JCSS

Joint Committee
on Structural Safety

Workshop on Assessment of Existing Structures
28th and 29th January 2021

Novel Techniques Regarding the Assessment and Monitoring of Structures

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CONTENT

fib MC2020 - AG9 “SHM and ndt” General Aspects

SHM for integral bridges

COST TU1406 - SHM vs. Performance indicators – Lifetime Assessment

Lifetime Assessment – Durability Monitoring

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SHM for integral bridges

COST TU1406 - SHM vs. Performance indicators – Lifetime Assessment

Lifetime Assessment – Durability Monitoring

I. INTRODUCTION

Objectives of study

Monitoring system of bridge – general definition

Generally monitoring system can be defined as **arrangement of all activities that are performed with the goal to collect data for bridge condition assessment** as a background for competent management.

II. CONCRETE BRIDGE DEFECTS

- **Bridge defect** can be defined as a phenomenon diminishing bridge technical and/or functional condition as a result of a degradation process.

- Term **bridge technical condition** is used as a general measure of differences between current and designed values of bridge technical parameters, e.g. geometry, material characteristics, etc.

- Bridge **functional condition** can be defined as a measure of conformity between actual operational conditions and conditions required by users, e.g. load capacity, clearance, maximum speed, etc.

- Effective monitoring of structure condition requires **consistent taxonomy of** possible **structural defects**.

- **Classification of concrete bridge defects** is based on a three-level hierarchical system:
  - level 1: basic **classes of defects**;
  - level 2: **types of defects** defined for each basic class;
  - level 3: **categories of defects** proposed for each type of defects.

Deformation	Incorrect geometry of constructed element	Incorrect shape of concrete
		Invalid arrangement of reinforcement
		Invalid arrangement of prestressing tendons
	Change of the geometry of element axis	Excessive elastic deformation
		Permanent deformation
	Change of the geometry along the element length	Excessive elastic deformation
		Permanent deformation
Destruction of material	Change of the chemical characteristics	Change of concrete characteristics
		Change of reinforcing steel characteristics
		Change of prestressing steel characteristics
		Change of protective layer characteristics
	Change of the physical characteristics	Change of concrete characteristics
		Change of reinforcing steel characteristics
		Change of prestressing steel characteristics
		Change of protective layer characteristics
Loss of material	Loss of structural material	Loss of concrete
		Loss of reinforcing steel
		Loss of prestressing steel
	Loss of material of protective layer	Loss of material of concrete protection
		Loss of protection of reinforcing steel
		Loss of protection of prestressing steel
Discontinuity	Crack	Crack of concrete
		Crack of reinforcing steel
		Crack of prestressing steel
		Crack of protective layer
	Fracture	Fracture of concrete
		Fracture of reinforcing steel
		Fracture of prestressing steel
		Fracture of protective layer
Contamination	Inorganic	Aggressive
		Neutral
	Organic	Aggressive
		Neutral
Displacement	Incorrect linear displacement	Excessive movement
		Restricted movement
	Incorrect rotation	Excessive movement
		Restricted movement

III. DEGRADATION MECHANISM

- Concrete bridge structures are influenced by various degradation mechanisms causing defects, failures and even collapses.

- Final degradation processes of bridge structures or their elements consist usually of two or more mechanisms acting simultaneously.

- Degradation mechanisms can be generally divided into three groups:
  - **chemical mechanisms** – causing structure deterioration as a result of chemical processes: carbonation, corrosion, reactions between aggressive material components, etc.,
  - **physical mechanisms** – when deterioration is a consequence of physical phenomena: erosion, overloading, fatigue, crystallization, extreme temperatures, freeze-throw action, rheological effects, etc.,
  - **biological mechanisms** – in the case of deterioration aroused by biological organisms: microbes, plants, animals, etc.

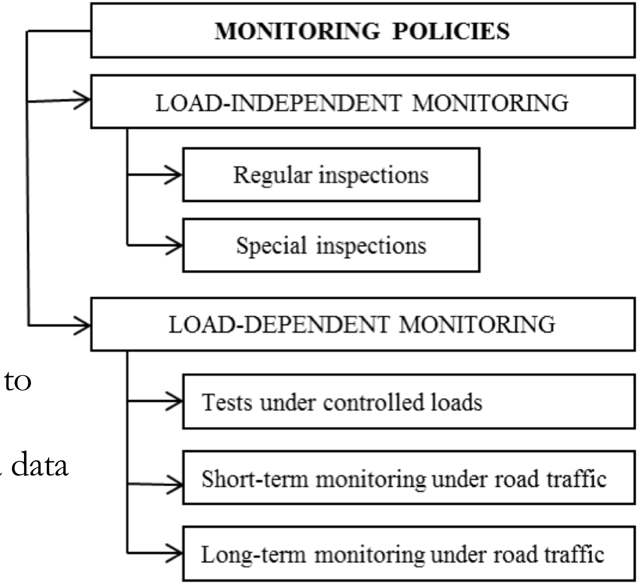
Degradation mechanisms		Class of defects					
		deformation	destruction	loss of material	discontinuity	contamination	displacement
Physical	Accumulation of inorganic dirtiness		□	□		■	■
	Cyclic freeze-throw action		■	■	□	□	
	Erosion		□	■			
	Crystallization		■	□	□		
	Extreme temperatures	□	□	□	□	□	□
	Creep	□					
	Relaxation	□			□		
	Shrinkage	□	□	□	■		
	Overloading	■	□	■	■		■
	Fatigue		■		□		
	Geotechnical condition changes	■		□	■		■
Chemical	Carbonation		■				
	Corrosion	□	■	■	□	□	
	Aggressive compounds action		■	□		□	
	Chemical dissolving/leaching		■	□		■	
	Reactions between material components	□	■	■	□		
Biological	Accumulation of organic dirtiness		□	□		■	□
	Activity of microbes		□	□		■	
	Activity of plants	□	□	□	□	■	□
	Activity of animals		□			□	

Legend: ■ – basic degradation mechanism, □ – additional degradation mechanism

IV. MONITORING STRATEGIES

Categories of monitoring policies

- **Load-independent monitoring** – comprises regular as well as irregular (special) inspections based on visual examination and results of the non-destructive testing (NDT) and/or semi-destructive testing (SDT).
- **Load-dependent (technical) monitoring** – includes observing of bridge structure response to loads by means of installed technical measuring equipment. A **technical monitoring** system is a data acquisition and processing unit which provides continuously and autonomously real-time information about a structure or structural component.



Technical monitoring is based on:

- application of transducers for sensing physical or chemical quantities,
- programmable electronic equipment for acquiring, processing and communicating data,
- utilization of algorithms that define how data acquisition, processing and communication is performed.

Assessment goals	Type of technical monitoring
Assessment of the magnitude as well as the spatial and temporal distribution of specific forces acting on a structure or a structural component, including traffic loads and environmental impacts.	**Action monitoring**
Assessment of the state of displacement, stress/strain level and distribution in a structure as well as vibration parameters caused by traffic loads and other influences.	**Reaction monitoring**
Assessment of whether a structure or a structural component meets the performance requirements under specific or any actions, defined by the performance indicators.	**Performance monitoring**
The real-time assessment and prediction of the health condition of a structure or a structural component by means of their safety and ser-viceability indicators.	**Health monitoring**

SHM for Integral Bridges
in Austria with Flexible Abutments

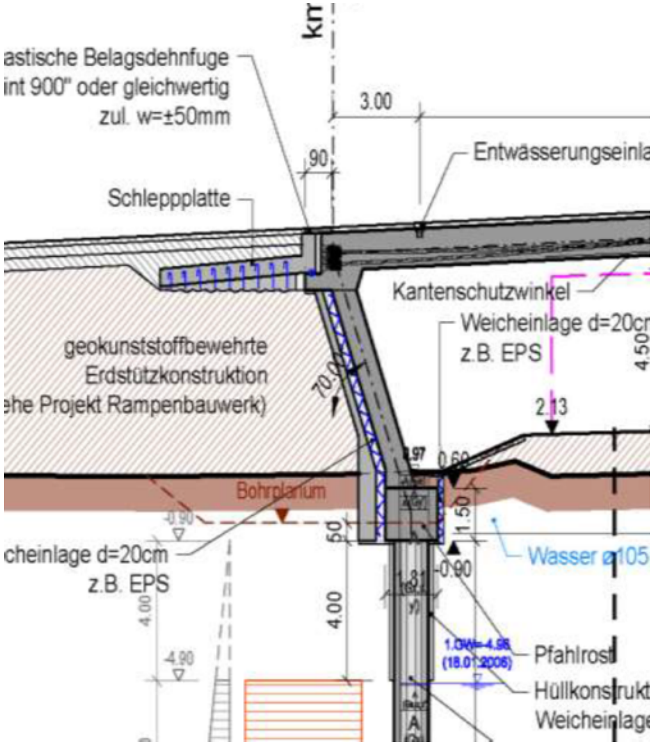
Alfred Strauss; Roman Geier; Thomas Mack

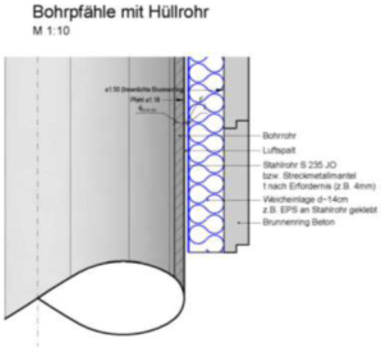
Problem Areas

Subsequent Damage

Subsequent Damage

New Design Issues





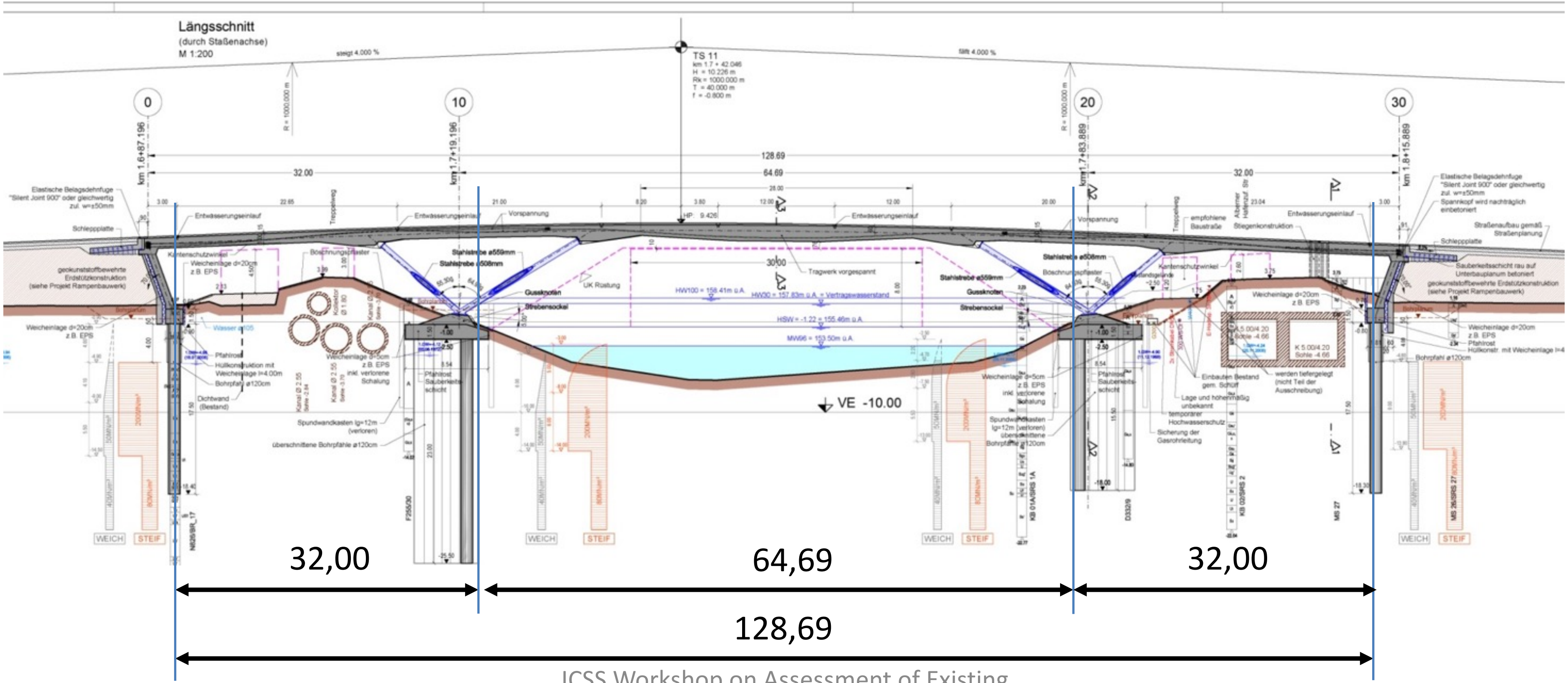
3 Statements

- Monitoring may not replace conventional inspection. It should be used as a powerful supplement:
  - Objective assessment based on measured data
  - Immediate action for improved knowledge about structural condition
- To observe known problems or damages and their changes over time (development of structural condition):
  - Focus on specific problem
  - Tailor-made monitoring system for the given task (costs!)
  - Surveillance until rehabilitation or replacement
- Verification of static calculation or input parameter for further investigations:
  - Comparison of design assumptions with real structure
  - Calibration of finite element models to real structural behavior
  - Documentation of construction period or specific loading conditions

Monitoring – Guideline RVS 13.03.01

- Monitoring of bridges and other civil engineering structures
- Measurement based investigations
- Different parameters which are under investigation:
  - Static: Deformation, Inclination, Strain, etc.
  - Dynamic: Acceleration (Vibration measurements)
- Global vs. local testing methods:
  - Global: a few measurement locations are sufficient to describe structural behavior or condition
  - Local: targeted investigation of a limited structural area or element
- Permanent or event driven measurements
- Comparative calculation with FE-simulation

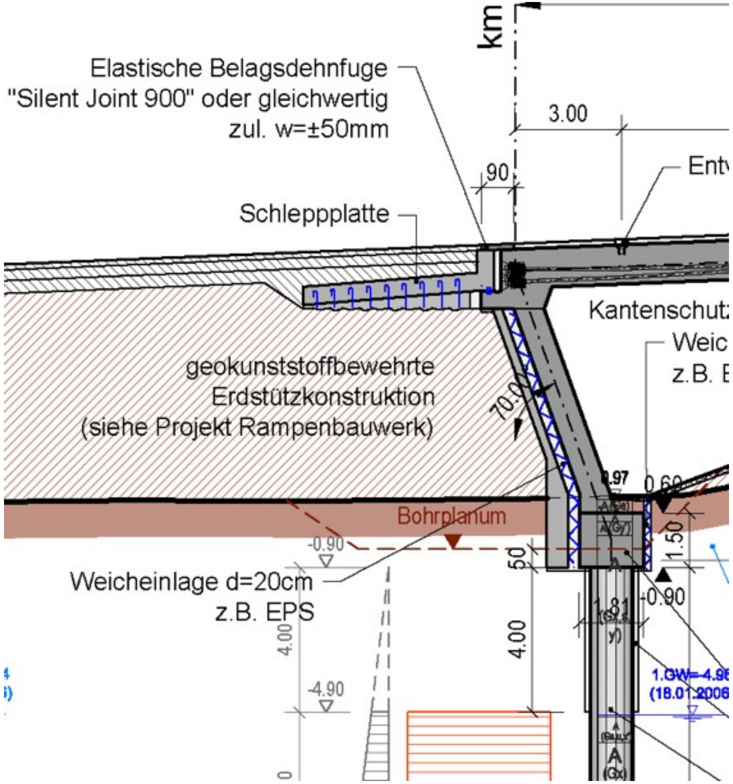
Seitenhafenbridge



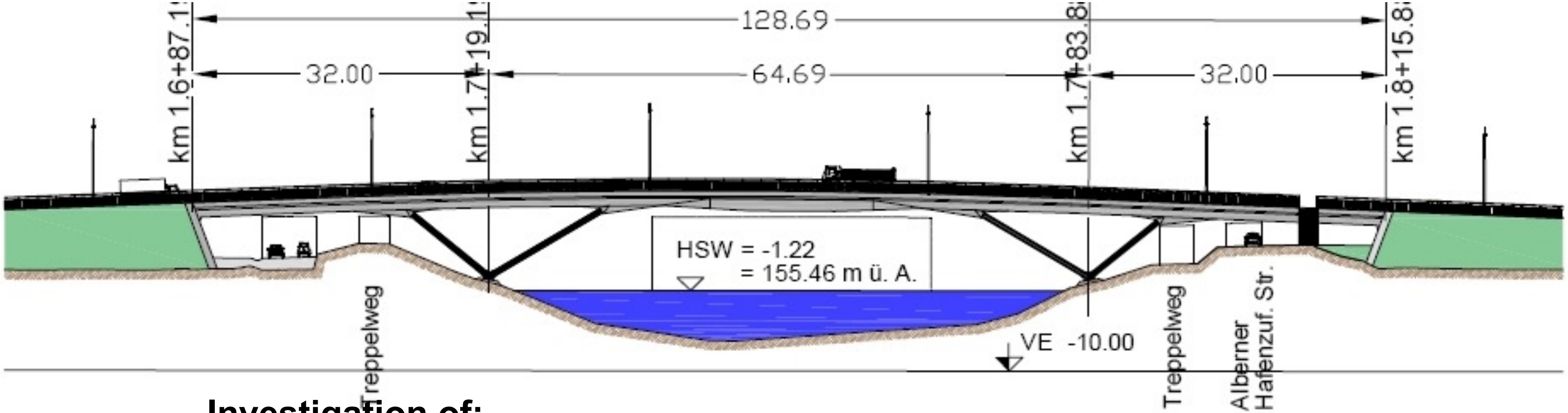
Realized Structure

Characteristics Seitenhafenbridge

- Semi-integrale structure with length of 130 m
- Structure: reinforced concrete slab resp. T-beam on steel columns and nodes
- Structure is post tensioned for all spans
- Concept of flexible abutment (first in Austria and currently the longest one in Europe)
- Pile foundation with flexible casing



Measurement Task

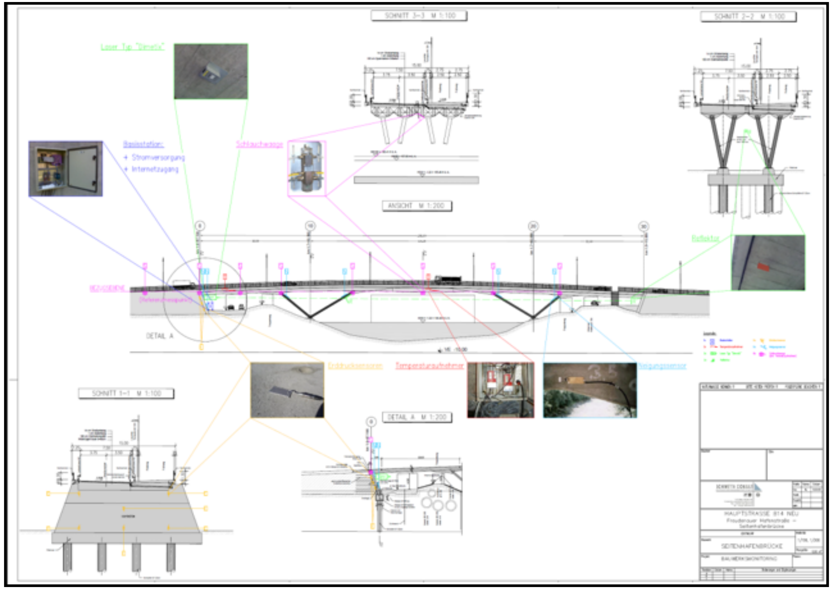


Investigation of:

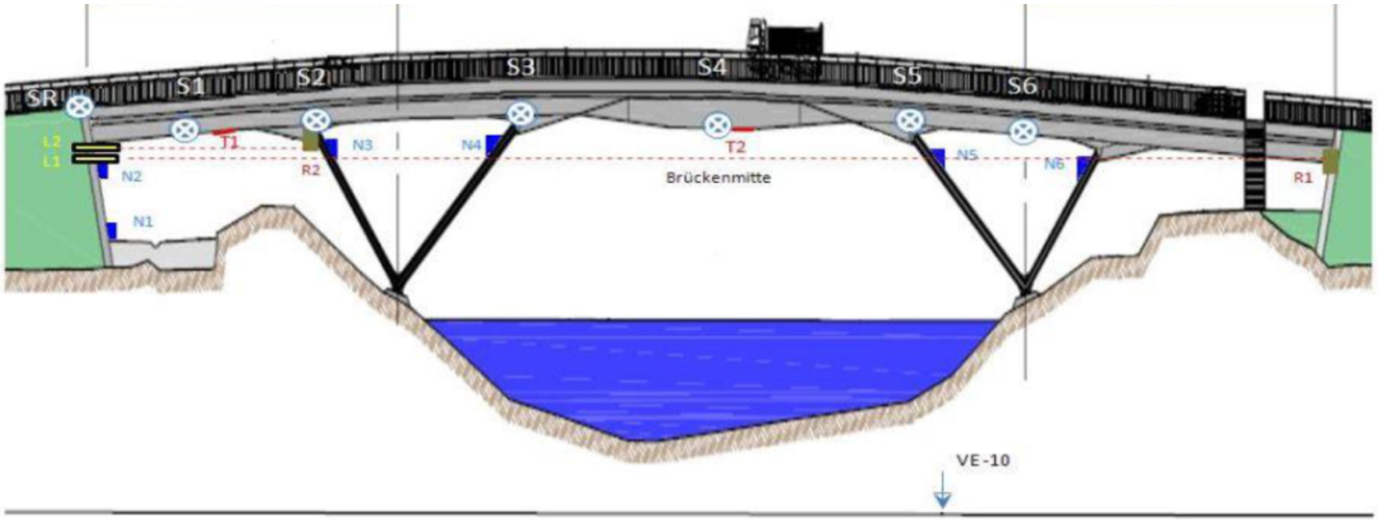
- Structural temperature
- Investigation of earth pressure (flexible abutment)
- Alternation of length
- Vertical deflection of selected locations
- Observation of changes in inclination of selected locations
- Data storage & transmission
- Regular reporting with regard to design assumptions

Tender Process

- Monitoring system was included in the tender for the bridge
- Tender design was prepared including specifications of sensors
- Detail design was already considering monitoring equipment



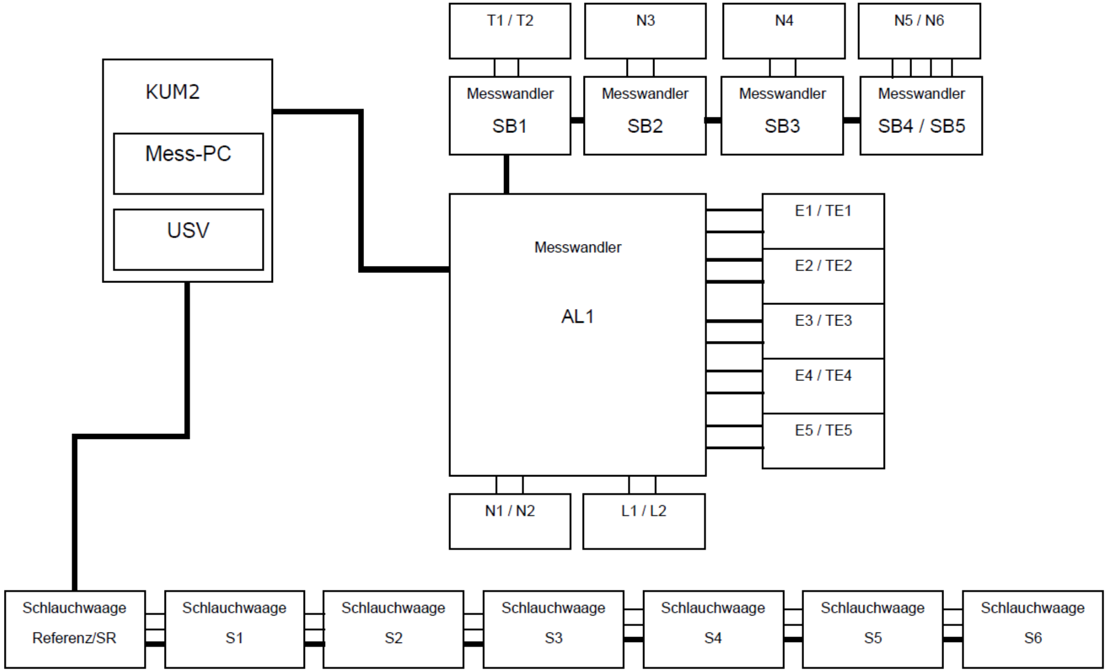
Measurement Task



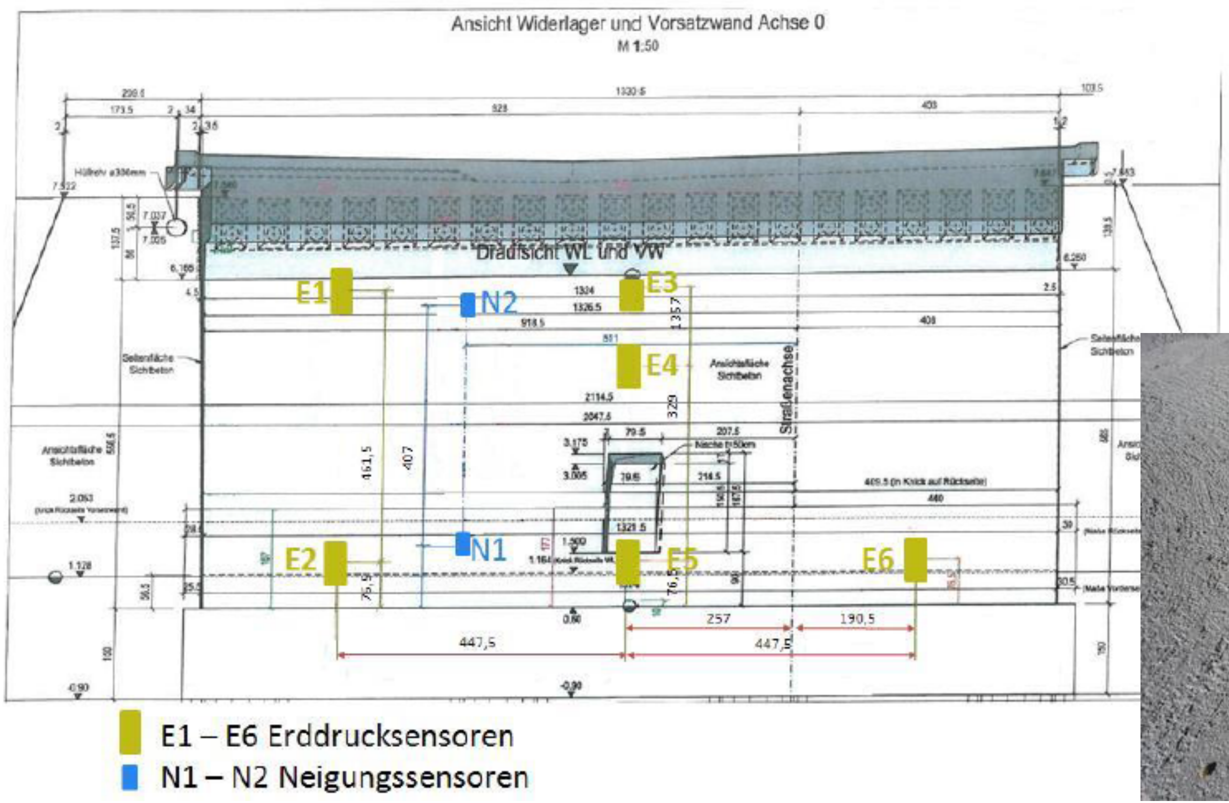
SR, S1 – S6 .... Deformation Sensors
N1 – N6 .... Tilt Sensors
T1, T2 .... Temperature Sensor

L1, L2 ..... Laser Distance Unit
R1, R2 ..... Passive Reflector

Central Unit & System Architecture



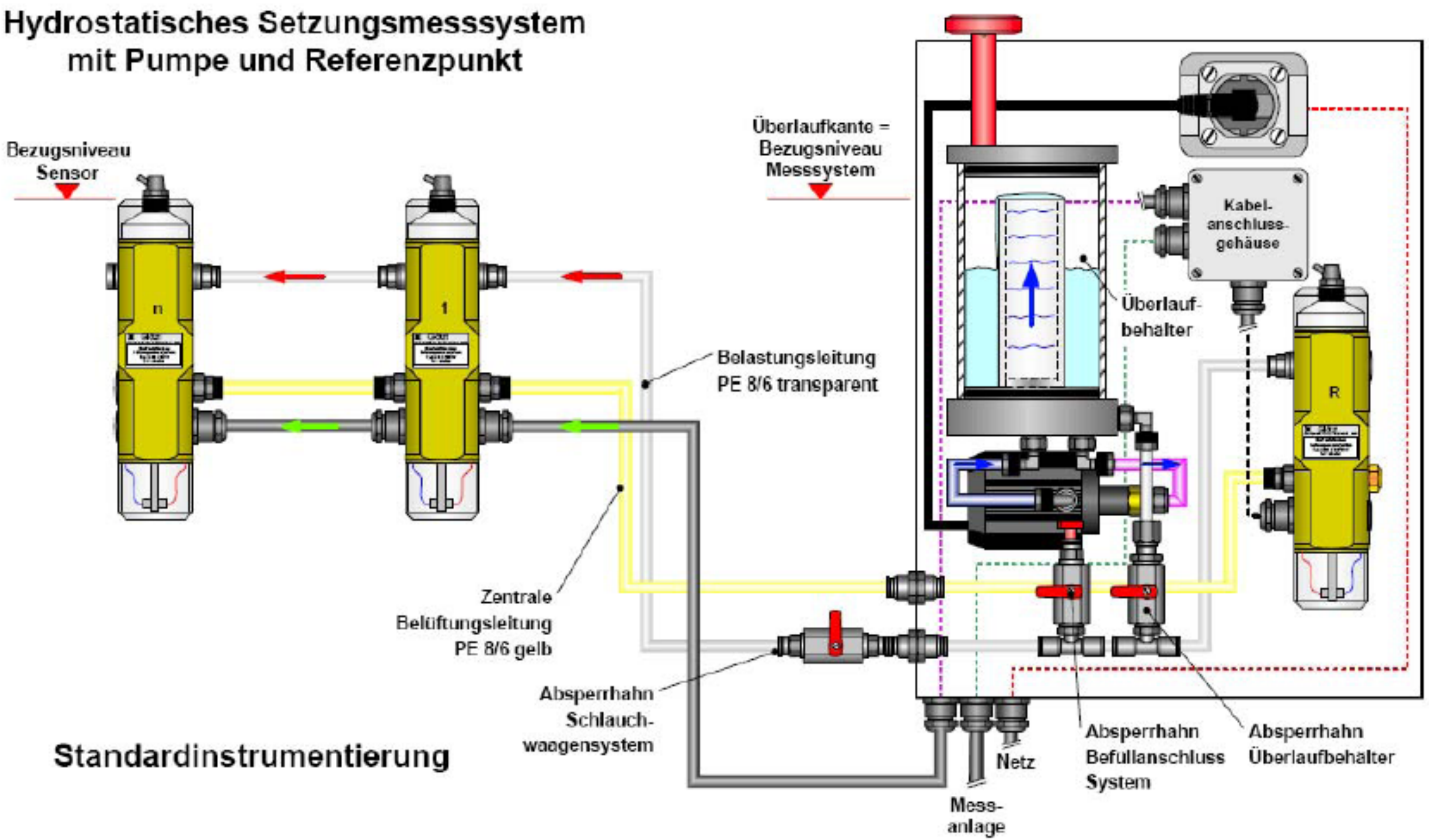
Earth Pressure Sensors



Laser Sensors

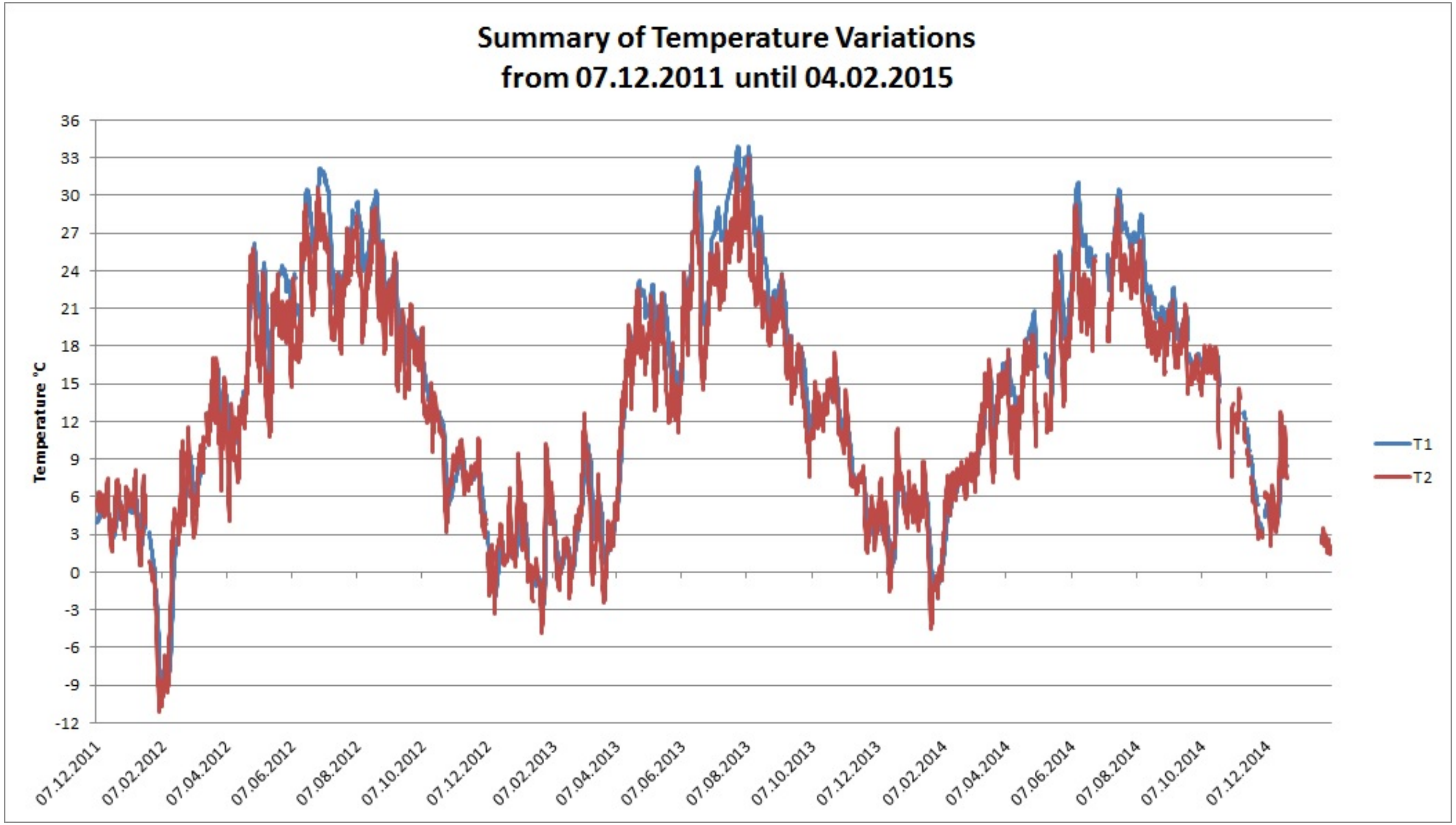
Passiv Reflecting Units

Deformation Measurement

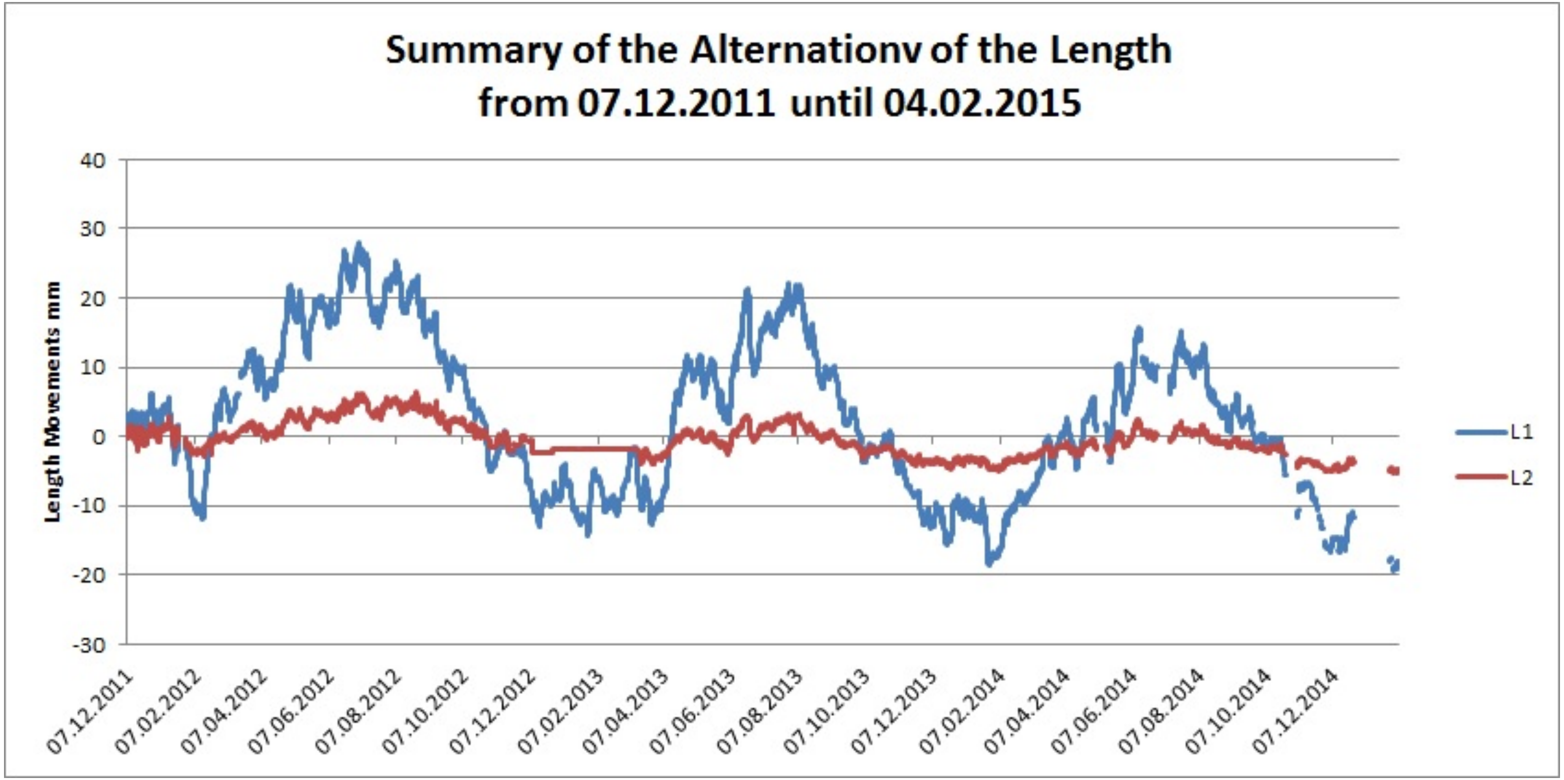


Hydraulic Levelling System

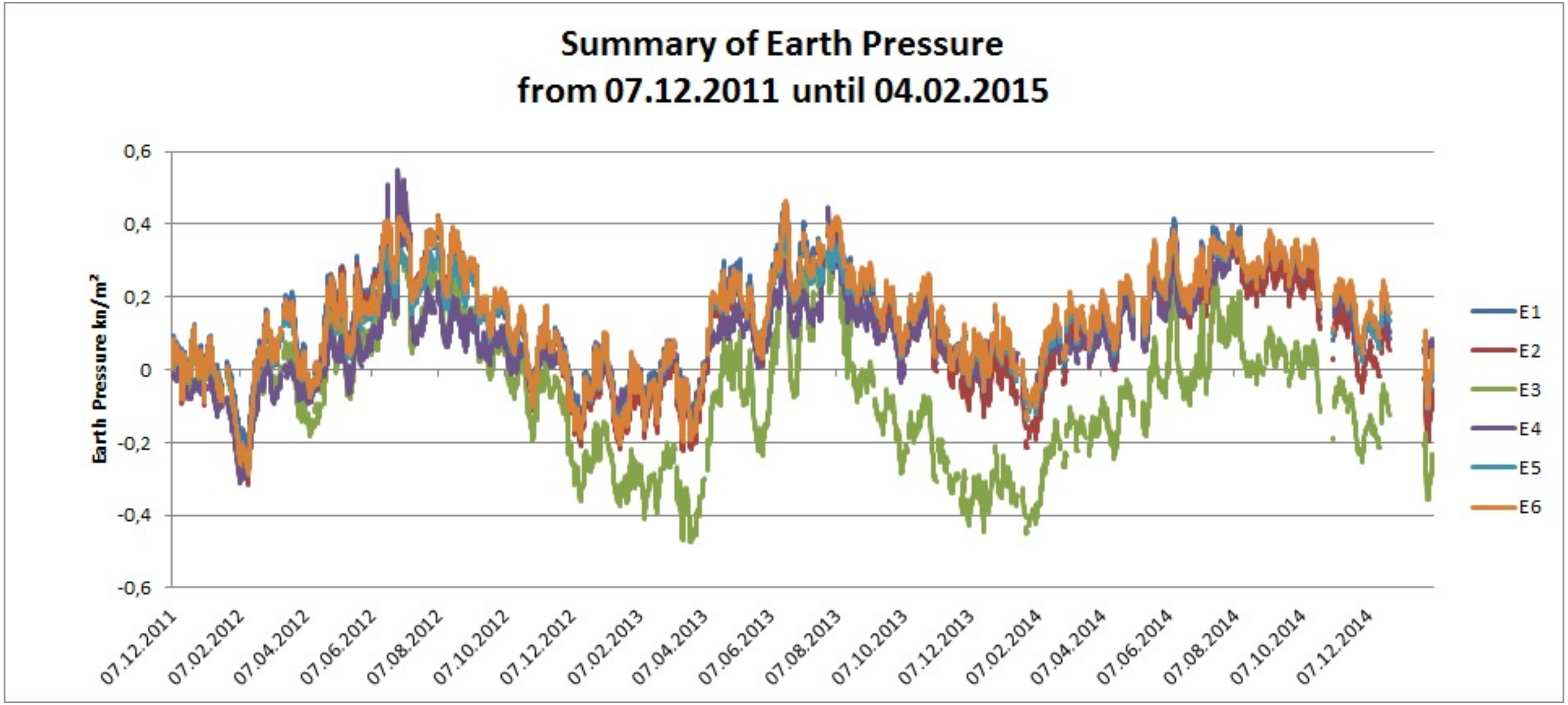
Temperature Measurements



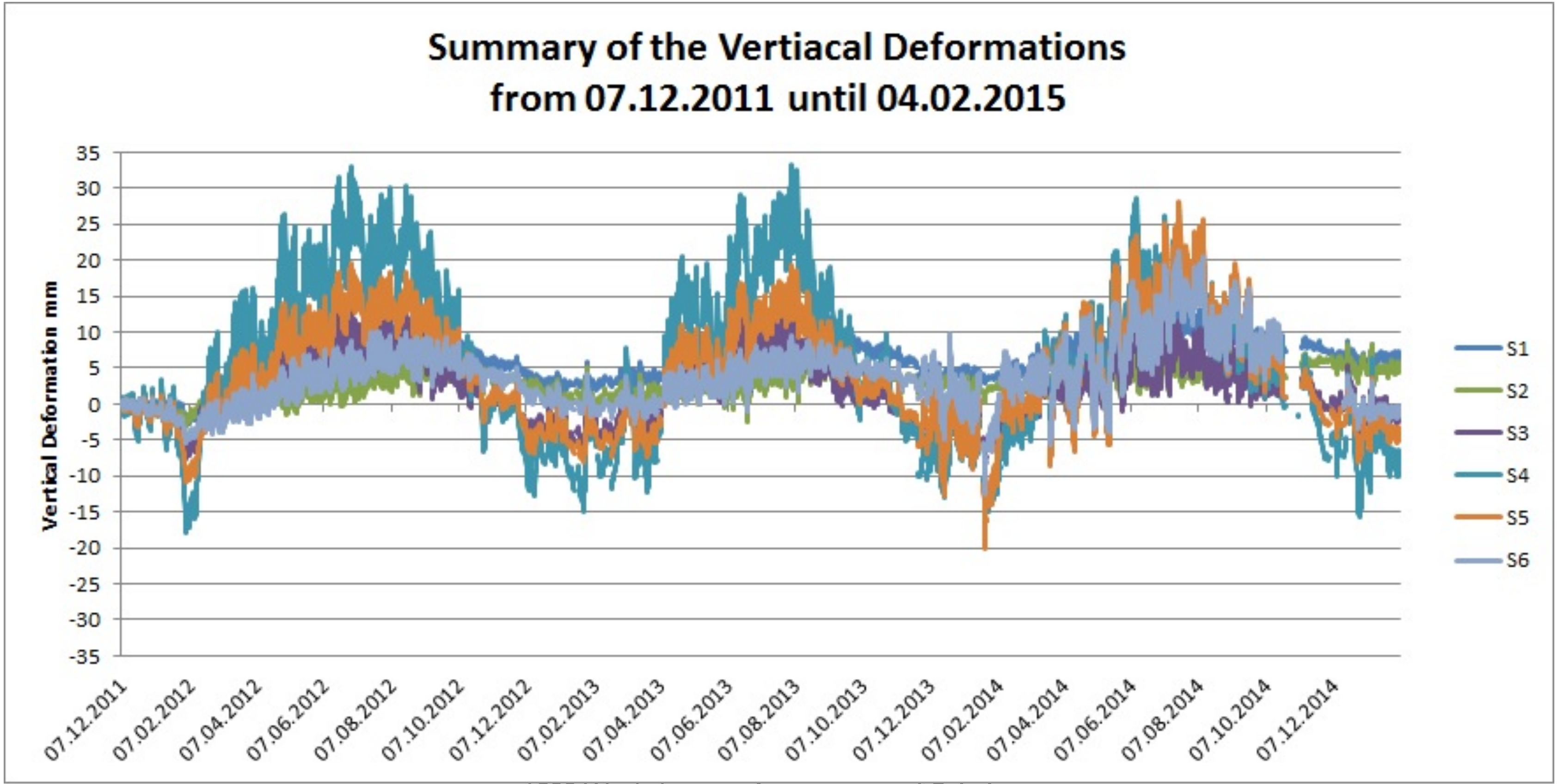
Alternation of Length



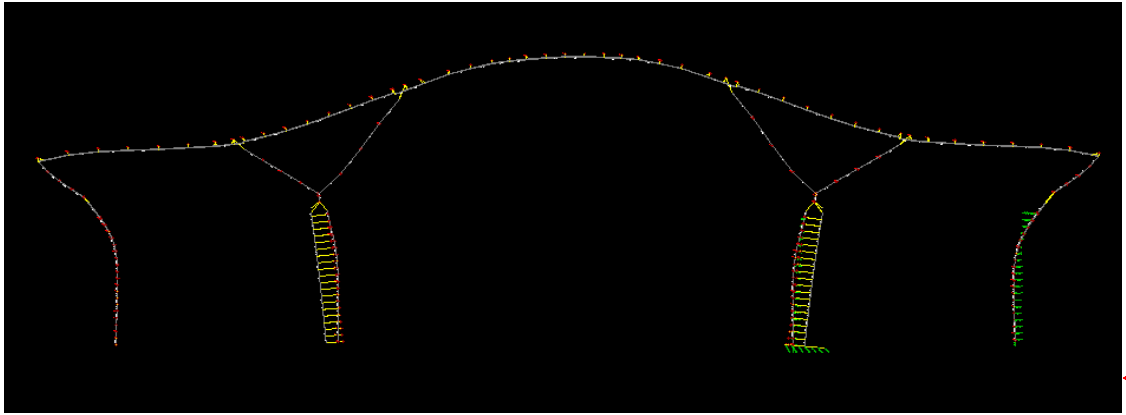
Earth Pressure

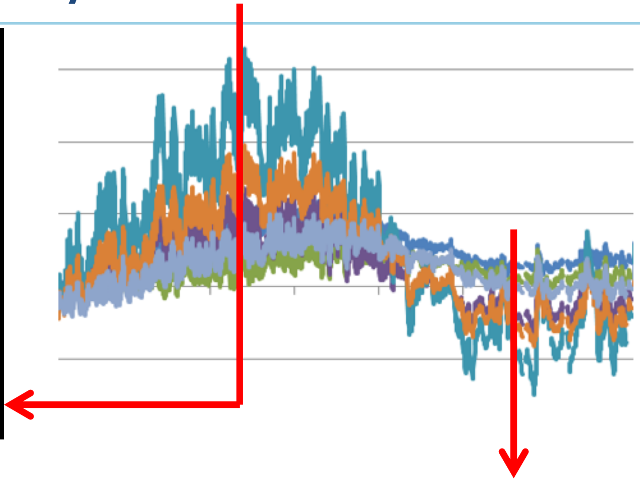


Vertical Deformation

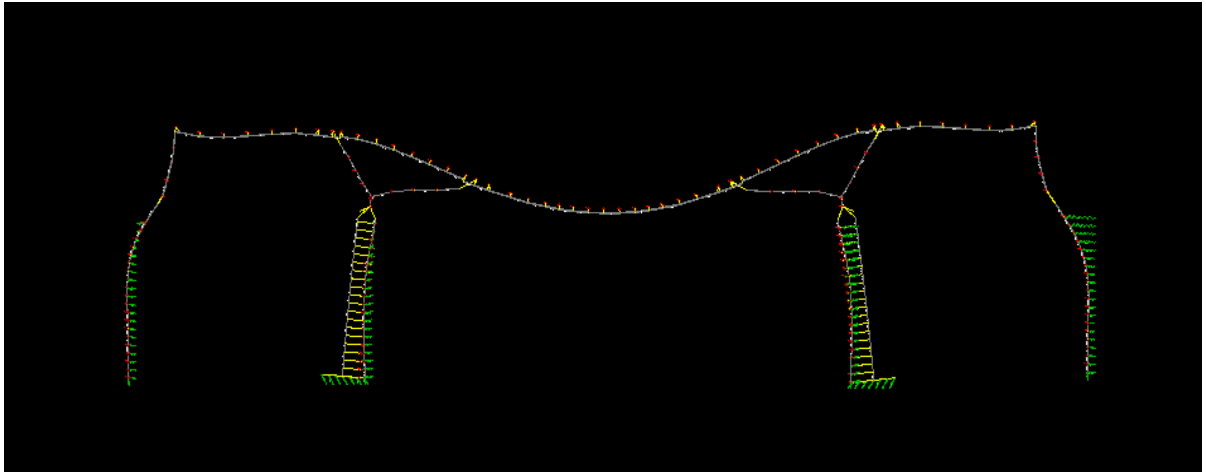


Finite Element Analyses



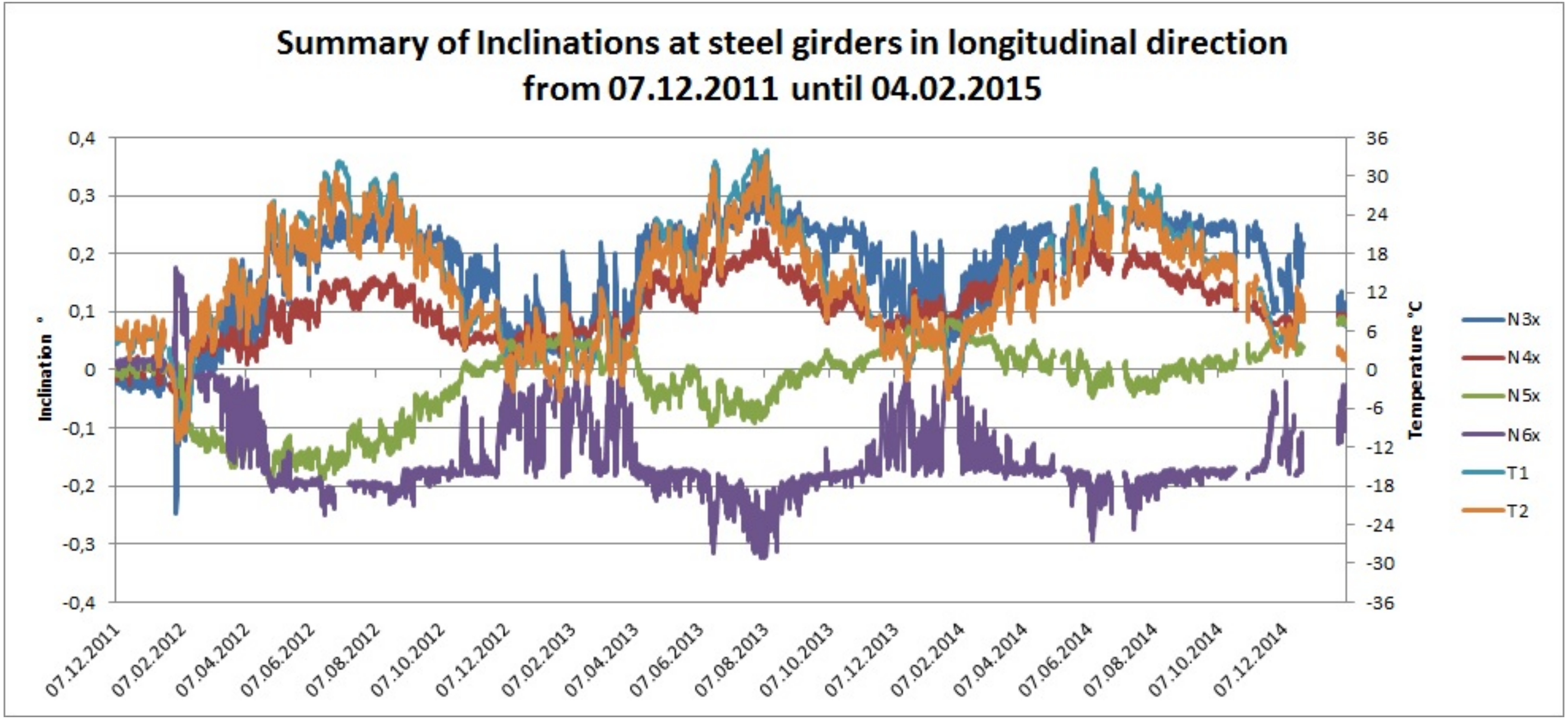


Summer



Winter

Inclination



Measurement Results

Measurement Parameter	Calculation		Measurement		Condition
	Max.	Min.	Max.	Min.	
Temperatur	+39°C	-18°C	+34°C	-11°C	
Alternation of Length	+50mm	-50mm	+28,5mm	-18,5mm	
Earth Pressure at Abutment	50 kN/m²		1,0 kN/m²		
Vertical Deformation	63 mm		57 mm		
Inclination Steel Columns and Abutment	+0,3	-0,3	+0,3°	-0,3°	

Summary

- Seitenhafenbridge:
  - Monitoring system is working since start for operation in 2011
  - Reporting and maintenance is awarded in regular intervals by client
  - System has shown that the structure behaves as assumed
  - Monitoring improves understanding and may influence future design

COST TU1406 Quality specifications for roadway bridges, standardization at a European level

Performance indicators, lifetime assessment – ?Monitoring?

Alfred Strauss, Jose Matos, Joan Casas, Rade Hajdin

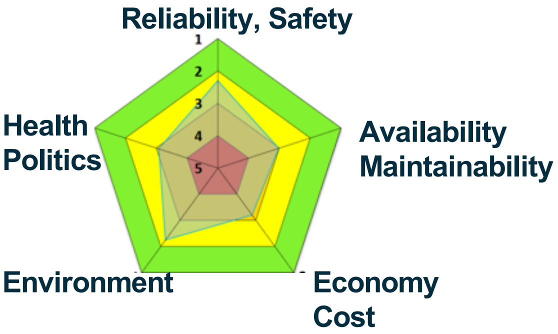
Past achievements

Key Performance Indicators, KPI's

KPIs relate to a whole bridge and are as follows:

- **Reliability** is the probability of structural failure (safety), operational failure (serviceability) or any other failure mode occurring during the service life of the bridge.
- **Availability** is the proportion of time a bridge is open for service. It does not include failure-related service outages but the ones due to planned maintenance interventions. Alternatively, the Availability can be measured as additional travel time due to an imposed traffic regime on bridge.
- **Safety** is the situation of life and limb being protected from harm during the service life of a bridge. Loss of life and limb due to structural failure is not included by this definition (since it would overlap with the Reliability).
- **Economy** is related to minimizing the long-term cost of maintenance activities over the service life of a bridge.
- **Environment** is related to minimizing the harm to environment during the service life of a bridge.

KPI_r	**Reliability**		$r = 3$
PI_6	displacement	weights	2
PI_3	cracking		3
	…		
PI_{13}	…		3
Component, k; System		α_{ik}	r_i



KPI_s	**Safety**		$s = 3$
PI_1	absence/missi	weights	3
PI_4	…		3
	…		
$PI_{…}$	…		3
Component, k; System		α_{ik}	s_i

KPI_E	**Economy**		$e = 3$
PI_{18}	maintenance	weights	3
PI_{15}			3
	…		
$PI_{…}$	…		3
System		α_i	e_i

KPI_a	**Availability**		$a = 3$
PI_{15}	deflection	weights	3
PI_2	…		3
	…		
$PI_{..}$	…		3
System		α_i	a_i

KPI_U	**Environment**		$u = 3$
PI_{23}	CO_2 footprint	weights	1
PI_{24}	…		3
	…		
$PI_{…}$	…		3
System		α_i	u_i

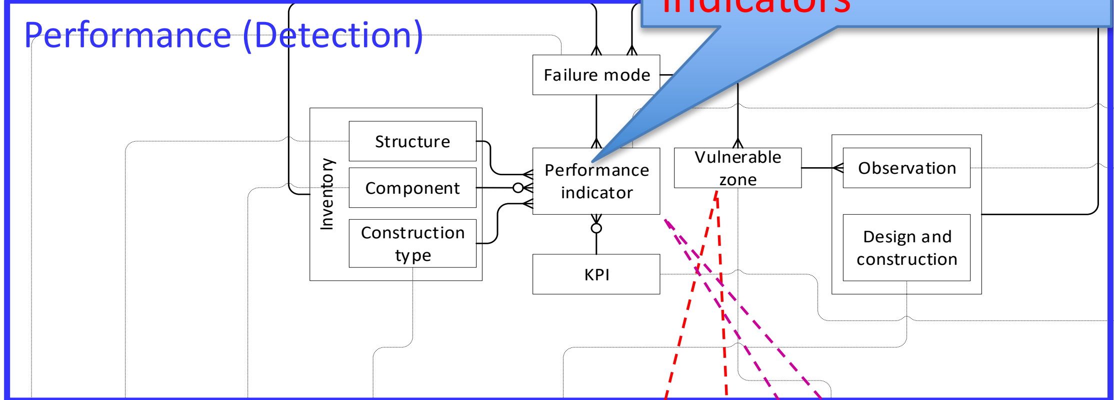
Performance (Detection) to Key Performance (Life Cycle Cost & LCA):

Strategic KPI's-based Decision-making Processes

Past achievements

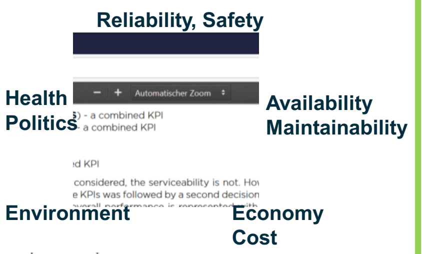
SHM vs. Performance indicators

Performance (Detection)



Key Performance

Asset Management Life Cycle Cost & LCA



Frame bridge	Deck (old)	Reinforced concrete	1963	Bending failure mode	HMS	Corroded reinforcement	Reliability (Structure safety)	3	3	15 years
	Deck (new)	Reinforced concrete	1977			Corroded reinforcement				
	Deck (old)	Reinforced concrete	1963			Spalling				
	Deck (new)	Reinforced concrete	1977			Spalling				
	Deck (new)	Reinforced concrete	1977		HMH	Corroded reinforcement				
	Deck (old)	Reinforced concrete	1963			Corroded reinforcement				
	Deck (new)	Reinforced concrete	1977			Spalling				
	Deck (old)	Reinforced concrete	1963			Spalling				
	Deck (new)	Reinforced concrete	1977			Efflorecences				
	Deck (old)	Reinforced concrete	1963			Efflorecences				
	Deck (old)	Reinforced concrete	1963	Shear failure mode	HSS	Crack		2		
	Deck (old)	Reinforced concrete	1963	Falling chunks		Spalling	Safety (Life and limb)	2	2	40 years
	Deck (new)	Reinforced concrete	1977			Spalling				
	Railings	Steel	1977	Falling of the bridge		Broken		2		

Performance (Detection) to Key Performance (Life Cycle Cost & LCA):

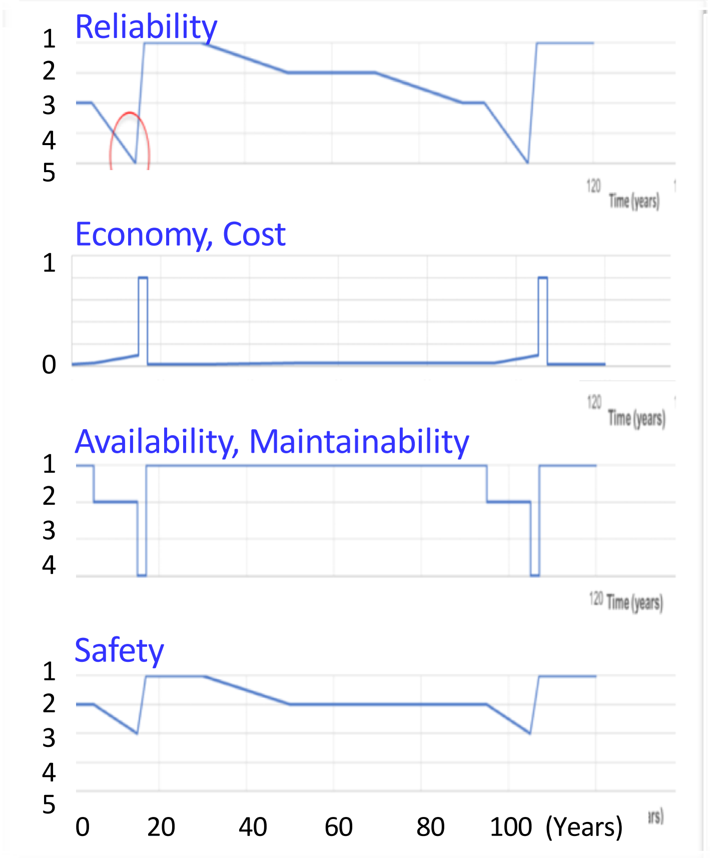
Quality Control Plan based on Key Performance Indicators for a Sustainable Asset Management

R. Hadin COST TU 1406

Past achievements and future vision

Maintenance Scenarios
Preventative

Asset Management
Life Cycle Cost & LCA



R. Hadin COST TU 1406

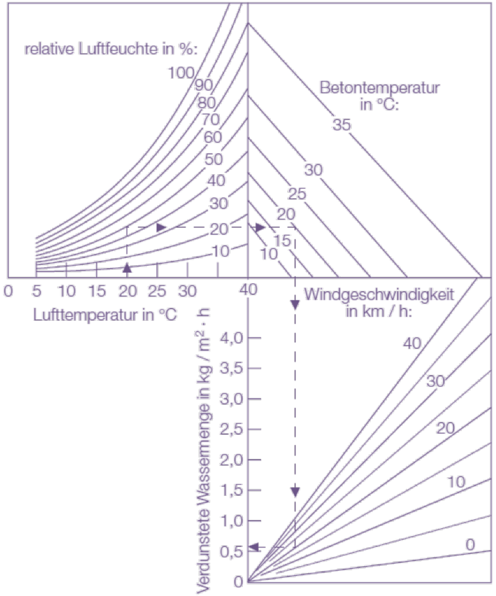
Maintenance Scenarios (Sustainability based)

Deterioration Processes – Prediction Methods – Digital Twin Approaches

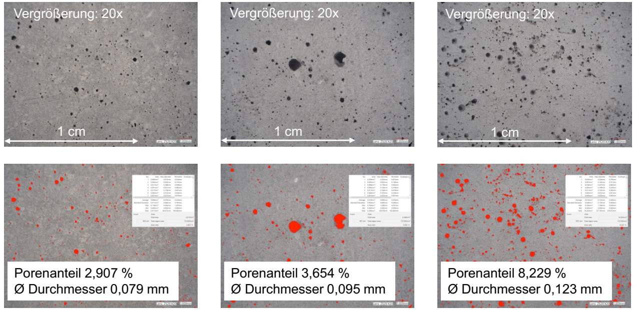
Lifetime Assessment – Durability Monitoring
Curing Issues

Alfred Strauss, BOKU
Martin Peyerl, SMART Minerals

Post-treatment of concrete

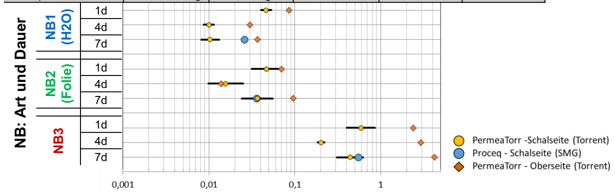


MICROSCOPY



GAS PERMEABILITY

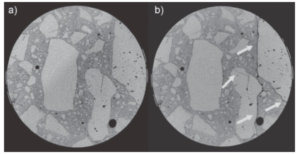
Oberflächenzustand	Sehr gut	Gut	Mittel	Schlecht	Sehr schlecht
Gaspermeabilität	Sehr niedrig	Niedrig	Mittel	Hoch	Sehr hoch

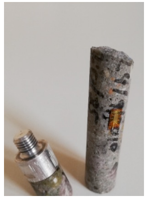


- Höhere GP bei schlechterer Nachbehandlung, insb. für längere NB-Dauer
- Höchste GP bei 1d NB-Dauer, für alle NB-Arten → Einfluss der Trocknung
- Höhere GP der Oberseite im Vergleich zur Schalseite
- **NB1** oder **NB2** im Alter von 7d → (sehr) guter Oberflächenzustand
- **NB3** im Alter von 7d → mittelmäßiger Oberflächenzustand

COMPUTER TOMOGRAPHY

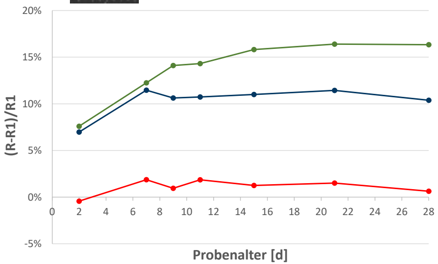
- Porositätsanalyse
- Schadens- und Versagensanalyse (z.B. bei Oberflächenzugfestigkeitsprüfung von Beton)
- Analyse von Rissen in Korn, Zement bzw.
- Grenzflächen
- Analyse Risswachstum
- Untersuchung der Kornverteilung





HYPERSPECTRAL ANALYSIS

BSTC



NB 2 - Folienlagerung
- Starke Änderung des Reflexionsgrades Tag 1 bis 9
- Moderate Änderung des Reflexionsgrades 7 bis 21 Tag
- Signifikanter Unterschied zu NB3

Ohne NB
- Starker Anstieg Tag 1 bis 7
- Ab Tag 9 gleichbleibend
- Signifikanter Unterschied zu NB3

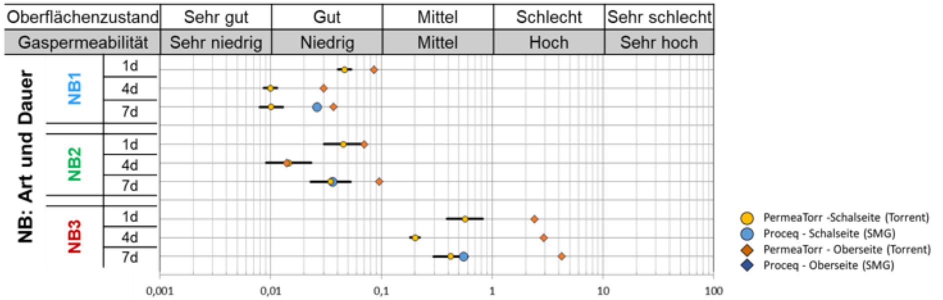
NB 3 - schlechte NB
- Reflexionsgrad steigt kaum an
- Signifikanter Unterschied

Understanding sustainable material performance (from the cradle to the bare) → Curing, Aging and Degradation

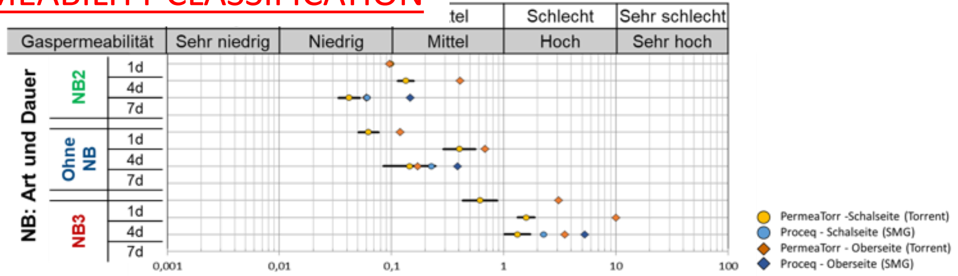
Project „Optimized material post-treatment for an improved structural performance (OptiNB)"

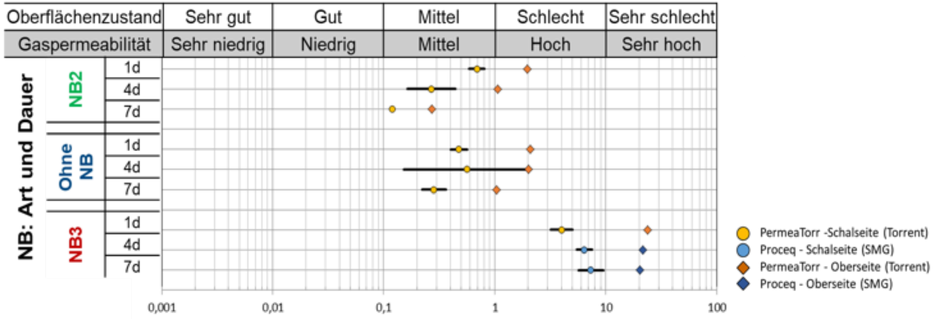
GOOD

BAD



GAS PERMEABILITY CLASSIFICATION





- **CONCRETE B5**

C30/37

CEM II/A-M (S-L)

42,5N; 12,5 % AHWZ

W/B-Wert = 0,48

L10 = 2,8-2,9 %

- **CONCRETE B3**

C25/30

CEM II/A-M (S-L)

42,5N; 13,8 % AHWZ

W/B-Wert = 0,53

L10 = 2,5-3,6 %

- **CONCRETE BS1C**

C25/30

CEM I 42,5N

SR0 WT27 C3A-frei

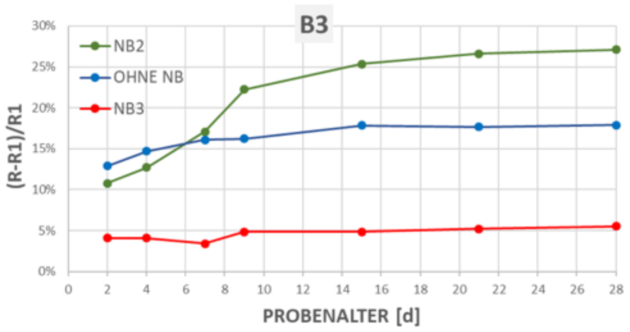
40 % AHWZ, XF4,

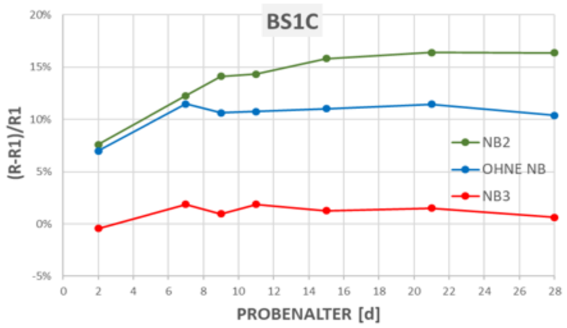
W/B-Wert = 0,48

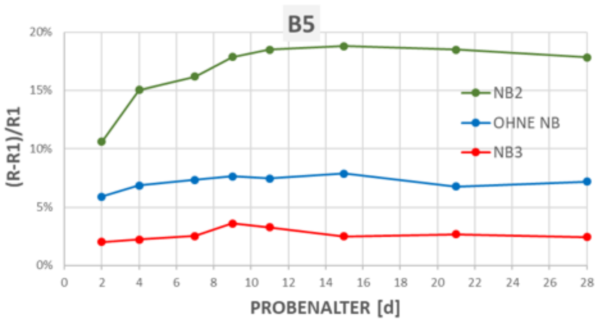
L10 = 5,8-7,3 %

Alternative sensor-based assessment options Hyperspectral analysis

HYPERSPECTRAL SIGNATURE CLASSIFICATION







- **Stärkster Reflexionsanstieg bei NB2 bis Tag 11 bzw. 15**
- **Geringste Veränderungen bei NB3, Verlauf relativ konstant**
- **Deutlichste Änderungen bis Tag 7 bei allen NB**

It is imperative

to have a sustainable management of our infrastructure by means of homogenized, *innovative, transdisciplinary*, robust performance

- detection and monitoring methods
- assessment & evaluation techniques
- analyses & prediction techniques

Thank you very much   Alfred Strauss