Large-scale Testing as a Precondition for the Development of SHM Systems

Wölfel

Large-scale Testing as a Precondition for the Development of SHM Systems

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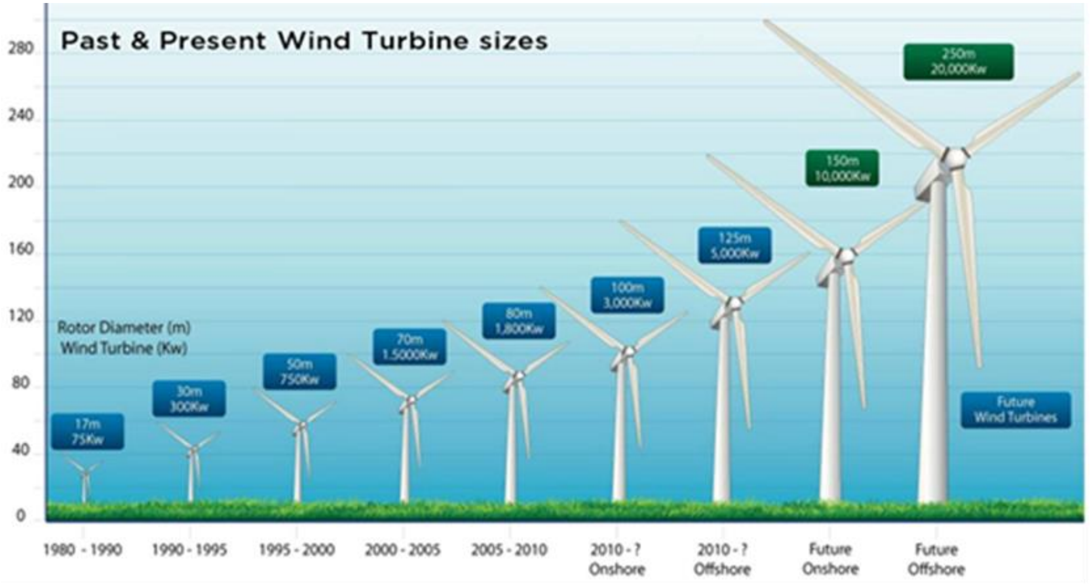
Outline

1. Why Structural Health Monitoring (SHM)?
2. What means SHM?
3. Large-scale experiment in the test center for load-bearing structures of University of Hannover, TTH
4. SHM of Offshore-Foundations
5. Summary

1. Why Structural Health Monitoring (SHM)?

Why wind turbines (WT) need to be monitored?

- WT are key elements of the energy turnaround
- In 2017, 17.7 % of gross electricity consumption in Germany
- Further size growth of turbines,
  current rotor blades from 60 to 80 m in length
- Extreme loads due to complex superposition of cyclical and stochastic dynamic loads from wind, waves and operation
- Service life of 25 to 27 years



- Difficult manufacturing conditions of all components
  (rotor blades, grouted joints, embedding in sediment, etc.),

→ imperfections must be expected.

- In combination with dynamic loads, imperfections are often the origin for damage

→ Wind turbines must be monitored!

2. What means SHM?

What is the monitoring subject of SHM?

Load-bearing structures or **supporting structures** like

- buildings, bridges, towers, foundations
- supporting parts of machinery and vehicles like aerospace structures, ship structures, rotor blades of wind turbines etc.
- Structures are **mainly statically loaded**
- Structures are often subjected to ambient excitation (e.g. wind, waves) or operational loads (from supported machines).

Pick-up of the rotor of a wind turbine with 117 m diameter

- Some monitored devices/plants consist of machine and structural components at the same time.
- A wind turbine consists of **load bearing** structural parts like foundation, tower and blades and **function related** machine components like main shaft, further shafts, gear box, roller bearings, generator, pitch and azimuth engines, etc.

Typical monitoring objects are **manually manufactured**:

→ The accuracy of the manufacturing process is more in the range of centimeters or decimeters

→ The **masses** and **stiffness** of such structures are **varying in percent range**.
(e.g. for 40 m RB with a weight of about 7 tons, a mass difference of 50 to100 kg is permissible

→ Each subject is **individual**. The first task is to become familiar with the subject to be supervised, meaning to get **reference values**

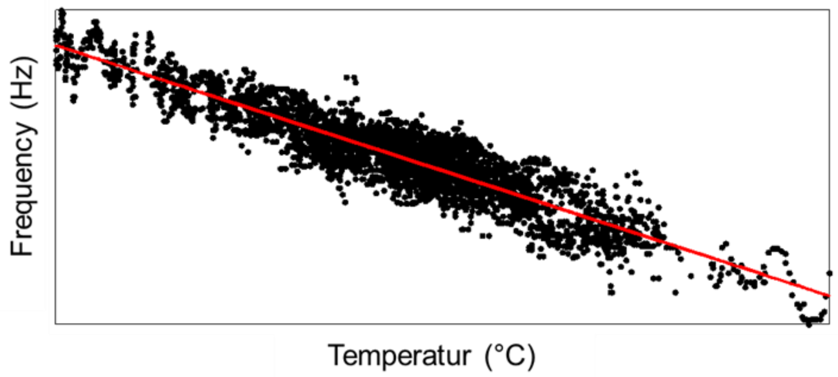
- Target of SHM consists in the assessment of the **load-bearing capacity** and the **stability** of the structure
- Usually no information about the **ultimate limit state** of the structure is available
- **Remaining life time** of supporting structures at the end of the design life is a very important topic
- SHM often is related to **novelty detection**, consisting in algorithms for unsupervised learning of the undamaged state, and is followed up by the application of change detection algorithms during the monitoring process.

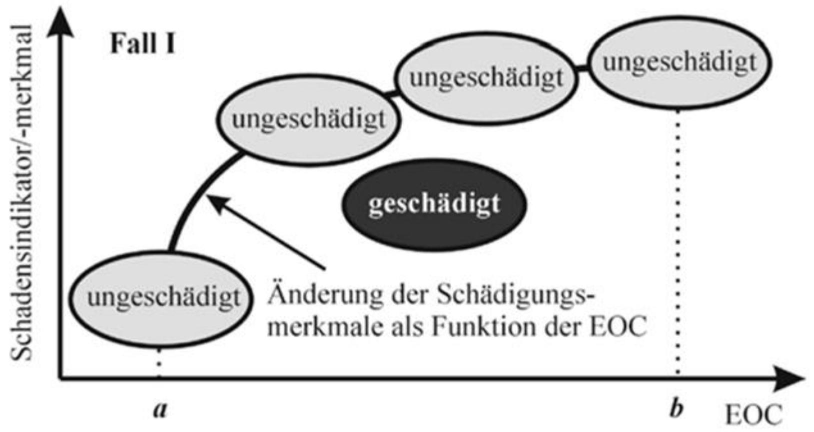
- Sensors cannot measure damages (Charles R. Farrar Keith Worden, 2012)
- Physical quantities that change during damage are measured
- The basis of SHM is therefore change detection and novelty detection.
- Feature extractions through signal processing and statistical classification are necessary to convert sensor data into damage information
- When a load-bearing structure is damaged, its stiffness changes
- The equation of motion shows us that this also changes the dynamics of the supporting structure:

$$\mathbf{M}\,\ddot{\mathbf{y}}_t + \mathbf{D}\,\dot{\mathbf{y}}_t + \mathbf{K}\,\mathbf{y}_t = \mathbf{u}_t$$

- With the dynamic SHM method, all modal quantities are measured and analyzed: Accelerations, vibration velocities, damping, phase …
- A great advantage of the dynamic SHM method is that vibrations cover the entire structure and therefore can be measured almost anywhere. Of course, there are very well suited measuring positions and those that are less suitable (near vibration nodes).

- One problem is the ambiguity of the dynamic messages.
  - increase of mass → natural frequency decreases
  - loss of stiffness → natural frequency decreases
- Compensation of environmental and operational conditions (EOCs) which also influence the dynamics of the structure.
- One way of compensating EOCs influences is the principal component analysis (PCA).
- Changes of the modal parameters are often very small, e.g. 0.5 % deviation of the natural frequency or 0.005 Hz for an offshore foundation.
- Powerful damage indicators are necessary





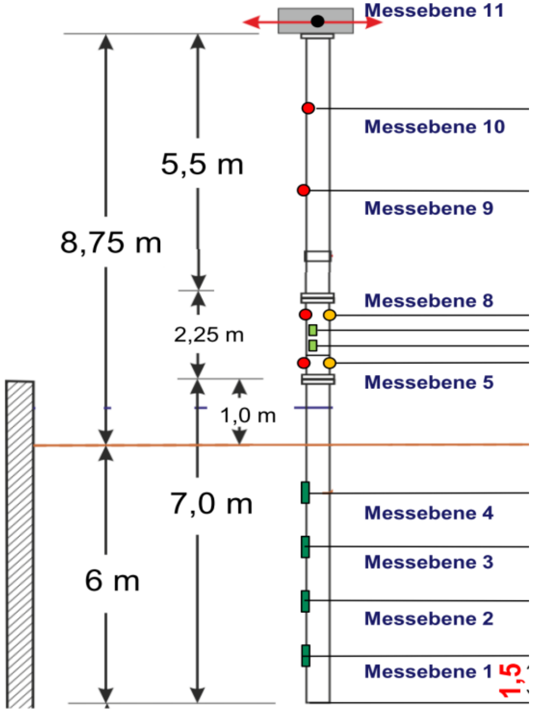
- The basic challenge with the dynamic SHM method is to distinguish between EOCs and damages, that both shift the natural frequency.

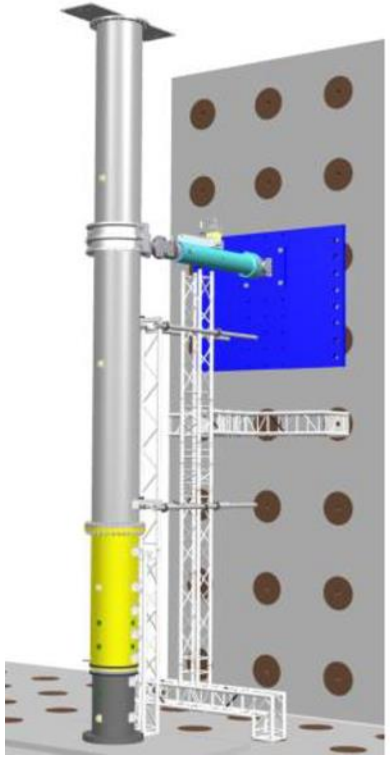
→ For the development of SHM systems, measurement data of damage and EOCs are a must!

3. Large-scale experiments in the test center for load-bearing structures of University of Hannover, TTH

- Measurement of EOCs and damage
- Development of different damage indicators:
  1. Covariance-driven Stochastic Subspace Identification Algorithm **(SSI-COV)**:
     Use in conjunction with output-only modal analysis. Stochastic state space models of lower order from measured time series; changes correspond to changes in vibration modes.
  2. Null Space-based Fault Detection Algorithm (**NSFD)**:
     Stochastic state space models of higher order from measured time series. NSFD method is more sensitive to structural changes than SSI-COV.
  3. Accumulated Energy **(AE)**:
     Defined as the integral of a power spectral density calculated on the basis of an auto or cross correlation between one or two different sensors. A change in the frequencies indicates an energy redistribution in the signal and thus a structural change.
- Test: How sensitive are the individual damage indicators?

Experimental setup





Sand Pit: Excitation by shaker

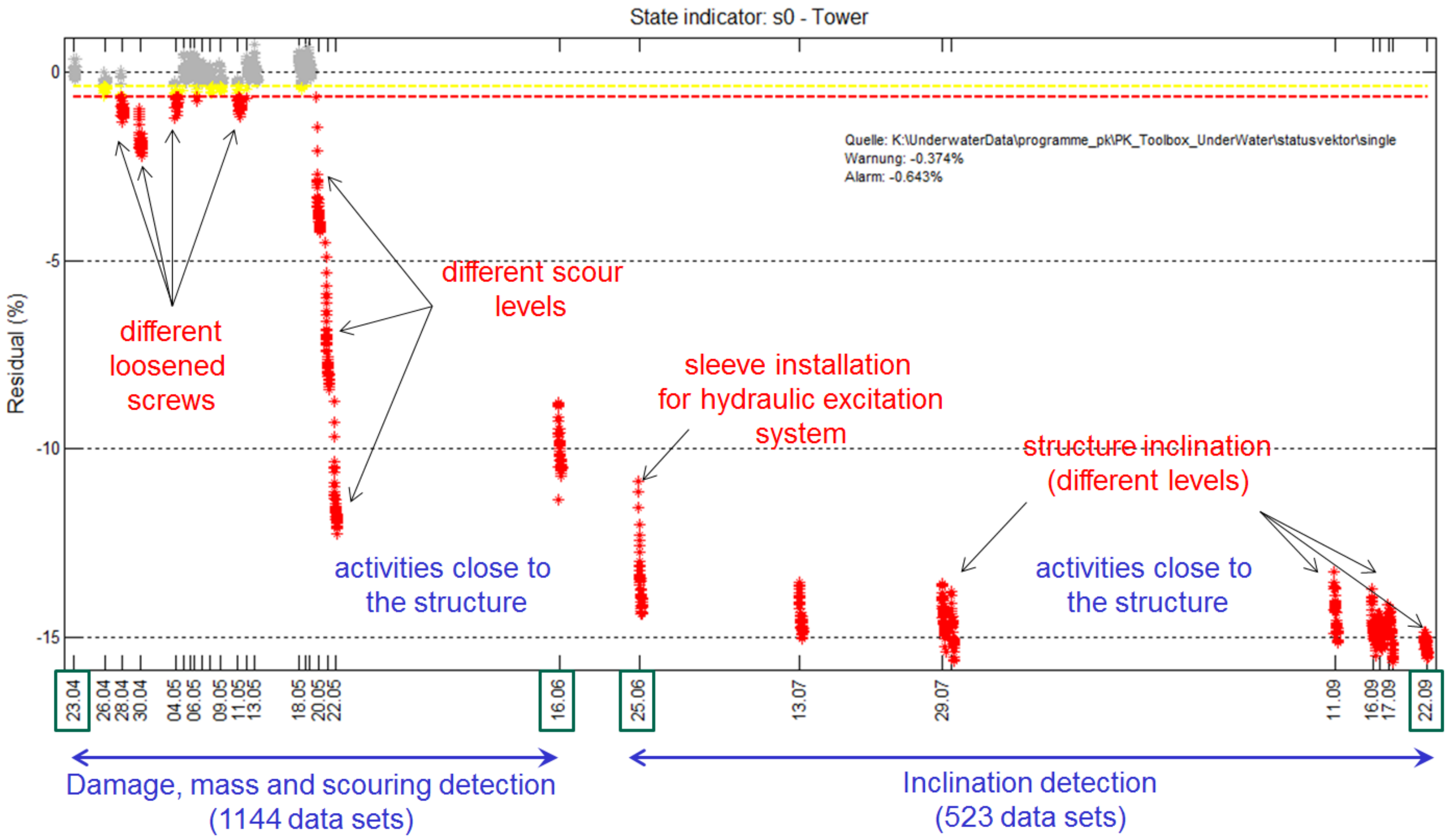
Span: Exitation by hydraulics and shaker

Sensitivity with regard to stability

Soil degradation

and scouring mask all other signal changes

→ Special analysis methods must be used to compensate for this effect



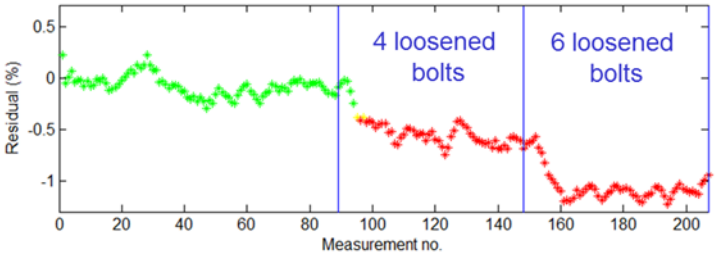
Pile stiffness loss

Reproducible structural damage to the flange (20 bolts) between the pile and tower.
Loosening of 2, 4 and 6 bolts.

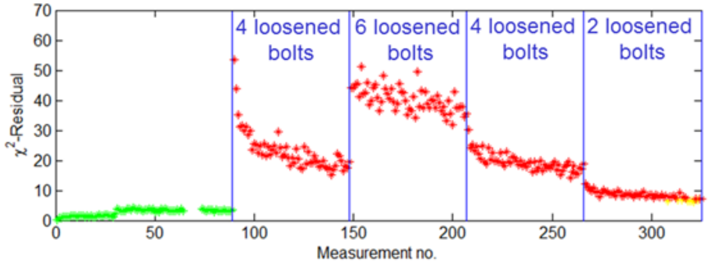
SSI-COV reliably detects 4 and 6 loosened screws

NSFD is much more sensitive and clearly recognizes all three damage states

SSI-COV-based Indiator



NSFD-based Indicator



Maritime fouling

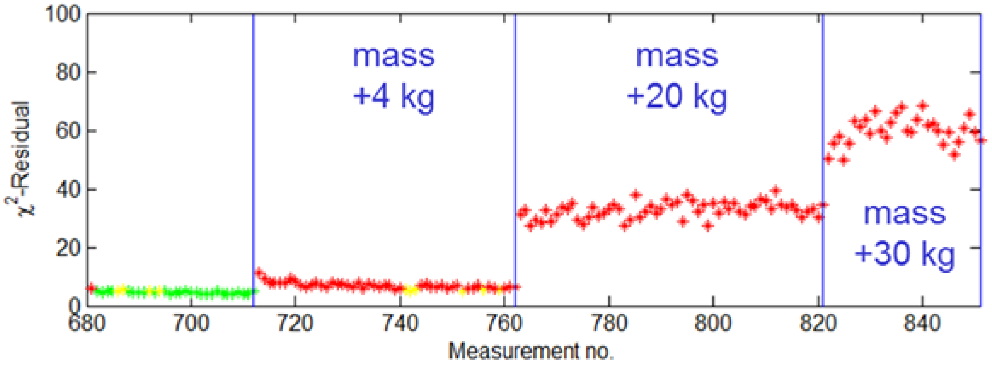
The simulation of fouling is problematic from an experimental point of view!

Special case: the vegetation in the changing water zone is hanging at low tide in the air additional masses of 4, 20 and 30 kg of oscillating mass of approx. 1 t

SSI-COV cannot reliably detect such small mass changes.

NSFD delivers very good results

Zusatzmasse 4, 20 oder 30 Kg



Scouring

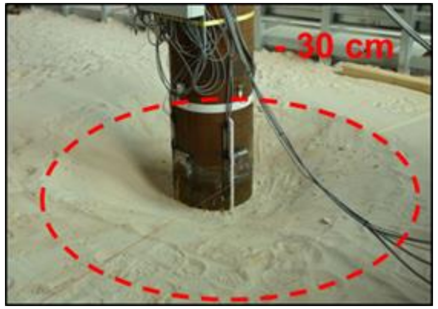
Scour formation changes the depth of embedment or the contact area between pile and sediment.
Experiments with 30, 60 and 80 cm deep scour

Changes in the boundary conditions of a cantilever beam have a significant effect on the eigenfrequencies

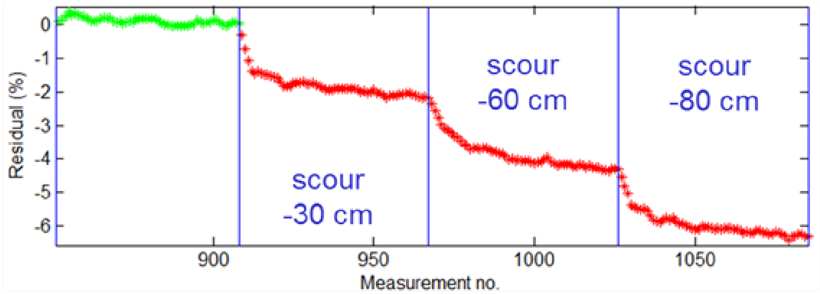
→ Scour formation can probably be reliably detected from a depth of 5 cm (scale 1 : 10)!

Both indicators SSI-COV and NSFD reliably detect the scour.

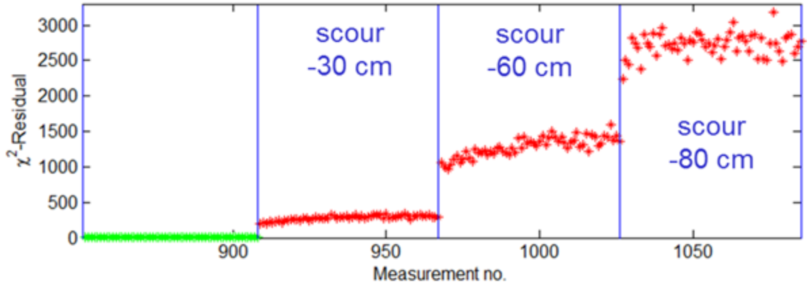
Problem of masking other, less significant signals



Depth of scour 30 cm



SSI-COV-Indicator



NSFD-Indicator

Test Procedure

Sequence for 1st Transition-Piece

1. Sand pit
2. Span: Load Amplitudes 10/25/50/75/90 kN
3. Sand pit

Loading by hydraulic cylinder

Before, between, and after loading, excitation by shaker through white noise (0 to 50 Hz) and sweeps

Sand pit

Sequence for 2nd Transition-Piece

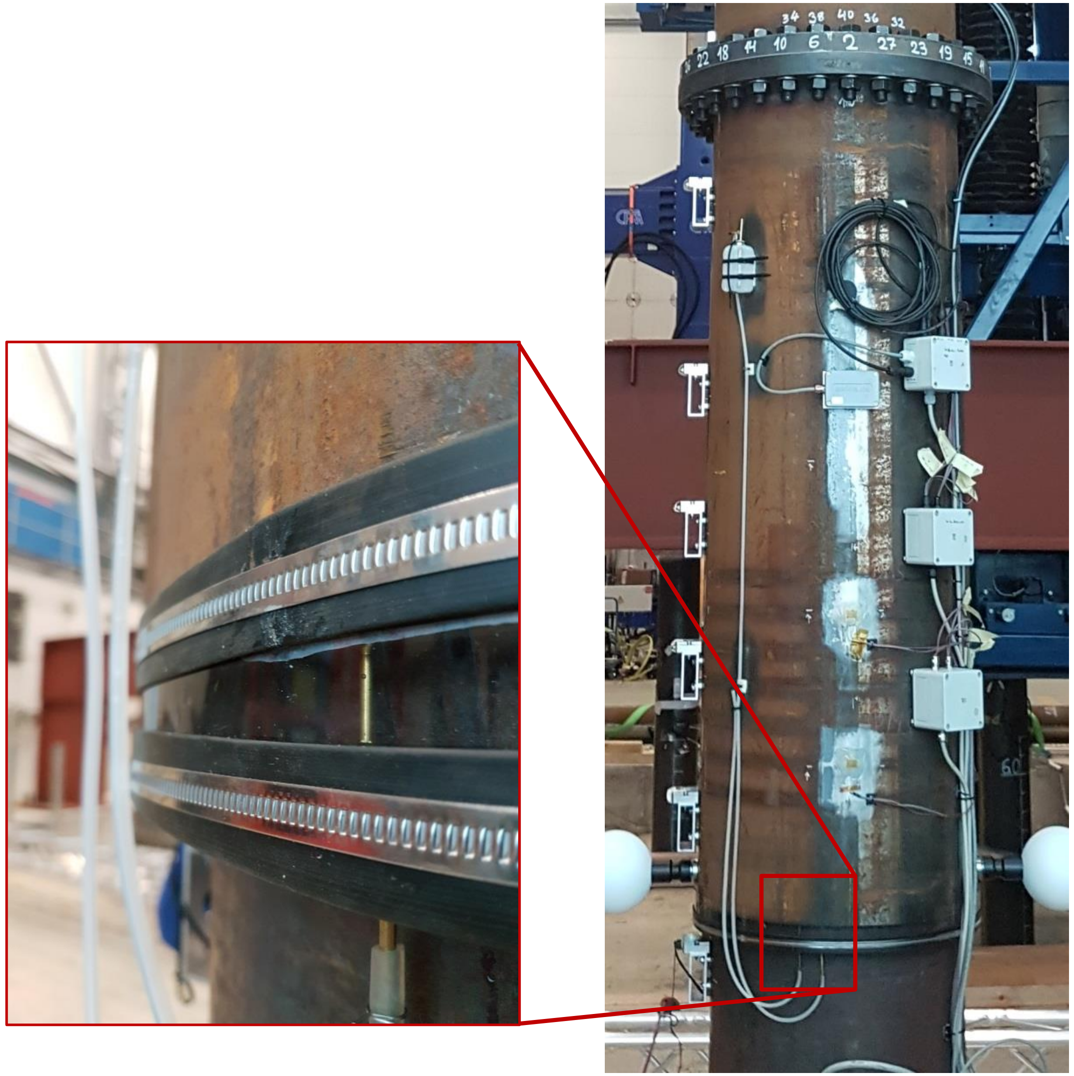
1. Sand pit
2. Span 10/25 kN
3. Sand pit
4. Span 50/75 kN
5. Sand pit
6. Span 90 kN
7. Break of 3 month
8. Span 90/90/100/100 kN

Loading: Similar to 1st TP

Span

Detail 2nd TP – Water Reservoir

- It was recently stated that water has a significant influence on the damage progression in grouted connections.
- This is due to a pumping-effect during cyclic loading, which evacuates grout material from cracks
- Hence, the second TP was equipped with a water reservoir.



Results

Damage indicators from accelerometers under white noise excitation

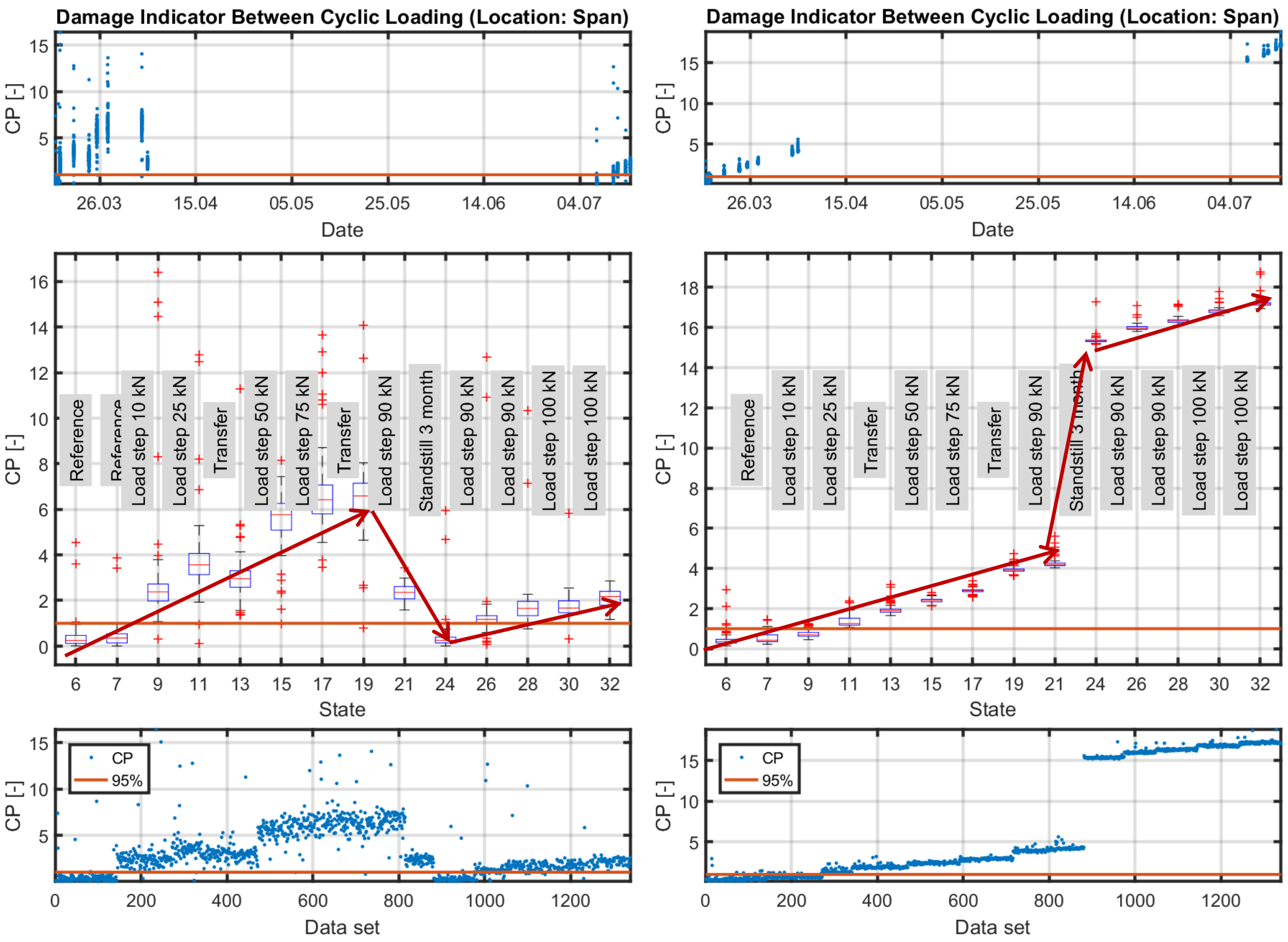
Values normalized to 95 % percentile of reference

Left: CP_{SSI}

- Increase up to 75 kN
- Decrease after 90 kN/standstill
- Slight increase for 90/100 kN

Right: CP_{AcEn}

- Increase up to 90 kN
- Strong jump after standstill
- Increase for 90/100 kN



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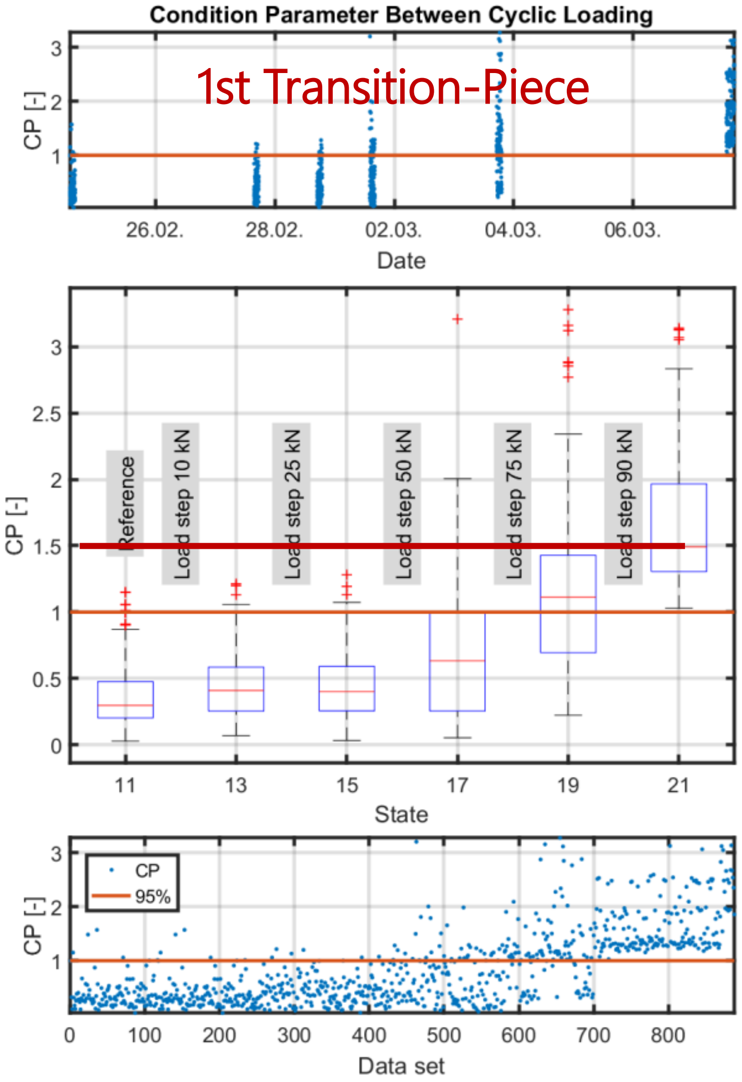
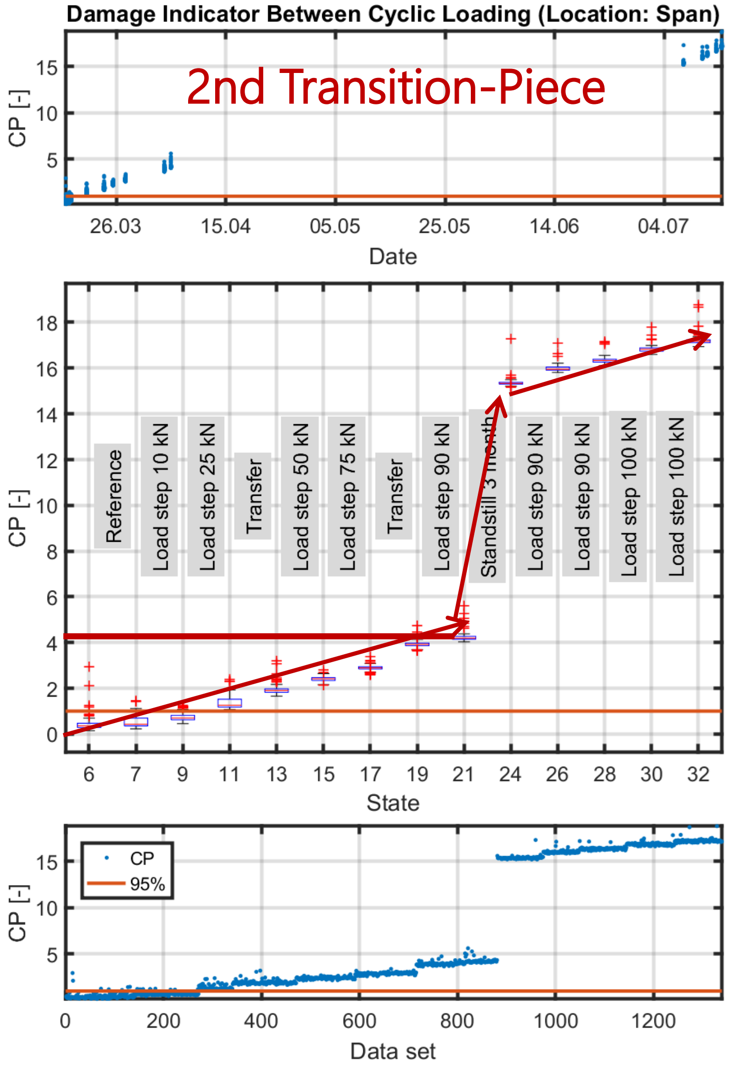
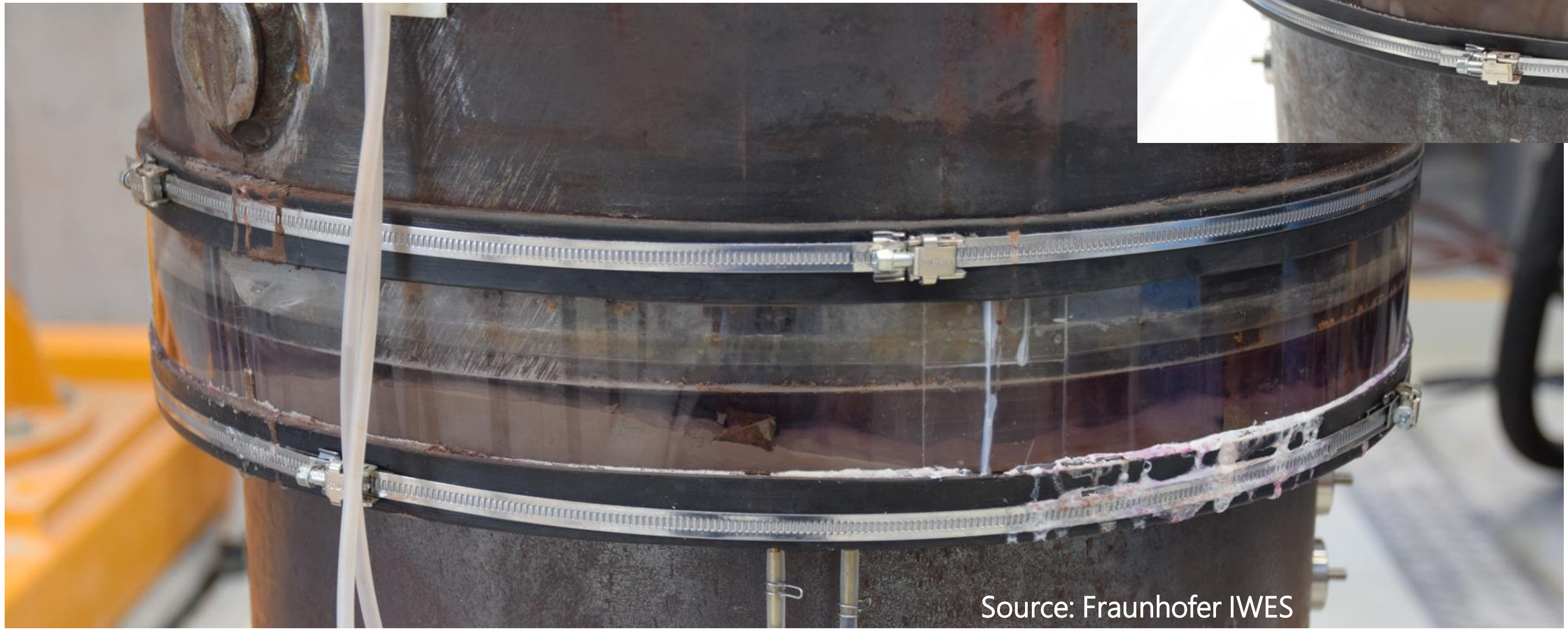
Stronger damage indication for CP_{AcEn} under water influence





Results – “Visual Damage”

Grout material in the water reservoir at TP2 below the grouted connection after final load cycle



5. Summary

- Due to size, load and manufacturing imperfections, offshore foundations must be monitored.
- SHM has been defined as the monitoring of the stability of load bearing structures.
- Vibration-based structural health monitoring detects changes
- In vibration-based SHM, defective changes in modal parameters must be distinguished from those that occur as a result of changes in environmental and operating conditions.
- For the development of SHM systems, measurement data of healthy structures, of changes in operating and environmental conditions, and of damage signals are necessary.
- The sensitivity of the damage indicators was successfully demonstrated in two research projects, UnderWater-Inspect and QS-M Grout.

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