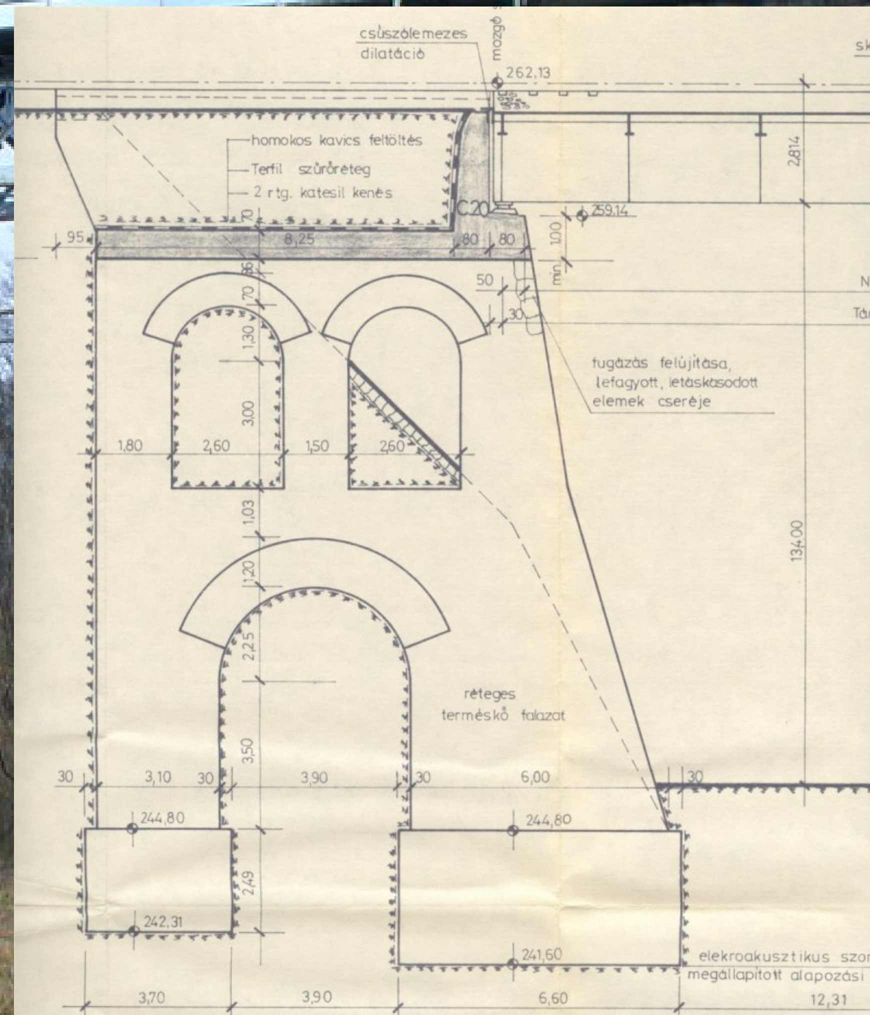
Parallel seismic method



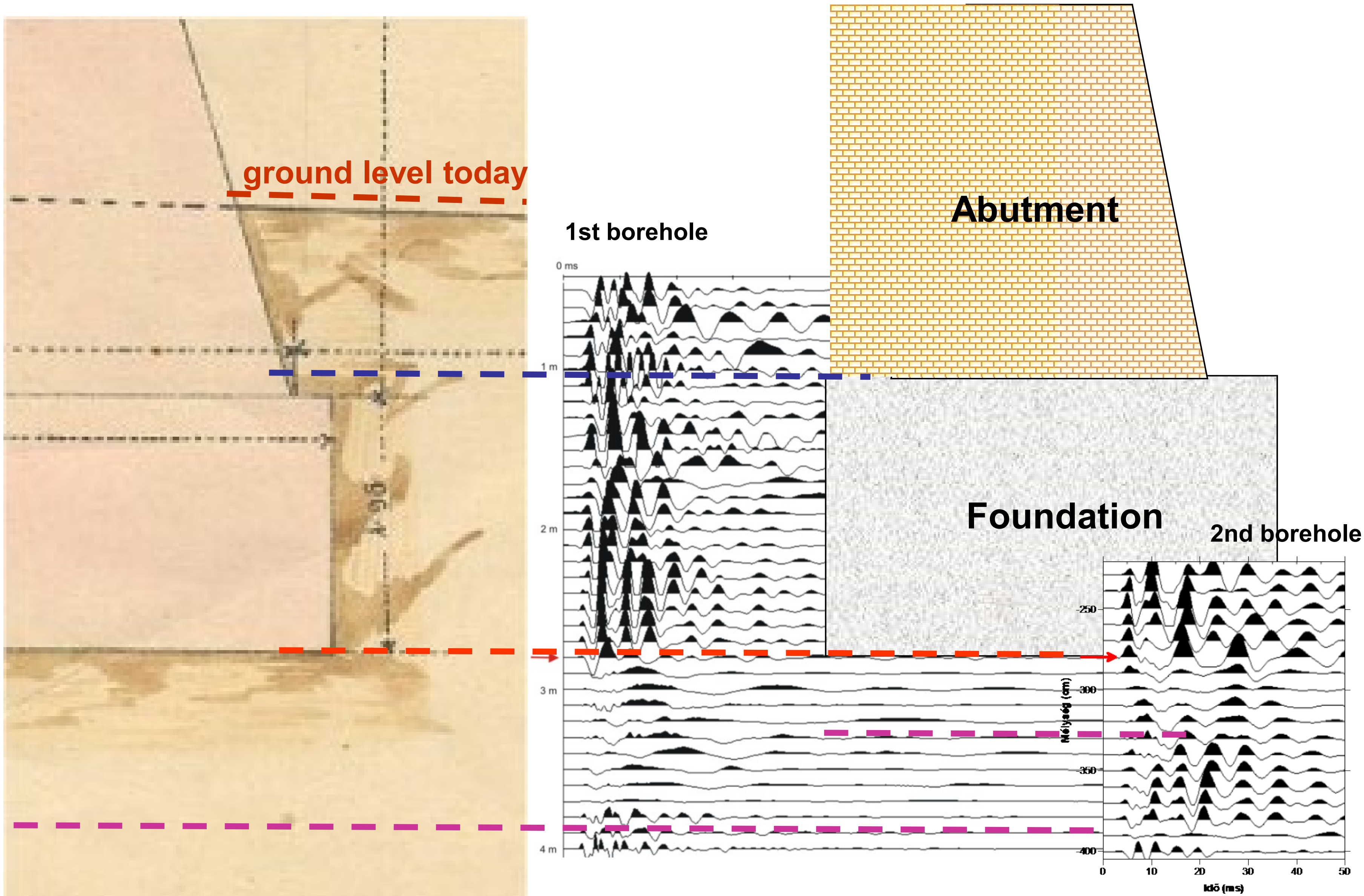
Field tests on a masonry abutment (Case Study)



Original plan



Reconstruction plan
(by later survey)



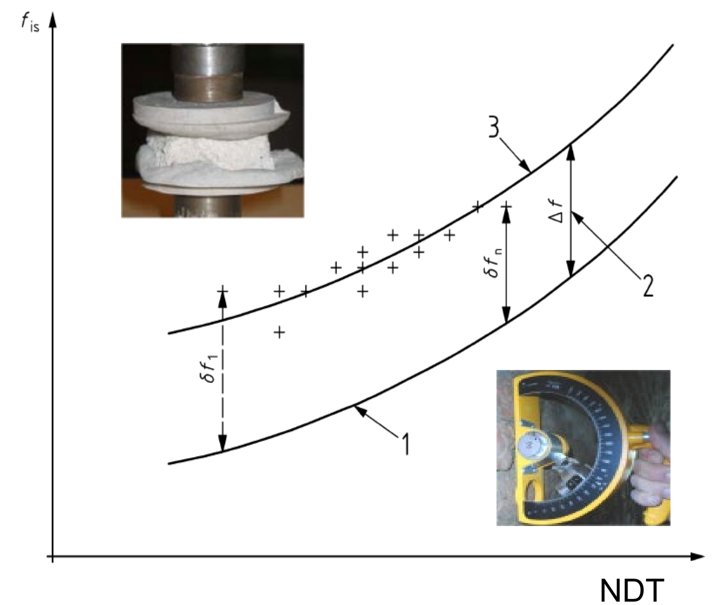
Interpretation of parallel seismic test results

Combination of test methods

Benefit:

The combination of techniques can improve the accuracy of estimation of properties or help reduce time to reach an answer.

- **Comparison of results to confirm measurements and recorded variations**
- **Comparison of results to improve the interpretation of results.**
- **Use of a "quick" technique to have a first rough mapping, followed by a second "slow" technique in the areas selected in the first step.**



Recommendations for use

Type of method	Name of method	Determinatin of construction materials	Testing mechanical properties	Testing physical or chemical properties	Survey of geometry (arch shape)	Survey of hidden geometry and features	Survey of defects	Validation of models	Overall view on bridge condition	Condition monitoring	Evaluation of the effects of intervention
		Purpose of measurement									
NDT METHODS	Sonic methods	3	3	3		2	2		2	3	2
	Georadar	3	3	2		2	2		2	3	2
	Infrared thermography	2	3	3		3	2		2	3	3
	Conductivity measurements	3	3	2		3	3		2	3	3
SDT METHODS	Coring and analysis of small diameter cores	1	1	1		2	3		3	3	1
	Boroscopy	1	3	3		1	2		3	3	1
	Flat-jack test		2					2	3	3	3
	Schmidt hammer rebound test	3	2				3		3		
	Penetration test on mortars	2	2	3			3		3	3	3
	Pull-out test	2	2	3					3		3
MONITORING METHODS	Hammer tapping	3	3	3		3	2		2	2	3
	Accoustic emmission						3	2	2	2	2
	Crack monitoring						3	3	3	2	3
	Laser profiling				1		2	3	2	2	
	Moisture monitoring		3	2		3	2		3	3	2
	Monitoring deformations and movements				3		2	2	3	2	2
	Dynamic monitoring (vibration test)						3	2	2	2	2

(UIC IRS 70778-3)

Application is recommended as:

1: Routine test

2: Supplementary test

3: Used only in special cases

Blank: not recommended

Conclusions

NDT can help assessment

- ⇒ Provides information on geometry and structural anomalies
- ⇒ Gives and overview on condition (and some material charact.)
- ⇒ Can increase confidence in input parameters and struct. model

Limitations

- ⇒ Strong reliance upon specialists
- ⇒ Correlation with mechanical parameters is limited

Combination of test methods is recommended

NDT can complement destructive tests but not replace